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16. Abstract
The results of an extensive study of a specific emulsified diesel fuel, PuriNOx, is reported. This study evaluates the continued use of PuriNOx by TxDOT's Houston District and possible extension to the AGC contractors in the Houston area. The evaluation criteria were: health risks (relative to diesel fuel), safety (both highway safety and fire hazards), performance failure (compatibility of equipment with PuriNOx and ability to perform the required tasks), and cost-effectiveness. It was found that summer-grade PuriNOx is suitable for use in most, but not all, equipment based upon health risks, safety, and ability to perform the required tasks. Therefore, cost-effectiveness is the major criterion for the use of PuriNOx by the TxDOT and AGC fleets in the Houston area. The cost-effectiveness of PuriNOx was also compared to alternative NOx control techniques. It is found that use of Texas Low Emission Diesel is more cost-effective than PuriNOx. However, it is believed that PuriNOx may be an excellent method for NOx control by fleets for which the equipment is used at least twice per week and that do not operate at very high loads often enough that productivity will suffer.

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TxDOT Emulsified Diesel Final Report

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Table of Contents

List of Figures

List of Tables

Executive Summary

1. Introduction

The State of Texas has 4 ozone nonattainment areas: Houston, Beaumont/Port Arthur, Dallas/Fort Worth, and El Paso. The federal Clean Air Act, as implemented by the U.S. Environmental Protection Agency (EPA), requires the state to get each of these areas into attainment on a prescribed schedule. Of Texas' 4 one-hour ozone nonattainment areas, Houston is the most severe and is one of the worst in the U.S. Because ozone is formed near ground level via reactions between the oxides of nitrogen (NOx) and hydrocarbons (HCs) in the presence of sunlight, reducing NOx emissions in the Houston air basin is a major concern. In the Houston-Galveston area attainment plan adopted by The Texas Commission on Environmental Quality (TCEQ) in December 2000, TCEQ estimated that the base NOx inventory for 2007 (without any additional NOx control between 2000 and 2007) is 1101 tons of NOx emitted into the air basin each day. The State Implementation Plan (SIP) states that this inventory must be reduced by "...more than 750 tons per day to reach attainment." Thus, NOx control for the Houston area is also a major challenge. Of this 1101 tons per day, TCEQ estimated that on-road vehicles contribute 215 tons of NOx per day and off-road equipment contributes 147 tons per day, with the remainder from point sources (721 tons/day) and natural sources (18 tons/day). Thus, on-road and off-road engines are estimated to be responsible for ~33% of the NOx emitted into the Houston air basin. Because the Texas Department of Transportation (TxDOT) operates the largest fleet in Texas, and the 7th largest fleet in the U.S., it seems logical to involve TxDOT in NOx reduction efforts.

The TxDOT Houston District and two counties in TxDOT's Beaumont District began using an emulsified diesel fuel in July 2002. These 8 counties were chosen because they correspond with the 1-hour ozone nonattainment area. A diesel fuel emulsion is a mixture of water and diesel fuel. Emulsified diesel fuel has been the subject of research for over 30 years. The key to development of a commercial product is generation of an inexpensive surfactant to keep the water stabilized as small droplets in the diesel fuel; otherwise, the two will separate. Lubrizol was the first company to mass-market an emulsified diesel fuel, PuriNOx, in the U.S. The findings of this report are specific to PuriNOx and, in general, should not be extrapolated to other emulsified diesel fuels.

The current version of PuriNOx contains 20% water and 3% additive package. The advantage of PuriNOx is that it provides important decreases in the emissions of NOx and particulate matter (PM). Of these two, the effect on PM is generally larger, but the effect on NOx is more important from the perspective of Texas' State Implementation Plans for getting its ozone nonattainment areas into compliance. The most obvious disadvantages of emulsions stem from the fact that water does not contain any chemical energy. This means that diesel engines that are fueled with emulsions produce less torque and suffer a fuel economy penalty. Additionally, PuriNOx currently costs more than diesel fuel (when the price of diesel fuel becomes sufficiently high, the cost of PuriNOx might be lower than for diesel fuel, under some projected PuriNOx cost scenarios). Therefore, cost-effectiveness is an issue. There are also concerns about health risks, safety, fuel separation, and engine durability.

Because of these concerns, TxDOT commissioned a study of the efficacy of its use of PuriNOx and potential extension of the use of PuriNOx to TxDOT's contractors (the Association of General Contractors, AGC). The prime contractor for this study is the University of Texas (UT). Three research teams at UT took part in this study: the Center for Transportation Research (CTR), the Engines Research Program, and the Materials Research Program. Two subcontractors were used for this project: Southwest Research Institute (SwRI, in San Antonio) and Eastern Research Group (ERG, in Austin). From virtually any perspective, this was an ideal research team to pursue this project.

As shown in Figure 1, four criteria were used to assess the use of emulsified diesel fuel: health risks (relative to conventional diesel fuel); safety hazards (fire hazards and highway safety); performance (ability of the TxDOT equipment to perform the required tasks); and cost-effectiveness. The first three of these primary criteria were used to make a go/no-go decision on the use of PuriNOx, either for specific types of equipment or for the TxDOT fleet as a whole. Each of the four criteria is discussed below.

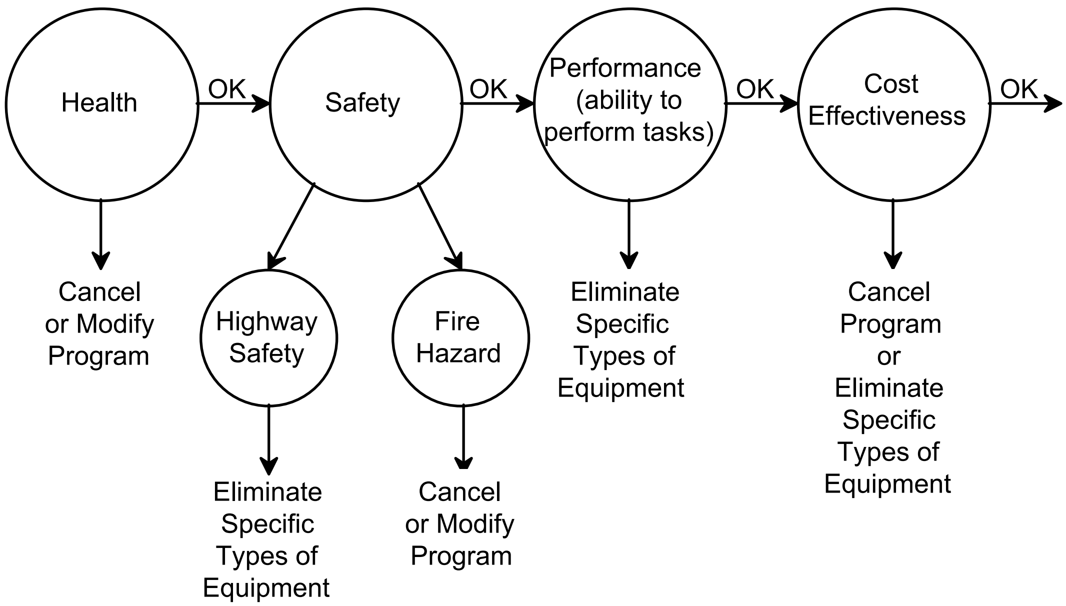

Figure 1 Global decision-making basis

2. Health Risks

A health risks analysis was included in this evaluation due to health complaints by TxDOT employees in the Beaumont counties that converted to PuriNOx. Because of these complaints, it was prudent to consider potential health risks in this evaluation. However, the present project was not designed to be a formal health effects study. Rather, the information for this analysis was obtained, primarily, from the Material Safety Data Sheets (MSDS) and from the results of prior studies. It must be noted that there are no standards for writing an MSDS. Therefore, conclusions drawn from comparing MSDS are tentative, at best.

There are three modes of exposure that present potential health risks: exposure to the liquid fuel (e.g., skin contact), inhalation of the fumes from the liquid, and exposure to the exhaust from diesel engines that are fueled with PuriNOx.

Based solely on the information in the MSDS, it does not appear that exposure to liquid summer-grade PuriNOx poses a greater health risk than does liquid diesel fuel. However, exposure to liquid winter-grade PuriNOx does pose a greater risk, due to the methanol that is used as an "anti-freeze" for winter-grade PuriNOx. This risk can probably be managed by the use of appropriate protective clothing. Therefore, neither summer-grade nor winter-grade PuriNOx can be excluded from use based upon the available information regarding exposure to the liquid.

There is also little information available to assess the health risks associated with inhalation of the fumes from the liquid, other than the MSDS. Again, the MSDS indicate that summer-grade PuriNOx poses about the same health risks as diesel fuel, and winter-grade PuriNOx presents a greater risk. However, approximately 30 TxDOT employees in the Beaumont District complained of headaches, eye irritation, nausea, and vomiting. Although this may have been due to exposure to the exhaust, a UT graduate student developed nausea from the fumes from summer-grade PuriNOx. This indicates that the health complaints may be related to the fumes rather than the exhaust. No health complaints were noted by TxDOT personnel in the 6 county Houston District, nor by any other PuriNOx users that we interviewed. We recommend that TxDOT take measures to minimize the potential for breathing the fumes – sound practice for the fumes from any liquid fuel.

Two occupational health studies of exposure to the exhaust indicate that PuriNOx does not yield products that are near or above safe limits. However, neither of these studies included the full list of Toxic Air Contaminants (TACs). During the present tests, the exhaust was "speciated" for the tests of one engine operating over the TxDOT Telescoping Boom Excavator Cycle and the AGC Wheeled Loader Cycle. Speciation involves detailed measurements of the composition of the exhaust, including the TACs. These results agreed with those from prior studies that found many of the TACs increase when summer-grade PuriNOx is used. Neither the EPA nor the California Air Resources Board (CARB) has established regulations for these TACs, other than formaldehyde. However, summer-grade PuriNOx has passed EPA's Tier 2 health risks analysis. That is, EPA has concluded that exposure to highly diluted exhaust from vehicles fueled with summer-grade PuriNOx does not pose a significant health risk to the public. However, TxDOT is concerned with exposure of its workers to close-vicinity exhaust. Neither of the occupational health studies (close-vicinity exhaust) was exhaustive. However, we are not aware of any health complaints outside of the TxDOT Beaumont District and the UT graduate student.

Thus, it appears that summer-grade PuriNOx does not pose health risks to the general public that exceed those for conventional diesel fuel. TxDOT workers should avoid skin contact with liquid PuriNOx, possibly via use of protective clothing. Also, as for all liquid fuels, it is prudent to avoid breathing the fumes. Workers in the vicinity of equipment that is using PuriNOx should take care to avoid breathing the exhaust.

However, partially based on health risks, if it is decided that TxDOT will continue using PuriNOx and that AGC will begin using it, we do not recommend that either use winter-grade PuriNOx. Winter-grade PuriNOx does pose a greater health risk than diesel fuel based on the MSDS. The emissions of TACs are somewhat higher when winter-grade

PuriNOx is used compared to summer-grade PuriNOx. No occupational health studies have been performed on winter-grade PuriNOx. Other reasons that we recommend against use of winter-grade PuriNOx are discussed later.

3. Safety

Safety concerns involve both traffic safety and fire hazards. Each is discussed below.

Although the torque loss resulting from use of PuriNOx penalizes acceleration, our studies do not indicate that this poses a safety hazard. However, some of TxDOT's vehicles cannot maintain 45 mph on the highway when using PuriNOx. We believe that this poses unnecessary risks to the driver, occupants, and other vehicles on the roadway. An example of TxDOT equipment with this problem is telescoping boom excavators. We do not recommend the use of summer-grade PuriNOx in telescoping boom excavators or any equipment that cannot maintain 45 mph on the highway when using PuriNOx. The safety criteria of acceptable acceleration and cruising speed for on-road driving are not relevant for off-road equipment. Therefore, use of summer-grade PuriNOx in equipment that is used solely for off-road activities is acceptable from the perspective of these safety criteria.

Our measured flash point for winter-grade PuriNOx, at 121 ºF, was higher than Lubrizol's minimum specification (97 ºF). However, we have found that the composition of summer-grade PuriNOx is variable. Thus, we cannot be certain that winter-grade PuriNOx will not be supplied with a flash point that is near the minimum specification. If so, it is of concern as a potential fire hazard for some situations. Thus, based upon this safety criterion, the uncertain health risks discussed previously, and practical reasons to be discussed later, we do not recommend the use of winter-grade PuriNOx by TxDOT or AGC.

4. Performance Failures

"Performance failure" can be a result of the torque loss resulting from the water in PuriNOx. The torque loss was also analyzed as a potential safety hazard, as discussed in Section 3, and is also accounted for as a potential loss of productivity in the cost-effectiveness analysis, as discussed in Section 5. However, performance failure can also result from other factors. The performance failure criterion is simple: can the vehicle perform its required tasks when using PuriNOx? One example of performance failure is the 6.5L GM engine with an optical sensor that detects water in the fuel. PuriNOx is not compatible with this sensor and, therefore, equipment that has this engine cannot use PuriNOx. Performance failure can also result from the torque loss associated with the water in the emulsion. For some pieces of equipment using PuriNOx, this torque loss is severe enough that the equipment cannot perform its required task. One example is the crane truck with the International T444E engine, which TxDOT quickly identified as unsuitable for PuriNOx use. Through surveys of TxDOT drivers and operators in the Houston District, surveys and quantitative data from the "Alternative Fuels Roadeo" staged for this project, and interviews with other PuriNOx users, the present research did not identify any performance failures that TxDOT had not already identified. If it is decided that TxDOT will continue using PuriNOx and that AGC will begin using it, we recommend that TxDOT continue its own determinations of performance failures, on a case-by-case basis, and that AGC should make a similar determination of what equipment cannot use PuriNOx due to inability to perform the required tasks.

5. Cost-effectiveness

The three go/no-go criteria discussed above resulted in TxDOT's elimination of ~50 pieces of equipment due to performance failures, our rejection of telescoping boom excavators and any other vehicles that cannot maintain at least 45 mph on the highway when using PuriNOx, and our rejection of winter-grade PuriNOx. For most diesel equipment, the only remaining criterion for the use of summer-grade PuriNOx is cost-effectiveness. The cost-effectiveness analysis required that we quantify the emissions and fuel consumption of PuriNOx relative to conventional diesel fuel for the equipment in TxDOT's fleet and for test cycles that reflect the way that TxDOT uses its equipment. We performed a similar cost-effectiveness analysis for AGC operations. These two analyses are discussed separately later in this section.

Because we could not test all of the various types of equipment in the TxDOT fleet, we had to first select equipment for testing. This was accomplished based upon TxDOT's records of fuel consumption in 12 of Texas' nonattainment counties in Fiscal Year 2001 (FY01). Telescoping boom excavators were chosen because they consume more fuel than any other type of off-road equipment. Similarly, single-axle dump trucks and tandem-axle dump trucks were chosen because they consume a significant fraction of the fuel used in TxDOT's on-road operations.

Our next task for the cost-effectiveness analysis was to generate TxDOT-specific test cycles. ERG, one of the subcontractors, accomplished this task by outfitting TxDOT equipment with data loggers, acquiring data during normal operations over at least a 1-week period, and using standardized techniques to extract a test cycle of about a 20-minute duration from the logged data. Additionally, because the AGC could be impacted by the results of this project, and because wheeled loaders are more typical of their equipment than telescoping boom excavators, ERG logged wheeled loader data, using AGC equipment and operators, and generated a test cycle from it. The four new test cycles that were developed are:

- TxDOT Telescoping Boom Excavator Cycle
- TxDOT Single-Axle Dump Truck Cycle
- TxDOT Tandem-Axle Dump Truck Cycle
- AGC Wheeled Loader Cycle

Each test cycle consists of a number of "microtrips," which typically consist of idle, acceleration, cruise, and deceleration back to idle. Each microtrip represents a typical mode of operation (from the analysis of the logged data), and the overall test cycle reflects the majority of typical use patterns.

SwRI measured the emissions and fuel economy of two different engines from telescoping boom excavators (on an engine dynamometer, and using both the TxDOT Telescoping Boom Excavator Cycle and the AGC Wheeled Loader Cycle), 4 different single-axle dump trucks, and 4 different tandem-axle dump trucks. The dump trucks were tested on a chassis dynamometer. PuriNOx and 2D on-road diesel fuel (which TxDOT uses in all of its equipment and has approximately 500 ppm sulfur) were compared for all of these tests. Additionally, a high sulfur (approximately 2,500 ppm) diesel fuel was used for the wheeled loader tests because many of AGC's members use a high sulfur off-road diesel fuel for their off-road equipment. A low sulfur (~500 ppm) off-road diesel fuel was also tested for the loaders, because this fuel is used by some AGC organizations. Finally, to ensure that the fuels provided to SwRI for emissions and fuel economy testing were representative of the commercial fuels in the Houston area, back-to-back tests were done to compare the supplied and commercial diesel fuels and to compare the test version of PuriNOx with commercial PuriNOx.

Previous comparisons of PuriNOx and conventional diesel fuel have suffered because, in our opinion, they did not properly account for the torque loss resulting from the water in PuriNOx. Most standardized test cycles for heavy-duty engines include one or more operating conditions for which 100% torque is required. However, 100% torque for PuriNOx is about 15% lower than 100% torque when using diesel fuel. Thus, over the test cycle the same work was not done by the engine using PuriNOx as the engine using diesel fuel. This difference in work affects emissions and fuel consumption. This poses the "hockey puck" question: "Would you get similar emissions and fuel economy from diesel fuel like PuriNOx if you put a hockey puck under the accelerator pedal so that the engine produced only 85% of its normal output?" To resolve this issue, we had to use "new science" for this project. Specifically, we had to develop a new means of comparing fuels. For the dump trucks, we call this the "route test cycle." Each microtrip has a physical meaning. For a dump truck, it might be idling at a traffic signal, accelerating away from the light and driving on the freeway, cruising until nearing the work site, and then decelerating to a stop at the work site. If the torque loss is sufficient enough that the vehicle could not cruise as fast on PuriNOx, the conventional comparison would require the dump truck to stop well short of the work site. Using the new route technique, the cruise is extended so that the PuriNOx-fueled vehicle actually reaches the work site before stopping. Although this makes sense and seems easy enough, development of the route technique required a major effort.

TxDOT also uses small utility diesel engines for herbicide sprayers, riding mowers, and traffic alerting signals. An engine of this type was tested at UT for operating conditions typical of TxDOT use.

The costs considered in the cost-effectiveness analysis for use of PuriNOx included:

- the initial costs of converting to PuriNOx and implementing its use,
- fuel economy effects,
- the higher cost of PuriNOx,
- the cost of refueling more often owing to the PuriNOx fuel consumption penalty,
- the cost of lower TxDOT and AGC equipment productivity owing to the loss of torque,
- increased maintenance, and
- various costs associated with the tendency of the emulsion to separate.

The cost-effectiveness of NOx control via the use of PuriNOx was compared with other alternatives, especially the use of an ultra low sulfur diesel fuel: Texas Low Emission Diesel (TxLED).

The tendency of emulsions to separate results in several problems that affect the cost-effectiveness. Examples are the emissions and fuel consumption penalties associated with the need to start PuriNOx-fueled engines twice weekly even when the equipment is not needed and the more frequent failure rates of injectors and fuel pumps. We performed fundamental studies of these cost-related issues, as discussed in the following paragraphs.

Our studies show that the fuel separates faster at higher temperatures, and in a non-linear manner (the separation rates at 35 and 73 ºF are very similar, but the separation rate is much higher at 130 ºF). During normal engine operation, the fuel in the fuel delivery system is heated via conduction from the engine and by the relatively high underhood air temperature. Heated fuel then returns to the fuel tank, where it heats the fuel in the tank. Hotter fuel is then delivered to the engine. The result is that the temperatures in both the tank and the fuel delivery system are higher than ambient during normal operation. However, the emulsion is probably well-mixed via agitation from the fuel that returns to the tank. When the engine is turned off, many of the components of the fuel delivery system hot soak to near coolant temperature (approximately 200 ºF). Also, radiation from the asphalt or concrete surface that the truck is parked on can elevate the tank temperature. Thus, separation may occur relatively rapidly after engine shut down.

Our tests revealed that corrosion does not occur in 2D diesel fuel for our test conditions, nor in a well-mixed emulsion, nor in the milky-white portion of the fuel after separation has occurred. Rather, corrosion only occurs in the transparent portion of the fuel after separation. Even though this upper portion has the appearance of diesel fuel, the fact that it corrodes whereas diesel fuel does not is strong indication that it contains one or more components that are not present in diesel fuel (possibly the additives) or is enriched in some diesel component(s) that may be corrosive. The upper portion of the separated fuel has a lower specific gravity than either PuriNOx or pure diesel fuel. This is additional evidence that the upper portion of the separated emulsion is enriched in light components. It is not known what these components are, but they must be responsible for the corrosive nature of the emulsion once it separates. In turn, it is possible that this could lead to corrosion of the tanks, injectors, and injection pumps. No complaints of tank corrosion have been noted during the period of this study, but that is undoubtedly a longer-term problem compared to the duration over which TxDOT has been using PuriNOx. However, TxDOT has noted increased failures of injectors and pumps. The present results may explain these failures as possibly resulting from separation within these components at elevated temperature.

Also, separation within the fuel delivery system, after engine shut down, may be the cause of hard starting. Our studies of the fuel that is injected after a shut down, hot soak, and 5 day period of non-use revealed evidence of separation in the fuel lines that can affect starting and idling.

TxDOT suffers a cost burden due to the need for starting each engine twice per week, even when not needed for normal service. There are also NOx and fuel consumption penalties associated with these extra starts. TxDOT also suffers a cost burden due to more frequent injector and pump failures. AGC will suffer from similar cost burdens. These factors have been accounted for in the cost-effectiveness analyses for TxDOT and AGC.

As an example of the productivity loss, at the Roadeo we found that wheeled loaders fueled with conventional diesel fuel could fill 5 dump trucks in 30 minutes, whereas loaders fueled with PuriNOx could only fill 4 dump trucks. Our analysis revealed that vehicles and equipment that are used with engine loads of about 80% or higher will experience a productivity loss. It appears that vehicles and equipment that spend little time with engine loads of more than ~80% will not experience any noticeable loss of productivity when using PuriNOx. Thus loss of productivity will depend upon the specific duty cycle for a given type of equipment: whether or not it performs work at more than

~80% torque and, if so, the percent torque and percent time it is required to work at these conditions. Any loss of productivity means that it will take longer and cost more to perform some jobs, for both TxDOT and AGC.

Too little information is presently available to account for longer-term effects in the cost analysis. Some of these long-term effects may be positive, such as the potential that PuriNOx results in fewer injector tip deposits and less wear of piston rings and liners. Some long-term effects may be negative, such as the possibility that PuriNOx might lead to fuel tank corrosion.

5.A. Cost-Effectiveness for TxDOT

Table 1 summarizes the estimated increase in the costs associated with the use of PuriNOx relative to diesel in all Houston District diesel equipment that was converted to PuriNOx and for each category of equipment that was included for detailed testing.

As shown in Table 1, the estimated annual costs incurred by TxDOT associated with the use of PuriNOx is in the range of $371,619 to $461,231, depending on how the implementation costs are accounted for.

*Table 1 Annual PuriNOx Cost Penalty for TxDOT's Houston District**

Cost Category	Houston Equipment (Total)	Excavator	Single-Axle Dump Truck	Tandem-Axle Dump Truck	Herbicide Sprayer	Arrow Board	Mower	Loader
Implementation/Conversion	84,504	4,123	19,209	10,237	1,724	4,885	4,003	4,184
Fuel Economy	40,280	5,813	6,596	7,370	860	156	298	1,113
Fuel Price	51,240	5,925	7,839	10,936	1,338	109	183	1,095
Re-fueling	15,393	1,620	2,415	3,369	412	30	50	299
Productivity	41,090	5,579	3,382	2,382	Negligible	Negligible	Negligible	5,034
Maintenance Cost	40,896	1,195	6,295	4,556	398	1,753	1,275	2,312
Maintenance Implementation	5,108	1,091	419	262	0	766	0	766
Starting	105,321	3,241	29,695	10,210	83	9,203	8,361	6,076
Fuel Storage	77,400	8,147	12,144	16,942	2,073	150	251	1,505
Total, including implementation costs ($)	**461,231**	**36,735**	**87,996**	**66,264**	**6,890**	**17,052**	**14,421**	**22,385**
Total, excluding implementation costs ($)	**371,619**	**31,521**	**68,368**	**55,765**	**5,166**	**11,401**	**10,418**	**17,435**
Total, including annualized implementation costs ($)	**382,124**	**32,132**	**70,669**	**56,996**	**5,368**	**12,064**	**10,888**	**18,015**

* - The "total" column includes all vehicles and equipment converted to PuriNOx in the Houston district. Also, "arrow board" refers to "traffic alerting signals".

State and local agencies use cost-effectiveness as one criterion when deciding whether to implement a particular emissions control program. Table 2 summarizes the calculated cost-effectiveness of using PuriNOx in TxDOT's Houston fleet.

Table 2 Cost-Effectiveness of PuriNOx for Reducing NOx Emissions (TxDOT, Houston)*

Cost Category	Houston Equipment (Total)	Excavator	Single-Axle Dump Truck	Tandem-Axle Dump Truck	Herbicide Sprayer	Arrow Board	Mower	Loader
NOx Benefit (tons/year)	1.157	0.356	0.220	(0.037)	0.054	0.001	(0.001)	0.042
Total Costs, including implementation costs ($)	461,231	36,735	87,996	66,264	6,890	17,052	14,421	22,385
Total Costs, excluding implementation costs ($)	371,619	31,521	68,368	55,765	5,166	11,401	10,418	17,435
Total Costs, including amortized implementation costs ($)	382,124	32,132	70,669	56,996	5,368	12,064	10,888	18,015
Cost-Effectiveness, including implementation costs ($/ton)	**398,644**	**103,188**	**399,980**		**127,597**	**17,051,938**		**532,969**
Cost-Effectiveness, excluding implementation costs ($/ton)	**321,192**	**88,542**	**310,762**		**95,668**	**11,401,244**		**415,109**
Cost-Effectiveness, including annualized implementation costs ($/ton)	**330,272**	**90,259**	**321,221**		**99,411**	**12,063,678**		**428,926**

* - In the cases of the tandem-axle dump trucks and mowers, the use of PuriNOx resulted in an increase in NOx emissions, because of the "extra starting" penalty.

Depending on the type of equipment, the cost-effectiveness associated with the use of PuriNOx varies from ~$90,000/ton for the telescoping boom excavators to more than $12 million/ton in the case of the traffic alerting signals if implementation costs are annualized. Even when excluding up-front implementation costs, because these have already been paid by TxDOT, the cost-effectiveness of reducing NOx emissions through the use of PuriNOx is ~$320,000/ton for the Houston District.

A number of options are, however, available to TxDOT to reduce the costs of using PuriNOx. The major cost categories are discussed below.

The **largest cost burden** for TxDOT is associated with the *need to start the PuriNOx-fueled engines at least twice weekly*, even when not needed for normal service. This requirement results from the tendency of the emulsion to separate. TxDOT determined, via trial-and-error, that all engines must be started at least twice each week to ensure that they can be started when needed. The costs related to this are the cost of the extra fuel used during the 45 minutes of idling that TxDOT uses to ensure that the fuel in the tank has become well mixed, and the cost of the labor. Of these two, the labor cost dominates by a large margin. TxDOT estimates that they devote 65 man-hours per week to these extra starts. We calculate, assuming 5 minutes to go to the equipment, start it, and make certain that it is idling stably and another 5 minutes to reverse this process, that it takes 78 man-hours per week. For items of equipment that are used seasonally or irregularly, like riding mowers, no options for decreasing this labor burden are apparent. For equipment that is used regularly, it is obvious that TxDOT has "favorites". For example, the newer dump trucks are preferred over the older ones. Thus, it might at first appear that TxDOT could optimize the scheduling to even out the use. However, if a newer dump truck is left on the lot for a week and replaced by an older one that is used during that week, then the newer one must be started twice, exactly replacing the two starts that the older dump truck would have had. An alternative is to get rid of equipment that is not used as often, such as some of the dump trucks. However, TxDOT has a minimum utilization policy that already ensures that vehicles and equipment that are not needed are sold. That is, it does not appear that any options are available for decreasing the labor cost resulting from the need for bi-weekly starts. However, the need for "extra" starts does depend upon equipment utilization. All of our calculations are based on fuel use in the Houston District during FY01, the most recent year for which complete records were available at the beginning of this project. Over the past 10 years, fuel use in FY01 was at a low point, ~11% below the average for the 10 year period. However, increasing the NOx benefit for normal operations by 11% while decreasing the NOx and cost penalties for the extra starts by, say 50%, still yields a cost-effectiveness of more than $200,000/ton, even when neglecting the extra fuel consumed for a higher equipment utilization scenario.

The need to start the PuriNOx-fueled engines at least twice weekly also results in a NOx penalty, reducing the tons of NOx removed annually from ~1.6 tons/year for normal operation to ~1.2 tons/year after accounting for the NOx emitted during the 45 minutes of starting and warm-up for each "unused" engine twice per week. In turn, this makes the cost-effectiveness of NOx removal worse. We assumed a 48% NOx benefit at idle (Musculus et al., 2002) together with data for fuel consumption and NOx emissions at idle (Lim, 2003; Storey et al., 2003) plus an assumption about how these scale with engine size. That is, there is some uncertainty in our calculations of the NOx penalty and additional uncertainty regarding whether 45 minutes is the optimum amount of agitation that is required to ensure that the fuel in the tank is well mixed. A research project is required to improve these uncertainties. However, even if the result of such a project decreases the labor cost (~$105,000/year) and NOx penalties for the extra starts (~0.43 tons/year) by a factor of 2, the cost-effectiveness would still be more than $230,000 per ton, as can be deduced from Tables 1 and 2.

The **second highest cost burden** is for *conversion and implementation*. This cost has already been paid by TxDOT's Houston District. As shown in Table 2, if this is taken to be a one-time up-front cost, the cost-effectiveness for the first year is almost $400,000/ton and in subsequent years it is ~$320,000/ton (assuming the same fuel use patterns and costs as in FY01). Alternatively, if the conversion and implementation costs are annualized over 10 years, the cost-effectiveness is ~$330,000/ton each year. No options exist for decreasing this cost category, only perspectives on how to account for it.

The incremental cost of PuriNOx relative to diesel fuel affects both the *fuel cost category and the fuel economy category*. Taken together, these represent the **third highest cost burden**. The Lubrizol vendor, JAM Distributing, has indicated that lower PuriNOx fuel prices can be obtained if economies of scale can be achieved in distributing the fuel to TxDOT sites, and if the fuel purchase contracts can be based on a PuriNOx Posted Price as opposed to the current practice of the base diesel price plus a constant. The vendor claims that a PuriNOx Posted Price contract will be especially beneficial to TxDOT in situations of higher base diesel prices. One PPP scenario, for which the rack price of diesel fuel is $0.28/gallon higher than the average for FY02, indicates a cost savings of ~$34,000/year by changing TxDOT's contract for PuriNOx. However, this is highly dependent upon the variable rack price of diesel fuel.

Another means for decreasing the cost burden associated with the incremental cost of PuriNOx is through the Texas Emission Reduction Plan (TERP) rebate program, which is intended to reward voluntary measures for reducing NOx emissions. Under the current TERP program[1] TxDOT will qualify for a TERP grant of $0.24/gallon for off-road equipment and

[1] An initial study by TCEQ determined that the incremental fuel cost – consisting of only the fuel economy and fuel cost penalties - of using PuriNOx to reduce NOx emissions justifies a rebate of $0.24/gallon for off-road and

$0.26/gallon for on-road vehicles. This TERP grant will reduce the fuel economy and fuel cost penalties to $32,016 and $3,874. Although this improves the cost-effectiveness, the effect is small, with the best being ~$69,000/ton for the herbicide sprayer. For the overall TxDOT fleet in the Houston District, a TERP rebate yields a cost-effectiveness of more than $270,000/ton. It must also be noted that a TERP rebate would decrease the cost to TxDOT, but because TERP funds are also state funds, the cost-effectiveness to the State of Texas does not benefit from a TERP rebate to TxDOT.

Table 3 Cost-Effectiveness of PuriNOx to Reduce NOx Emissions Including a TERP Grant (TxDOT, Houston)

Cost Category	Houston Equipment (Total)	Excavator	Single-Axle Dump Truck	Tandem-Axle Dump Truck	Herbicide Sprayer	Arrow Board	Mower	Loader
NOx Benefit (tons/year)	1.157	0.356	0.220	(0.037)	0.054	0.001	(0.001)	0.042
Total Costs, including implementation costs ($)	405,601	30,819	79,117	54,248	5,428	16,932	14,214	21,283
Total Costs, excluding implementation costs ($)	315,990	25,605	59,489	43,749	3,704	11,282	10,211	16,333
Total Costs, including amortized implementation costs ($)	326,495	26,216	61,790	44,979	3,906	11,944	10,680	16,914
Cost-Effectiveness, including implementation costs ($/ton)	**350,563**	**86,570**	**359,623**		**100,518**	**16,932,418**		**506,746**
Cost-Effectiveness, excluding implementation costs ($/ton)	**273,111**	**71,925**	**270,406**		**68,589**	**11,281,724**		**388,886**
Cost-Effectiveness, including annualized implementation costs ($/ton)	**282,191**	**73,624**	**280,865**		**72,332**	**11,944,158**		**402,703**

However, as discussed in Chapter 5, the results of the present study indicate that the TCEQ criterion of $13,000 per ton of NOx, based solely upon the fuel penalties (cost and economy), justifies only a rebate of $0.095/gallon. TCEQ is currently evaluating the rebate program, and may make changes in the near future. If so, rebates of $0.24-0.26 per gallon of PuriNOx, as currently available, may be reduced in future years. However, the results presented in Tables 3 and 4 are for the currently available rebates of $0.24/gallon for off-road equipment and $0.26/gallon for on-road vehicles.

The **next highest cost category** is *fuel storage*. TxDOT can consider purchasing the fuel storage tanks rather than renting them. The quoted cost for seven 2,000-gallon tanks and one 4,000-gallon tank, including circulation pump, delivery and installation, amounts to $165,000 (Personal communication with TxDOT, 2002). If annualized over 10 years at a 3% discount rate, the fuel storage tank costs will amount to $19,343/year for 10 years – compared to $77,400/year for the rental of the skid-mounted tanks. Table 4 summarizes the cost-effectiveness of using PuriNOx to reduce NOx emissions from the Houston TxDOT fleet, considering both the TERP rebate and assuming that TxDOT purchases the fuel storage tanks. For the overall TxDOT fleet in the Houston District, purchase of the fuel tanks plus a TERP rebate yields a cost-effectiveness that is still more than $220,000/ton. Even if these are taken

$0.26/gallon for on-road vehicles/equipment. In these initial calculations it was found that these rebates will allow the state to obtain the NOx emissions reductions at $13,000/ton – the TCEQ cost-effectiveness criterion.

together with some (unknown) means of decreasing the NOx and labor penalties for the extra starts by 50% and an increase in the NOx removed by 11% for a higher equipment utilization scenario (but neglecting the additional fuel used and other factors associated with increased utilization), the cost-effectiveness is still more than $110,000/ton.

Table 4. Cost-Effectiveness of PuriNOx to Reduce NOx Emissions
(Including TERP Grant and Fuel Storage Tank Purchase)

Cost Category	**Houston Equipment (Total)**	**Excavator**	**Single-Axle Dump Truck**	**Tandem-Axle Dump Truck**	**Herbicide Sprayer**	**Arrow Board**	**Mower**	**Loader**
NOx Benefit (tons/year)	1.157	0.356	0.220	(0.037)	0.054	0.001	(0.001)	0.042
Total Costs, including implementation costs ($)	347,544	24,708	70,008	41,540	3,873	16,820	14,025	20,154
Total Costs, excluding implementation costs ($)	257,933	19,494	50,380	31,041	2,149	11,169	10,022	15,204
Total Costs, including amortized implementation costs ($)	268,438	20,105	52,681	32,272	2,351	11,832	10,491	15,784
Cost-Effectiveness, including implementation costs ($/ton)	**300,384**	**69,404**	**318,217**		**71,718**	**16,819,786**		**479,861**
Cost-Effectiveness, excluding implementation costs ($/ton)	**222,932**	**54,759**	**228,999**		**39,789**	**11,169,092**		**362,001**
Cost-Effectiveness, including annualized implementation costs ($/ton)	**232,012**	**56,476**	**239,458**		**43,532**	**11,831,525**		**375,818**

To examine the effects of using PuriNOx in future years as TxDOT replaces older equipment with newer equipment, the emissions reductions and cost-effectiveness of using PuriNOx in a future TxDOT fleet with only electronically-controlled engines in the single-axle dump trucks, excavators, and loaders were also analyzed. In agreement with the findings of an EPA evaluation of PuriNOx (EPA, 2002a), we found that engines that were designed to meet less stringent emissions standards enjoyed a NOx benefit of ~23% due to use of PuriNOx, whereas those that were designed to meet more stringent emissions standards (which we roughly segregated as those that are electronically-controlled) had a benefit of only ~12%. Therefore, PuriNOx will result in smaller reductions in NOx emissions as the fleet is upgraded to cleaner electronically-controlled engines[2]. As can be seen from Table 5, the smaller emissions reductions associated with cleaner electronically-controlled excavator and loader engines result in a worse cost-effectiveness for these categories of equipment. The emissions benefit associated with the single-axle dump trucks is largely dominated by the significant NOx benefits associated with the electronically-controlled T444E single-axle dump truck tested. (This was the only electronically-controlled engine tested that had a NOx benefit of more than 13.6% and, in fact, had a NOx benefit of 32.7%. It is believed that this unusual behavior is due to the fact that this appeared to be the most under-powered vehicle tested and, thus, suffered most from the torque loss associated with the water in the emulsion.) However, even though the cost-effectiveness for the single-axle dump trucks improved for the scenario of an all-

[2] In the case of the tandem-axle dump trucks it was found that the use of PuriNOx in the electronically-controlled engines resulted in an increase in NOx emissions due to the "extra" starting penalty.

electronic fleet, it is still very high, at almost $240,000/ton. The best case for an all-electronic fleet is the telescoping boom excavators, at ~$166,000 per ton of NOx removed.

Table 5 Cost-Effectiveness of Using PuriNOx in Electronically Controlled Engines

	Houston Equipment			Electronically Controlled Engines		
	Excavator	**Single-Axle Dump Truck**	**Loader**	**Excavator**	**Single-Axle Dump Truck**	**Loader**
NOx Benefit (tons/year)	0.356	0.220	0.042	0.188	0.291	0.032
Total Costs, including implementation costs ($)	36,735	87,996	22,385	35,807	86,005	22,154
Total Costs, excluding implementation costs ($)	31,521	68,368	17,435	30,593	66,378	17,204
Total Costs, including amortized implementation costs ($)	32,132	70,669	18,015	31,204	68,679	17,784
Cost-Effectiveness, including implementation costs ($/ton)	**103,188**	**399,980**	**532,969**	**190,462**	**295,551**	**692,305**
Cost-Effectiveness, excluding implementation costs ($/ton)	**88,542**	**310,762**	**415,109**	**162,729**	**228,102**	**537,614**
Cost-Effectiveness, including annualized implementation costs ($/ton)	**90,259**	**321,221**	**428,926**	**165,980**	**236,009**	**555,748**

This cost-effectiveness calculation excludes the emissions and fuel penalties associated with the additional cold starts required. A lack of data prevented the calculation of these penalties for an all-electronic fleet. The labor cost associated with the additional cold starts is, however, considered.

The research team interviewed a number of different agencies, including representatives from the EPA's Voluntary Diesel Retrofit Program, the Diesel Technology Forum, the Department of Energy, Argonne National Laboratory, Good Company Associates, AAE Technologies, and the Manufacturers of Emissions Control Association, to identify alternative emission abatement strategies for NOx in heavy-duty diesel engines. The available information suggests that a number of technologies currently being researched and demonstrated, such as Selective Catalytic Reduction (SCR) and Exhaust Gas Recirculation (EGR), would reduce NOx emissions significantly in the future. However, both SCR and EGR require electronic controls and, therefore, are best suited to new engines that already have computer control systems. Although some aftermarket systems are being developed for use on older engines, very few NOx control technologies have CARB or EPA verification. Additionally, costs, durability, and warranty issues for such devices are uncertain. Therefore, the only EPA-verified options at the present time are fuels (e.g., PuriNOx) and replacement of older engines with new, electronically-controlled engines with superior emissions controls.

However, there is one other important option available to both TxDOT and AGC that is recognized by CARB and EPA. Texas Low Emission Diesel is a specially formulated, low-emission diesel fuel that is estimated by TCEQ to reduce NOx emissions by 7% in off-road applications and 5.7% in on-road applications[3], which have been recognized by EPA for SIP credit. No modifications are required to existing fueling infrastructure or diesel vehicles/equipment, and no other implementation, maintenance or performance costs are

[3] These estimates are subject to change during the mid-course review process at TCEQ.

anticipated with the use of TxLED. Additionally, the NOx emission reduction potential of TxLED is slightly higher than for PuriNOx (~1.3 vs ~1.1 tons), in spite of the 5.7-7% NOx benefit of TxLED relative to the ~12-23% benefit for PuriNOx. The overall decrease in NOx for TxLED relative to PuriNOx occurs for two reasons: 1) TxLED does not suffer from the NOx penalty associated with the need to start engines fueled with PuriNOx at least twice each week, and 2) the ~50 vehicles and pieces of equipment in the Houston District that could not be converted to PuriNOx for various reasons can use TxLED. Given that the incremental fuel cost for use of TxLED in the Houston area is estimated at between $0.12 and $0.21/gallon, the calculated cost-effectiveness of using TxLED to reduce NOx emissions ranges between ~$23,000 and $39,000/ton, for the overall TxDOT Houston District fleet, as shown in Table 6.

Therefore, TxLED is a much lower cost strategy for achieving NOx emissions reductions than PuriNOx in the TxDOT Houston District fleet. The available TERP rebate for TxLED is currently $0.07/gallon. Given this rebate, the annual fuel cost penalty associated with the use of TxLED will decrease to $35,149 and $12,553 under the high and low fuel cost scenarios, respectively. This results in a cost-effectiveness of $26,275 and $9,384/ton, respectively. Of course, as for PuriNOx, a TERP rebate would improve the cost-effectiveness for TxDOT but would have no effect on the cost-effectiveness for the State of Texas, since TERP funds are state funds. Additionally, no rebate for use of TxLED will be possible beginning in 2005, if its use becomes mandated.

Table 6 Cost-Effectiveness of TxLED for Reducing NOx Emissions (TxDOT, Houston)

Cost Category	**Houston Equipment (Total)**	**Excavator**	**Single-Axle Dump Truck**	**Tandem-Axle Dump Truck**	**Herbicide Sprayer**	**Arrow Board**	**Mower**	**Loader**
NOx Benefit (tons/year)	1.338	0.120	0.164	0.193	0.068	0.002	0.004	0.022
Cost-Effectiveness; High Fuel Cost ($/ton)	**39,413**	**34,152**	**37,461**	**43,971**	**38,659**	**31,413**	**29,516**	**34,566**
Cost-Effectiveness; Low Fuel Cost ($/ton)	**22,521**	**19,515**	**21,406**	**25,127**	**22,091**	**17,950**	**16,866**	**19,752**

5.B. Cost-Effectiveness for AGC

The AGC vehicle and equipment fleet in the Houston area is quite different from TxDOT's fleet. TxDOT's fuel use is dominated by on-road vehicles whereas AGC's is dominated by off-road equipment. In the cost-effectiveness analysis for AGC, on-road vehicles were neglected because they represent less than 10% of NOx emissions (due to the low percentage of fuel used by AGC's on-road vehicles coupled with the "cleaner" engines used in on-road vehicles). For the AGC analysis, fuel consumption penalties and NOx benefits were estimated from the SwRI tests for 2 different engines operating over the AGC Wheeled Loader Cycle. One of these was electronically-controlled while the other was mechanically-controlled. A range of cost-effectiveness estimates was developed for AGC use of PuriNOx, accounting for a number of different cost and emission scenarios. The "low" cost scenarios assumed minimal extra engine starts, low-cost performance penalty assumptions, and delivered fuel costs based on a variable PuriNOx Posted Price (PPP). The "high" cost scenario assumed the maximum number of extra engine starts, high-cost performance penalty conditions, and the current TxDOT constant fuel cost increment. We believe it is highly unlikely that the actual cost-effectiveness will approximate either the low or high end value, but will most likely fall well in between these extremes. The "midpoint" cost between these two extremes is shown in Table 7.

Table 7 AGC Midpoint Cost Summary

Implementation(1)	$64,158
Maintenance(2)	$201,424
Fuel Storage(3)	$0
Refueling Time	$30,387
Fuel Cost	$938,784
Extra Starts	$95,899
Performance Penalty	$3,132,507
Total	**$4,463,158**

(1) - 5 yr, amortized at 10%
(2) - includes year one annualized costs
(3) - NA, part of fuel delivery cost

Like that for TxDOT, the AGC cost-effectiveness evaluation also found that TxLED is likely to be more cost-effective than the use of PuriNOx. Taking the midpoint of the dollar-per-ton ranges, TxLED reductions would cost approximately $8,000 per ton of NOx, while PuriNOx reductions would cost about $41,000/ton (current engine mix scenario). However, in terms of absolute emission reductions, PuriNOx use could generate about 108 tons per year of NOx reductions, compared to only 42 tons per year of reductions from TxLED use. Therefore, the "first" 42 tons of reductions could be obtained at the relatively low cost of about $8,000 per ton. However, the *marginal cost-effectiveness* of the remaining 66 tons of reduction potential is even higher than $41,000/ton, at about $62,000 per ton, using the midpoint value for incremental TxLED costs.[4] To the extent that cost-effectiveness is an important decision criterion, it is instructive to look at marginal as well as average cost-effectiveness levels.[5]

Note that these cost-effectiveness values are static estimates, only applicable to the current AGC fleet mix. As discussed for the TxDOT fleet, as electronic engines penetrate the AGC fleet more and more, potential NOx reductions will fall and dollar-per-ton values will increase. This trend may be accelerated to the extent that AGC contractors participate in the TERP program through re-engining and early retirement of mechanical engines. Such a trend will tend to increase dollar-per-ton estimates for TxLED as well as PuriNOx.

The cost-effectiveness of control options will also change as baseline fuels change. Most notably, if TxLED use becomes mandated in 2005, TxLED will become the new baseline fuel. Accordingly, PuriNOx use will lead to significantly lower NOx reductions from 2005 onward, simply due to the cleaner baseline fuel. In other words, the marginal cost-effectiveness of PuriNOx discussed above ($62,000/ton) will become the *average* cost-effectiveness once TxLED is adopted region wide.

[4] Here marginal cost-effectiveness attributes the <u>entire</u> cost of PuriNOx adoption, net of the higher baseline cost of TxLED, only to the incremental reductions over and above those obtainable from TxLED (i.e., about $4.1M/66 tpy).
[5] Note that the Clean Air Act Amendments do not consider cost-effectiveness in the determination of compliance with the Act's requirements.

In all cases, the cost-effectiveness of PuriNOx use is expected to increase above the current estimates over time. Given these findings, we do not anticipate that PuriNOx will meet the cost-effectiveness level obtainable through the use of TxLED. Based on this criterion alone, we cannot recommend that AGC contractors use PuriNOx in their current operations. As discussed above, the cost-effectiveness of PuriNOx is likely to increase even further once newer equipment, with improved NOx control, replaces older equipment.

However, we must acknowledge that PuriNOx is capable of generating substantially larger NOx reductions than TxLED (approximately 66 tons per year in 2002 for the AGC operations in the Houston area). Since NOx reductions are critical to the ultimate attainment of the NAAQS in the Houston area, and since the Clean Air Act Amendments do not permit emission reduction strategies to be rejected solely on the basis of cost, the use of PuriNOx in the AGC fleet may require further evaluation.

In this light, two additional questions should be answered. 1) Will the Houston area require an additional 66 tons or more per year of NOx reductions in order to meet the NAAQS standards?[6] 2) If so, are there other NOx control strategies that can obtain similar or greater reductions at a lower dollar per ton value?

The answer to the first question is almost certainly "yes." However, the answer to the second question is not immediately clear. Based on this analysis we do not know whether or not PuriNOx is more cost-effective than retrofitting engines with EGR or SCR, for example. For this reason, it may be necessary to refine the current cost-effectiveness estimates for PuriNOx use in the AGC fleet.

The following additional steps would be needed to more accurately quantify potential emission reductions and costs for the AGC fleet.

1. Develop representative operating cycles for key high-load equipment types to refine potential performance penalties, and assess the need for engine upgrades.
2. Measure emissions and PuriNOx benefits over other cycles (beyond the AGC Wheeled Loader Cycle).
3. Measure fuel economy impacts for specific cycles.
4. Re-evaluate equipment type groupings based on new cycle information to refine extrapolation of costs and emissions to the AGC fleet as a whole.
5. Evaluate the impacts for the on-road portion of the AGC fleet (which may include cycle development and emissions measurements).
6. Measure the impacts for Tier 2 and Tier 3 engines as they become available. Extrapolate findings to future analysis years.

There are several ways that the cost-effectiveness of PuriNOx use in the AGC fleet might improve. As discussed above, PuriNOx is more cost-effective when used in the dirtiest engines (i.e., mechanical engines without emissions controls). In addition, if key costs could be lowered, dollar-per-ton values could improve substantially. Due to differences in the AGC and TxDOT fleets, the ranking of the cost burdens is quite different for AGC.

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[6] The NAAQS must be met by the 2007 attainment deadline. The actual reductions obtainable from PuriNOx use in 2007 are likely to be somewhat less than 66 tons due to the penetration of electronic engines into the fleet, although industry growth would temper this trend somewhat.

As shown in Table 7, for AGC performance penalties are by far the largest single cost estimated in this study. This analysis assumed a relatively small performance penalty of about 4 to 5% in a subset of "high load factor" engines. To the extent that AGC operators can selectively place their higher power equipment to minimize performance losses, these costs could be lowered and cost-effectiveness improved. In addition, a detailed study characterizing operating cycles for the various types of AGC equipment could provide key information on which engines may or may not experience significant performance penalties in the field. Nevertheless, even in the unlikely event that performance penalties could be entirely eliminated without additional equipment costs, our sensitivity analysis found that cost-effectiveness values will remain high, at least above $12,000 per ton for use of PuriNOx priced at the PPP in the small subset of AGC equipment that is used at least twice per week and does not operate above ~80% torque, and even higher for the remaining AGC equipment.

Fuel costs are the second most important item in Table 7. These costs might be reduced substantially if contracting is based on the low cost scenario – the PuriNOx Posted Price - rather than on the high scenario - base fuel cost plus a fixed cost increment. (Table 7 presents the mid-point between these two extremes.) However, the PPP is a variable cost dependent on daily diesel rack prices. Therefore final incremental fuel costs incurred over time using this pricing mechanism would vary with diesel costs, and would be difficult to predict.

Of the remaining cost categories, only maintenance costs are relatively significant contributors to overall cost-effectiveness. Again, a detailed study of actual AGC engines using PuriNOx in real-world applications could provide a more realistic estimate of expected maintenance costs. To the extent that the costs incurred during TxDOT maintenance would not be incurred by AGC, cost-effectiveness would be improved.

6. Estimated Contributions to the Houston NOx Inventory

Table 8 summarizes total NOx emissions into the Houston air basin, including our estimated contributions by TxDOT and AGC.

Table 8 Estimated NOx Inventories and PuriNOx Effects

	Total Houston Area	TxDOT Houston District	TxDOT Houston District	PuriNOx Benefit - TxDOT	PuriNOx Benefit - TxDOT	AGC Houston Area	AGC Houston Area	PuriNOx Benefit - AGC	PuriNOx Benefit - AGC
	tons/day	tons/day	% of total	tons/day	% of total	tons/day	% of total	tons/day	% of total
On-road	215	0.078	0.036%	0.003	0.0012%	NQ*			
Off-road	147	0.013	0.009%	0.002	0.0014%	2.724	1.853%	0.432	0.294%
Subtotal	362	0.091	0.025%	0.005	0.0013%	2.724	0.752%	0.432	0.119%
Point sources	721								
Biogenic	18								
Total	1101	0.091	0.008%	0.005	0.0004%	2.724	0.247%	0.432	0.039%

* - not quantified, as a relatively minor contributor for AGC

We estimate that TxDOT's diesel vehicles and off-road equipment in the 6 counties in the Houston District contribute ~23 tons of NOx per year to the Houston air basin: 3.3 tons per year from off-road equipment and 19.4 tons per year from on-road vehicles. Given that 250 days/year is generally used for these inventory analyses, these values translate to ~0.01 tons/day from TxDOT's off-road equipment, ~0.08 tons/day from on-road vehicles, and ~0.09 tons of NOx per day total from TxDOT's diesel equipment in the Houston District. For the Houston area, TCEQ estimates 215 tons per day from all of the on-road vehicles and 147 tons per day for off-road equipment. That is, even though TxDOT operates the largest fleet in Texas, its operations in the Houston District represent ~0.04% of the total on-road, ~0.01% of the total off-road, and ~0.03% of the total on-road plus off-road NOx emissions in the Houston area. We estimate that use of PuriNOx by the TxDOT equipment in the Houston District will decrease NOx emissions by ~1.1 tons per year, or ~0.005 tons/day. In turn, this represents a reduction of ~0.001% of the total on-road plus off-road NOx emissions in the Houston area.

We estimate that AGC's off-road diesel equipment in the 8 counties in the Houston area contribute ~681 tons of NOx per year, or ~2.7 tons/day, to the Houston air basin. This represents 1.85% of all NOx emitted by off-road equipment in the Houston area. Use of PuriNOx by AGC would reduce the total on-road plus off-road NOx emissions in the Houston area by ~0.12%.

7. Conclusions and Recommendations

An extensive evaluation of use of PuriNOx in TxDOT's Houston District and by their contractors (AGC) in the Houston area has been conducted. This study was the most extensive examination of PuriNOx to date, involving a field test of 386 diesel engines in normal service, plus emissions and fuel consumption tests of 8 dump trucks, 2 engines used for off-road applications, and a small utility engine. The major recommendations resulting from this study are:

- Even though TxDOT's operations in the Houston area play a minor role in NOx emissions, TxDOT should continue to take a leading role in decreasing emissions. Because maintaining this leading role involves use of public funds, cost-effectiveness should be a primary criterion in choosing between alternatives. In this regard, TxLED is a much more cost-effective strategy for reducing emissions from the TxDOT fleet than is PuriNOx.
- AGC should follow TxDOT's lead in using TxLED, for both its off-road and on-road equipment. If TxDOT specifies the use of TxLED by its contractors, they will not be

eligible for TERP rebates. TxDOT should consider the costs of a requirement that its contractors use TxLED.

- Both TxDOT and AGC should begin using TxLED as soon as possible.
- AGC should not be required to use PuriNOx in absence of an in-depth study focused upon AGC operations, similar to the present study for TxDOT's Houston District.
- We encourage exploration of the use of PuriNOx in fleets that lack the characteristics that make TxDOT and AGC poor candidates for its use.

The rationale for these recommendations is summarized below. Should policy-makers choose to adopt PuriNOx instead of TxLED, we offer additional recommendations to temper the effects of continued use of PuriNOx by TxDOT and expansion to AGC. Use of PuriNOx by other, more suitable, fleets is also briefly discussed.

From the perspectives of health risks, safety, and ability to perform the required tasks, summer-grade PuriNOx is suitable for use – and offers a NOx benefit – in most diesel vehicles and types of equipment. However, the NOx benefit must be weighed against the costs of using PuriNOx. That is, for both the TxDOT and AGC fleets, the primary criterion for use of PuriNOx is cost-effectiveness.

The cost-effectiveness analyses for TxDOT and AGC operations included the costs of converting to PuriNOx and implementing its use, fuel economy effects, the higher cost of PuriNOx, the cost of refueling more often owing to the PuriNOx fuel consumption penalty, the cost of lower equipment productivity owing to the loss of torque, increased maintenance, and various costs associated with the tendency of the emulsion to separate. Because PuriNOx contains water, which has no chemical energy, equipment that operates predominately at high loads will experience a loss of torque. In turn, this means that it may take longer to accomplish a required task. This productivity loss, even though assumed to be small (4-5%) and affecting only a portion of the equipment, was the dominant cost for AGC use of PuriNOx. Fundamental studies of separation, corrosion, and hard starting were performed to gain a better understanding of these issues. The tentative conclusions from these studies are that separation within the fuel delivery system may be responsible for both the starting difficulties and more frequent replacements of fuel injectors and pumps for engines fueled with PuriNOx. TxDOT's more frequent replacements of injectors and pumps are accounted for as an increased maintenance cost for both TxDOT and AGC. The starting difficulties have led TxDOT to start all engines twice each week, even when not needed for normal service, to ensure that they can be started when needed. In turn, this produces a labor cost penalty, a fuel consumption penalty, and a NOx penalty. For some TxDOT equipment, the NOx penalty for these bi-weekly starts is higher than the NOx benefit from use of PuriNOx during normal service, such that the net effect is increased annual NOx emissions when using PuriNOx compared to conventional diesel fuel. For TxDOT's operations, the labor cost penalty of these bi-weekly starts is the major cost of using PuriNOx.

The likely cost to TxDOT, for both its Houston District operations and its subcontracts to AGC in the Houston area, is estimated to be more than $4,500,000 per year above the costs for use of diesel fuel. Various recommendations for decreasing the costs for both TxDOT and AGC operations were summarized in Section 5. One method for decreasing the cost is via TxDOT application for TERP rebates. AGC can qualify for TERP rebates assuming that TxDOT does not explicitly mandate its use contractually. However, TERP funds are also state funds, derived from the citizens of Texas. Thus, although the direct costs to TxDOT and AGC decrease with TERP rebates, the costs to the State of Texas are not affected.

We estimate the cost-effectiveness for use of PuriNOx in TxDOT's Houston District at more than $300,000 per ton of NOx removed. In a high fuel utilization year, if TxDOT buys the PuriNOx storage tanks instead of renting them, applies for a TERP rebate, and develops some method (as yet unknown) for decreasing the bi-weekly starting penalties by 50%, the cost-effectiveness might be reduced to ~$110,000/ton. The cost-effectiveness for AGC is better, primarily because it uses older engines for which PuriNOx offers a larger NOx benefit. The cost-effectiveness for AGC's current engine and equipment mix is about $41,000/ton. This might be reduced to ~$12,000/ton, but only for an improved PuriNOx pricing structure and, even then, only for the subset of AGC's equipment that is used at least twice per week and rarely operates above about 80% torque. While this latter value may appear to be relatively cost-effective, our evaluation for AGC was based upon very limited data compared to that for TxDOT. As discussed in Section 5.B, we believe that a detailed research project, focused upon AGC, must be performed prior to establishing a policy that AGC must convert to PuriNOx.

Our cost-effectiveness evaluations, for both TxDOT and AGC, note that NOx benefits will decrease with time for two reasons: 1) introduction of TxLED, which may be mandated for the region in 2005 but will be used by TxDOT and available to AGC within the next few months, and 2) replacement of older engines/vehicles/equipment with newer versions that have better NOx controls (a natural trend that could be accelerated by TERP rebates to AGC). That is, the cost-effectiveness of using PuriNOx for NOx reductions will be worse in future years. Although the Clean Air Act Amendments do not consider cost-effectiveness in the determination of compliance with the Act's requirements, the State of Texas should focus its limited resources on the most cost-effective solutions.

For both TxDOT and AGC, TxLED is a much lower cost strategy for reducing NOx emissions. Additionally, the NOx emission reduction potential of TxDOT's use of TxLED is slightly higher than for PuriNOx (1.3 vs 1.1 tons), in spite of the 5.7-7% NOx benefit of TxLED relative to the ~12-23% benefit for PuriNOx. The overall decrease in NOx for TxLED relative to PuriNOx use by TxDOT occurs for two reasons: 1) TxLED does not suffer from the NOx penalty associated with the need to start engines fueled with PuriNOx at least twice each week, and 2) the ~50 vehicles and pieces of equipment in the Houston District that could not be converted to PuriNOx for various reasons <u>can</u> use TxLED. For TxDOT, the cost-effectiveness for TxLED is ~$23,000-39,000/ton, depending upon the incremental cost of TxLED as delivered to the Houston area. A TERP rebate of $0.07/gallon would reduce this cost to TxDOT to ~$9,000-$26,000/ton but, as for PuriNOx, TERP rebates improve the cost-effectiveness for TxDOT and AGC but not for the State of Texas (since TERP funds are state funds). Additionally, TERP rebates for use of TxLED may not be possible beginning in 2005, when its use may become mandated. Nevertheless, even the high-end estimate of ~$39,000/ton for TxDOT's use of TxLED compares favorably with the >$100,000/ton for PuriNOx. For AGC, the cost-effectiveness of TxLED is about $8,000/ton, compared to over $41,000/ton for PuriNOx. PuriNOx can produce a better NOx benefit than TxLED for the AGC operations, at ~0.26 tons/day more. However, the marginal cost-effectiveness of PuriNOx (with TxLED as the baseline) is ~$62,000/ton. The likely cost to TxDOT, for both its Houston District operations and its subcontracts to AGC in the Houston area, for use of TxLED is estimated to be less than $400,000 per year above the costs for use of conventional diesel fuel, compared to more than $4,500,000 per year for PuriNOx.

Because the cost-effectiveness of PuriNOx is much higher than for TxLED, and because the annual cost to the State of Texas for use of TxLED by TxDOT's Houston District and its contractors is more than 10 times lower than for PuriNOx, we recommend that TxDOT discontinue use of PuriNOx and not require AGC to use it. Instead, we recommend that both TxDOT and AGC begin using TxLED as soon as possible.

Although we believe that PuriNOx is not suitable for either the TxDOT or AGC fleets, we are certain that there are fleet operations for which PuriNOx is an excellent method for NOx reductions. The main problem for the TxDOT operations is that they have too much equipment that is not used at least twice per week, resulting in the "extra starts" penalties for labor, fuel consumption, and NOx emissions. The main difficulty for AGC is that a portion of their equipment will suffer a performance penalty that results in additional time required to perform the necessary tasks. Our results indicate that vehicles and equipment with engines that spend little time above ~80% torque will not have a notable performance penalty. From the interviews we conducted with other PuriNOx users and testers, it is obvious that PuriNOx works well for some fleets. Centrally fueled bus fleets and the Port of Houston's crane applications are two examples where PuriNOx seems very appropriate.

If it is decided that AGC must begin using PuriNOx, it is likely that TxDOT will continue using it as well. In this case, we recommend:

- Use protective clothing whenever there is a risk of skin contact with the liquid fuel.
- Take actions to minimize the possibility of inhaling fumes from the liquid (prudent practice for any liquid fuel).
- Avoid breathing the exhaust.
- Use conventional diesel fuel (especially TxLED) rather than winter-grade PuriNOx when ambient temperatures are so low that summer-grade PuriNOx cannot be used. We base this recommendation on five factors. It is known that winter-grade PuriNOx poses a greater health risk than diesel fuel, but the severity of this risk is uncertain. Also, winter-grade PuriNOx has a relatively low flash point that might pose a fire hazard in some situations. Winter-grade PuriNOx contains methanol, which is very corrosive, but no studies have been performed regarding possible effects on durability of fuel pumps and fuel injectors. Also, TxLED provides a larger NOx benefit than winter-grade PuriNOx. Finally, in the winter months, ozone nonattainment episodes are rare.
- Do not use PuriNOx in telescoping boom excavators or any other equipment that cannot maintain at least 45 mph when traveling on public roadways.
- Do not use PuriNOx in small utility engines. Because these are small engines, the NOx emissions rate is small and, therefore, the NOx benefit of using PuriNOx is smaller still. However, even if these engines are used regularly, the other costs of using PuriNOx are high relative to the NOx reduction. Therefore, the cost-effectiveness of using PuriNOx in these engines can be quite high, such as the >$11,000,000/ton for TxDOT's traffic alerting signals (e.g., arrow boards).
- Determine, on a case-by-case basis, which specific pieces of equipment cannot use PuriNOx because the torque loss is sufficiently severe that the required tasks cannot be performed.

1. Introduction

On June 4, 2002, Governor Rick Perry requested that the Texas Department of Transportation (TxDOT) begin using cleaner diesel fuel (specifically, an emulsified diesel fuel) in 75 % of its Houston District fleet to help improve air quality in this ozone nonattainment area. The governor also requested that TxDOT establish rules by January 2003 requiring that all TxDOT contractors working on Southeast Texas projects use emulsified diesel fuel in their off-road equipment. Additionally, the governor also requested that TxDOT collect data about the cost, emissions, and efficiency of using emulsified diesel fuel versus fuels used by the rest of the TxDOT fleet, and provide that information to local officials in urban areas. TxDOT contracted with JAM Distributing to provide a specific emulsified diesel fuel, PuriNOx, which was developed by Lubrizol, for the 6 counties in the TxDOT Houston District and the 2 nonattainment counties within the Beaumont District. The findings in this report are specific to PuriNOx.

On June 5, the Administration of TxDOT requested that 100% of TxDOT vehicles in the affected counties use PuriNOx. They also sought testing to verify the claims of the developer, Lubrizol. In response, on June 28 TxDOT awarded a contract to the University of Texas (UT) for Research Project 0-4576 for a detailed study of Lubrizol's emulsified diesel fuel, PuriNOx. PuriNOx is verified by the California Air Resources Board (CARB) for a 14% NOx reduction and recognized for use in Texas by the Texas Commission for Environmental Quality (TCEQ) at 19% NOx reduction. PuriNOx is currently the only NOx reduction technology or fuel that has been registered by EPA. As discussed in Section 5, another study by EPA found that the NOx benefit from using PuriNOx is smaller for engines that are designed to meet more stringent emissions standards (~14%) than for engines designed to meet less stringent standards (~24%).

By July 12, 60% of TxDOT's diesel equipment was running on PuriNOx in the Houston and Beaumont Districts. As of December 18, a total of 445 pieces of diesel equipment had been converted to use PuriNOx. This included 386 pieces of equipment (86% of the diesel fleet) in the 6-county Houston District and 59 in the two affected counties in the Beaumont District (Chambers and Liberty, which are in the Houston/Galveston nonattainment area). In both districts, the converted equipment represented an approximately 50-50 mix of on-road vehicles and non-road equipment. However, the two counties in the Beaumont District switched back to conventional diesel fuel in early August because of employee complaints about eye irritation, headaches, nausea, and vomiting. In response to this, TxDOT commissioned a study by the Rimkus Consulting Group to examine health risks associated with exposure to the exhaust from vehicles fueled with PuriNOx (Drysdale et al., 2002).

The problem statement for Project 0-4576 is provided in Section 1.A. This is followed by a summary of the literature review that was the first deliverable for this project. The research team is introduced in Section 1.C. The goals and tasks for this project are presented in Section 1.D. This subsection also overviews the general duties and responsibilities of each of the team members. The methodology used to assess the use of PuriNOx by TxDOT and its contractors is discussed in Section 1.E.

Section 2 is a summary of our findings regarding emissions and fuel consumption. Our analyses concerning the effects of PuriNOx on performance (specifically, the ability of the equipment to perform the expected tasks) are summarized in Section 3. Our examination of health and safety issues is summarized in Section 4. The cost-effectiveness analysis is provided in Section 5. Details for these various analyses are provided in the appendices. The conclusions and recommendations from this study are discussed in Section 6.

1.A Problem Statement

The overall objective of this project was to make recommendations regarding future use of PuriNOx in TxDOT operations, including possible expansion of the program to include TxDOT's contractors (the Association of General Contractors, AGC). These recommendations are based on all test data, analyses, findings, assessments, and economics generated directly from Project 0-4576 and from relevant publicly available information.

1.B Summary of the Literature Review

The first deliverable for this project was a review of the literature on emulsified diesel fuels. This review (Matthews, 2002) is summarized in this section.

The available literature on emulsified diesel fuels presents a lot of conflicting data. For some engines and test conditions, the emissions of hydrocarbons (HC), carbon monoxide (CO), and Toxic Air Contaminants (TACs) decrease while other studies show these emissions increase. However, although some studies show increases in HC emissions by a factor of 2 to 3 (e.g., Khalek et al., 2000), no studies appear to show increases in HCs or CO that would fail the emissions standards. This is due to the very low HC and CO emissions from diesels relative to the standards. Some studies conclude that emulsions are more beneficial at low speeds and low loads (e.g., Storment and Coon, 1978; Nazha et al., 2001) whereas others reveal that they are more beneficial at high speeds and loads (e.g., Park et al., 2001). Some studies show the soluble organic fraction of the particulate emissions decreasing (Rosenblatt and Ainslie, 1999) while others show an increase (e.g., Brown et al., 2000; Khalek et al., 2000) owing to increased condensation of the lube oil in the combustion chamber on the particulates (Bailey et al., 1999).

It is obvious that the results from using emulsified diesel fuels depend upon the engine, the test cycle, the baseline diesel fuel used for comparison, whether or not the baseline diesel fuel was blended to make the emulsion, and the properties of the diesel fuel in the emulsion. This is made even more complicated by the torque loss caused by the water in the emulsion. For both engine dynamometer (dyno) tests and vehicle tests, there are usually conditions for which the peak torque is required, but the peak torque is lower for the emulsion. Performing the baseline test at higher torque than the test for the emulsified fuel affects emissions in and of itself.

In spite of all the conflicting results, some things are known with relative certainty. Emulsified diesel fuel always provides a benefit in the emissions of the oxides of nitrogen (NOx) and, with one exception (Henningsen, 1994), decreased particulate matter (PM) emissions when tested over any cycle. The magnitude of the advantage depends upon the engine, the operating conditions (test cycle), the properties of the baseline diesel fuel, the properties of the diesel fuel that is blended into the emulsion, and the properties of the emulsion (e.g., water content and possibly the additive package). All of the studies reviewed in the literature survey also found a fuel consumption penalty for emulsions. Thus, to perform a relevant cost-effectiveness analysis, data are required for the various engines in the TxDOT fleet, under operating conditions that simulate their actual use, to assess the NOx emissions benefits of PuriNOx.

The PM advantage is thought to be especially engine dependent. Until recently, the PM advantage was believed to result primarily from "microexplosions" (e.g., Sheng et al., 1995) and augmented by generation of hydroxyl radicals from the water in the emulsion (Samec et al., 2002). The water in the emulsion is stabilized as small droplets within the diesel fuel. Because water boils at a lower temperature than most of the components of diesel fuel, the water within the injected diesel fuel droplets evaporates first. Based upon experiments outside of engines, it was thought that this "exploded" the diesel fuel drops into much smaller droplets. For modern engines that have extremely high injection pressures, the fuel droplets are already quite small, so the microexplosions may not be as beneficial (Samec et al., 2002). However, recent experiments (after the literature review deliverable was completed) in a diesel engine with optical access for various laser-based measurements failed to reveal any microexplosions when using PuriNOx (Musculus et al., 2002). These investigators found an increased liquid column penetration and a larger flame lift-off length. The latter of these results in more air entrainment and thus a less-rich combustion process during the mixing-controlled portion of combustion in a diesel. In turn, this results in less PM formation, and is especially important at higher loads, for which the mixing-controlled regime of diesel combustion dominates. The first, longer liquid penetration, also results in more entrainment and thus less PM formation during the premixed regime of combustion, which is most important at lower loads. However, the increased length of the liquid column at low loads can also result in liquid fuel hitting the surface of the piston bowl. This results in increased PM formation and high HC emissions. For the engine they studied, this second effect was more important than the less-rich premixed burning process. Of the 8 operating conditions they examined, the lowest load case produced the highest PM and HC emissions relative to diesel fuel: 580% and 140%, respectively. However, these results are insufficient to completely explain their data. For the four tests at almost constant speed, PM and HCs increased not only for the lowest load case but also for the highest load examined. They postulated that the end of combustion may be occurring too late in the cycle for the highest load case, such that temperatures are too low for effective oxidation of the PM that is formed during mixing-controlled combustion. That is, even though these experiments did much to improve our understanding of the effects of emulsions on PM emissions, the effects are still not completely understood.

However, the State of Texas is primarily interested in NOx. This is because Texas has four ozone nonattainment areas, with four more that are near nonattainment. Ground level ozone is formed due to reactions between HCs and NOx in the presence of strong sunlight. Generally, the NOx benefit of emulsions is not as strong as its effect on PM.

It is also known that emulsions offer a small benefit in thermal efficiency (e.g., Yoshimoto et al., 1996; Ryan et al., 2001). This occurs because of a cascade of factors. The water in the fuel increases its "activation energy," resulting in a longer ignition delay. In turn this results in more premixing during the longer delay, and thus more fuel burning during the premixed phase of combustion in a diesel (e.g., Tsukahara and Yoshimoto, 1992). Therefore, even though the duration of injection is longer to get the same chemical energy into the chamber, the duration of combustion is shorter with an emulsion. A shorter duration of combustion increases the thermal efficiency. Additionally, the reduced PM results in lower flame luminosity, and therefore, less heat loss to the walls, (e.g., Tsukahara and Yoshimoto, 1992; Park et al., 2001). This also increases thermal efficiency. Even though diesel fuel consumption decreases, overall fuel consumption increases, and PuriNOx is more expensive than diesel at the present time. This means that the NOx benefit, once quantified for the TxDOT fleet, must be weighed against the increased operating cost. The effects of the torque loss on operations must also be weighed in decisions regarding adoption of emulsified diesel fuels.

In addition to emissions and fuel consumption, the literature also contains information relevant to the present analysis of maintenance issues. Data from tests commissioned by Lubrizol (Strete, 1998a), plus information from the literature (Gonzalez et al., 2001), shows that stabilized emulsions like PuriNOx have superior lubricity compared to diesel fuel, in spite of the large fraction of water in the emulsion. This indicates that injector pump durability might not be adversely affected by the water in PuriNOx. The injector deposit tests that have been performed also appear to be conclusive (Strete, 1998b). At present there is no reason to doubt that PuriNOx will decrease deposits on the injectors. The results from two 1,000 hour durability tests (Sarlo, 2001; Zaiontz, 2002) revealed less wear when using PuriNOx, especially of piston rings and liners. However, concern remains over the durability of fuel injectors, and possibly fuel pumps, especially for engines that use very high fuel injection pressures.

The health risk analysis of the present study also benefited from information available in the literature. The exhaust species of most interest are the sulfates, nitrates, and TACs. The sulfates are of interest owing to the potential for the water in the emulsified fuel to react with the sulfur impurity in the diesel fuel to form sulfuric acid, which is captured on the particulate filter as a contributor to the sulfates. The nitrates are of interest because the PuriNOx additive package includes octyl nitrate and ammonium nitrate. The TACs (discussed in Section 2) are of interest specifically because they have been identified as hazardous. No studies were found that quantified the effects of PuriNOx on nitrate emissions. Only two studies were found that examined the effect of emulsions on sulfates, one showing a decrease by a factor of almost 2 and the other showing an increase by a factor of 2. These opposite results could stem from a number of factors. First is whether or not the emulsion was made from the baseline diesel fuel (i.e., both fuels start with the same sulfur impurity), and neither report is clear on this point. Second, the study that found the increase (Gonzalez et al., 2001) used a microemulsion whereas PuriNOx, used in the other study (Khalek et al., 2000), is a macroemulsion. (Water is dispersed so finely in a microemulsion that the mixture is transparent; the encapsulated water droplets in a macroemulsion are not as small, resulting in a milky-white appearance.) Owing to this lack of sufficient data, it was of interest to examine sulfates in the present study. A study of PuriNOx at SwRI (Khalek et al., 2000) found that the brake specific emissions (mg/hp-hr) of all of the TACs they measured increased except for benzene, which was unchanged. (Our analysis of their data, discussed in Section 4, revealed that only 3 of the 12 TACs they measured can be positively identified as increasing with 95% confidence: formaldehyde, acetaldehyde, and 1,3-butadiene.) In contrast, a study of London buses fueled with PuriNOx (Bailey et al., 1999) revealed a decrease in all of the TACs in mg/km, with three exceptions: benzene, toluene, and the total xylenes increased. A study using a 12% microemulsion (Gonzalez et al., 2001), which is not directly relevant because PuriNOx is a macroemulsion and contains 20% water, found increases in formaldehyde, acetaldehyde, 1,3-butadiene, and benzene, with decreases in toluene, the total xylenes, and ethylbenzene. Again, this lack of consistency supports the measurement of the TACs during the present study. A final study that is relevant from the health risk perspective was performed by two occupational hygiene consultants for Lubrizol (Robertson and Miles, 2002). They studied exposures to various exhaust products inside two bus garages in London. PuriNOx was used by the buses in one garage and a European ultra-low sulfur diesel was used in the other. Measurements were taken during the morning "run-out" period, which includes starting, warm-up, and eventually leaving the garage. The measurements included total inhalable dust, respirable dust, formaldehyde, acetaldehyde, acrylaldehyde, SO_2, CO, total HCs, and NOx as NO_2. The most important finding was that the exposure levels for all species were well below the guidelines. After our literature review was completed, summer-grade PuriNOx passed EPA's Tier 2 health risks evaluation. Although this yields additional support to the conclusion that exposure to the exhaust from PuriNOx-fueled vehicles does not pose a health risk, it was still of interest to examine the speciated exhaust in the present study because the EPA analysis was based upon limited data and it is known that the effects of PuriNOx are dependent upon both the engine and the test cycle.

1.C Research Team

The TxDOT contract for this project was with the University of Texas through the UT Center for Transportation Research (CTR). This project involved three research teams within UT and two subcontracts. In addition to CTR, the two other UT research groups involved were the Engines and Combustion Research Program and the Materials Research Program. The subcontracts were to Southwest Research Institute (San Antonio) and Eastern Research Group (Austin).

CTR is the largest purely academic transportation research center in the southwest. The primary CTR personnel on this project were Professor Randy Machemehl (Director of CTR) and Jolanda Prozzi (Research Associate). CTR was responsible for the Houston District driver and maintenance personnel surveys, the interviews with other PuriNOx users, all facets of the Roadeo (except for the datalogging and associated data analysis), and the cost-effectiveness analysis for TxDOT operations.

The UT Engines and Combustion Research Program is one of the Top 5 engines research programs among U.S. universities. The principal investigators on this project were Professor Ron Matthews (Head of the Engines Research Program and Project Supervisor for the present project), Professor Matt Hall (Associate Head of the Engines Research Program), and Professor DK Ezekoye. In addition to directing the overall project, the Engines Research Program was responsible for the literature review, selection of equipment for emissions and fuel consumption testing, testing one of the engines, conducting experiments regarding various separation issues, analysis of all emissions and fuel consumption data, including developing a methodology for its use in the cost-effectiveness analysis, contributing to the torque loss and safety analyses, and the health risk evaluation.

Professor Harovel Wheat, of the UT Materials Research Program, directed the study of corrosion. She is the foremost authority on corrosion at UT.

SwRI is the largest independent automotive research and development facility in the U.S. They regularly perform tests for the Environmental Protection Agency (EPA), Department of Energy (DOE), auto manufacturers, engine manufacturers, and others. The supervisory personnel on this project were Dr. Terry Ullman and Joe Anthony. They were responsible for all of the emissions and fuel consumption testing during this project, except for the engine tested at UT.

ERG has extensive experience in on-board datalogging and use of such data for developing standardized test cycles for the EPA and others. Their personnel on this project were Sandeep Kishan (Vice President), Dr. Tim DeFries, Michael Sabisch, Rick Baker, and Mike Smith (a subcontractor with EEDesign). Mike Smith, with the aid of ERG personnel and graduate students from the UT Engines Research Program, was responsible for datalogging, both for cycle generation and for the Roadeo. ERG developed the TxDOT-specific and AGC-specific operating cycles. They also analyzed the data acquired during the Roadeo from the performance and safety perspectives and performed the AGC cost-effectiveness analysis.

1.D Project Goals and Tasks

The goals of this project were to develop criteria from which recommendations could be made and to generate data to support these analyses. The primary issues were emissions, fuel consumption, performance, and cost-effectiveness. Analysis of health risks was not a major component of the proposal but was later included for completeness.

The first deliverable for this project was a literature review and analysis, as summarized in Section 1.B. This report also included a consolidation of Lubrizol's recommendations regarding conversion, handling, and use of PuriNOx, and a comparison of the Material Safety Data Sheets (MSDS) for PuriNOx and conventional diesel fuel.

Because the advantage of PuriNOx is its effect on emissions, and because the NOx and PM benefits of PuriNOx depend upon the specific engine and test cycle (as discussed in Section 1.B), the second task was to choose the types of TxDOT equipment to be subjected to emissions tests. Although EPA has standardized test cycles available for heavy-duty equipment, there is no guarantee that these cycles are representative of the way that TxDOT equipment is used. Additionally, the Association of General Contractors will be affected by the results of this study. Thus, the third task was to generate TxDOT-specific and AGC-specific test cycles. The fourth task was emissions and fuel consumption testing of the selected equipment.

Because PuriNOx is 20% water by mass and because water does not contain chemical energy, there is a full-load torque and peak-power loss associated with its use. This affects the performance of the diesel equipment. Performance was evaluated from three perspectives: ability to perform the required tasks, safety, and productivity. Two of the tasks used to assess performance were surveys of TxDOT drivers and operators in the Houston District and interviews with other PuriNOx users. These involved personnel who knew they were using an emulsified diesel fuel. A related task was a double-blind survey in which neither the drivers/operators nor the surveyors knew what fuel was being used. This task was accomplished at a "Roadeo" that was organized as part of this project. The vehicles and equipment used for the Roadeo were datalogged to acquire quantitative data as another measure of performance. The final task in examining performance was a comparison of full-load torque curves, both from the literature and from the present tests.

Because PuriNOx decreases emissions of NOx and PM, but costs more than diesel fuel, a cost-effectiveness analysis was a main goal of this project. In addition to the higher cost of PuriNOx, other cost factors included implementation, fuel consumption, refueling, productivity, maintenance, etc. Analysis of the maintenance costs involved several tasks. Houston District maintenance personnel were surveyed. The interviews with other PuriNOx users noted previously also aided this assessment. Several tasks were focused upon maintenance issues associated with the separation of the emulsion. These tasks included examination of the factors that affect the separation rate, corrosion, and hard starting.

Potential health risks may be associated with skin contact with the liquid fuel, inhalation of the vapors from the liquid fuel, and exposure to the exhaust emissions. Except for the exhaust emissions, this analysis relied primarily upon the MSDS for PuriNOx and conventional diesel fuel. Health risks associated with the exhaust emissions were analyzed from the results of prior studies, the results of the Rimkus study for TxDOT (Drysdale et al. 2002), "speciation" of the exhaust as part of the present project, and EPA's Tier 2 health effects analysis of PuriNOx.

1.E Overall Assessment Methodology

The methodology used to assess whether TxDOT's use of PuriNOx should be abandoned, contracted, continued, or expanded is discussed in this section.

Four criteria were used to assess the efficacy of the use of emulsified diesel fuel in general, and PuriNOx specifically. These criteria, and the decision-flow scheme, are illustrated in Figure 1.1.

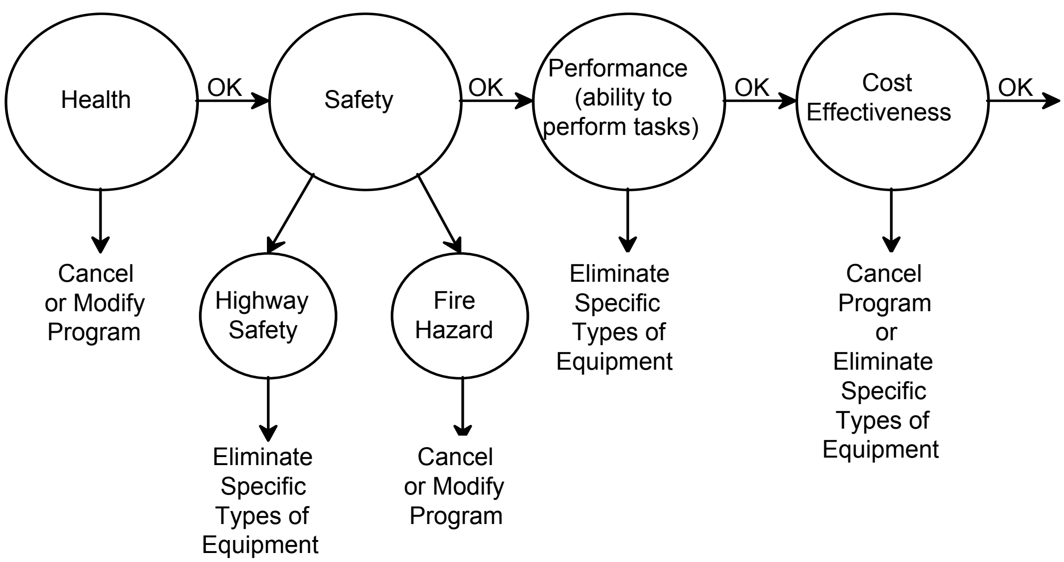

Figure 1.1 Global decision-making basis

If a significant health risk above that from conventional diesel fuel is associated with use of PuriNOx, the result could be the recommendation to either cancel or modify the program. Health risks may be associated with exposure to the liquid (e.g., skin contact), inhalation of the fumes from the liquid, or inhalation of the exhaust products from engines using PuriNOx. If for example, there is a health hazard resulting from skin contact, the recommendation could be that TxDOT employees must always wear protective clothing whenever there is any possibility of contact. On the other hand, if the exhaust proves to be more hazardous, the recommendation could be to discontinue use of PuriNOx. The health risk assessment is discussed in Section 4.A.

Two safety criteria were used. The first is related to the torque loss associated with the water in PuriNOx. If a specific group of vehicles (e.g., single-axle dump trucks) cannot accelerate well enough or cannot cruise fast enough, this could pose a safety hazard to the driver, the occupants, and other vehicles sharing the roadway. In this case, the recommendation could be to discontinue use of PuriNOx in that specific type of vehicle. The second safety criterion is the potential that PuriNOx poses a fire hazard that is greater than that from use of conventional diesel fuel. In this case, the recommendation would be to discontinue use of PuriNOx. The analysis of safety hazards is discussed in Section 4.B.

The third criterion is performance from the perspective of ability of specific types of equipment to perform the required tasks. One example of a performance failure is the GM engines in TxDOT's fleet that have an optical sensor that detects water in the fuel. PuriNOx is not compatible with this sensor. Another example results from the torque loss associated with the water in the emulsion. If this torque loss is sufficiently severe that the equipment cannot perform its required task when using PuriNOx, the recommendation would be to discontinue use of PuriNOx in this type of equipment. Performance is discussed in Section 3.

The final criterion is cost-effectiveness, especially of NOx control. Cost-effectiveness is discussed in Section 5 and includes not only considerations of fuel economy and the higher cost of PuriNOx, but also conversion costs, maintenance costs, etc. Additionally, in this section the cost-effectiveness of PuriNOx is compared to alternative NOx control technologies.

2. Emissions and Fuel Consumption

As found in the prior literature (discussed in Section 1.B) and in the present tests (discussed in detail in Appendix B), PuriNOx always provides a NOx benefit and usually decreases PM emissions. PuriNOx also affects the fuel consumption and the emissions of HCs, CO, and the toxic air contaminants (listed in Table 2.1). The effects of PuriNOx on emissions and fuel consumption are summarized in this section of the report.

Table 2.1 California Air Resources Board List of Gas Phase Toxic Air Contaminants

Carbonyls:
- Aldehydes:
  - Formaldehyde*
  - Acetaldehyde*
  - Propionaldehyde
  - Acrolein (propenal)
- Ketones:
  - Methyl ethyl ketone (MEK)

Aromatics:
- Benzene*
- Toluene
- Ethylbenzene
- Meta-xylene (m-xylene)**
- Para-xylene (p-xylene)**
- Ortho-xylene (o-xylene)

Alkanes and Alkenes:
- 1,3-butadiene*
- Hexane

* - also on EPA's list of "exhaust toxics"
** - m-xylene and p-xylene are eluted at the same time, so a single value is measured for the sum of the two

The brake-specific emissions of the oxides of nitrogen, particulate matter, hydrocarbons, and carbon monoxide found in the present study of telescoping boom excavators, wheeled loaders, and small utility engines are summarized in Tables 2.2 and 2.3. The brake-specific fuel consumption is also shown in this table. For the telescoping boom excavators, wheeled loaders, and small utility engines, the test results for emissions and fuel consumption were measured in g/hp-hr (rate of emissions or fuel consumption per rate of work performed). For the telescoping boom excavators and wheeled loaders, these measurements were made for the typical use patterns of each of these two types of equipment, as discussed in detail in Appendix A. A 2002 Yanmar 10 hp herbicide sprayer engine was used to represent the various small utility engines used by the Texas Department of Transportation. TxDOT uses these engines for herbicide sprayers, traffic-alerting signals (e.g., arrow boards), and riding mowers. The typical operating conditions for these engines are discussed in Appendix B.6.

Table 2.2 Brake Specific Emissions and Fuel Consumption of the Telescoping Boom Excavators and Wheeled Loaders

Engine	Control	Fuel	bsNOx g/hp-hr	bsPM g/hp-hr	bsHC g/hp-hr	bsCO g/hp-hr	bsfc g/hp-hr
TxDOT Telescoping Boom Excavator Cycle							
ISB-190	elect.	2D on-road	3.55	0.083	0.02	0.73	174.6
		PuriNOx	3.07	0.054	0.16	1.06	217.1
		% change	-13.6	-35.0	622	44.6	24.4
6BTA5.9	mech.	2D on-road	5.02	0.087	0.17	0.72	169.2
		PuriNOx	3.87	0.081	0.45	1.39	222.7
		% change	-22.8	-7.4	165	93.8	31.6
AGC Wheeled Loader Cycle							
ISB190	elect.	2D on-road	3.42	0.069	0.02	0.57	165.8
		high S off-road	3.60	0.121	0.04	0.60	169.8
		PuriNOx	2.98	0.034	0.08	0.53	205.3
		% change: PuriNOx vs. on-rd	-13.1	-51.2	413	*-6.3*	23.8
		% change: PuriNOx vs. off-rd	-17.3	-72.0	104.6	*-11.1*	20.9
		% change: on-rd. vs. off-rd	-4.8	-42.7	-60.1	*-5.2*	-2.4
6BTA5.9	mech.	2D on-road	4.70	0.080	0.13	0.63	163.4
		low S off-road	4.80	0.140	0.23	0.83	170.5
		PuriNOx	3.79	0.053	0.29	0.92	211.0
		% change: PuriNOx vs. on-rd	-19.3	-33.5	122	47.8	29.1
		% change: PuriNOx vs. off-rd	-21.0	-61.7	*29.2*	*11.4*	23.8
		% change: on-rd. vs. off-rd	*-2.1*	-42.5	-41.8	-24.6	-4.1
Average % change, PuriNOx vs. On-road, Heavy-Duty Engines							
		electronic	-13.4	-43.1	517	19.2	24.1
		mechanical	-21.0	-20.4	144	70.8	30.4

Percent change in italics = difference not statistically significant with 95% confidence

Table 2.3 Brake Specific Emissions and Fuel Consumption of the Small Utility Engines

	bsNOx	bsfc	bsPM
	g/hp-hr		
2D on-road diesel fuel			
high speed & load	5.87	215.9	0.86
mid-speed, low load	15.04	403.0	8.64
composite-mowers	6.79	234.6	1.64
composite-signals	5.87	215.9	0.86
composite-sprayers	10.46	309.5	4.75
Summer-grade PuriNOx			
high speed & load	5.66	279.3	0.62
mid-speed, low load	9.40	434.6	7.37
composite-mowers	6.03	294.9	1.30
composite-signals	5.66	279.3	0.62
composite-sprayers	7.53	357.0	4.00
Winter-grade PuriNOx			
high speed & load	4.99	288.6	0.40
mid-speed, low load	12.52	528.6	5.79
composite-mowers	5.74	312.6	0.94
composite-signals	4.99	288.6	0.40
composite-sprayers	8.76	408.6	3.09
TxLED			
high speed & load	5.40	205.3	0.78
mid-speed, low load	15.27	385.7	1.31
composite-mowers	6.39	223.4	0.83
composite-signals	5.40	205.3	0.78
composite-sprayers	10.33	295.5	1.04
% change: SG PuriNOx vs. 2D on-rd diesel			
mowers	-11.1	25.7	-20.9
signals	-3.6	29.4	-27.8
sprayers	-28.0	15.4	-15.9

For the single-axle dump trucks and the tandem-axle dump trucks, the emissions were measured in g/mi and the fuel economy was measured in mpg. Again, these measurements were performed for operating conditions that reflect typical use, as discussed in Appendix A. The results for the dump trucks are summarized in Table 2.4.

Table 2.4 Composite Emissions and Fuel Economy of the Dump Trucks

Engine	Control	Fuel	NOx g/mi	PM g/mi	HC g/mi	CO g/mi	Fuel Econ. mpg
TxDOT Single Axle Dump Truck Cycle							
3126B	elect.	2D on-road	21.33	0.135	0.20	1.70	6.85
		PuriNOx	19.56	0.147	0.96	1.47	5.84
		% change	-8.3	*8.6*	380	-13.4	-14.6
T444E	elect.	2D on-road	8.93	0.188	0.31	1.67	6.91
		PuriNOx	6.02	0.233	2.40	3.39	6.44
		% change	-32.7	24.0	663	103	-6.8
7.6T-I6	mech.	2D on-road	10.73	0.392	0.34	1.74	6.36
		PuriNOx	8.06	0.176	0.80	1.83	5.68
		% change	-24.9	-55.1	136	*5.1*	-10.8
1060	mech.	2D on-road	11.72	0.187	0.12	0.75	6.90
		PuriNOx	8.94	0.148	1.04	1.89	5.80
		% change	-23.7	-20.6	764	154	-15.9
TxDOT Tandem Axle Dump Truck Cycle							
90 L10-300	mech.	2D on-road	14.50	0.983	2.36	4.63	5.29
		PuriNOx	13.43	1.017	4.47	4.24	4.53
		% change	-7.4	*3.4*	89.6	-8.5	-14.3
C10	elect.	2D on-road	10.82	0.276	0.57	3.59	5.00
		PuriNOx	9.45	0.181	1.30	3.21	4.36
		% change	-12.7	-34.3	128	-10.4	-12.7
89 L10-300	mech.	2D on-road	16.05	0.982	1.94	6.66	5.20
		PuriNOx	15.34	0.69	3.09	3.20	4.63
		% change	*-4.5*	-29.8	59.9	-52.0	-10.9
3176	elect.	2D on-road	17.86	0.248	0.40	2.17	5.04
		PuriNOx	15.46	0.213	0.59	1.35	4.66
		% change	-13.4	-14.4	45.2	-38.1	-7.4
Average % change, electronic*			-11.5	-13.4	184	-20.6	-11.6
Average % change, mechanical**			-24.3	-37.9	450	79.6	-13.3

* - w/o T444E   ** - w/o L10-300s

Percent change in italics = difference for hot starts not statistically significant with 95% confidence; it is assumed that this is also true for the composite results.

The results of these tests (detailed in Appendix B) showed that, compared to 2D on-road diesel, PuriNOx provides a NOx benefit with a fuel economy penalty for all engines and all cycles, with one exception. The exception was a 1989 White/GMC with a mechanically-controlled Cummins L10-300 engine tested over the TxDOT Tandem-Axle Dump Truck Cycle. In this case, the 3.8% NOx benefit for the average hot start was not statistically significant with 95% confidence. It is assumed that the 4.5% NOx benefit for the composite cycle is not statistically significant either, primarily because the composite results are weighted 86% to the hot starts. However, the cost-effectiveness analyses were performed on an Emissions Index basis, and the difference in EINOx for the 1989 L10-300 was statistically significant with 95% confidence. The NOx benefit for the 1990 L10-300 was also small compared to the other mechanically-controlled engines. EPA (2002a) found that the non-road equipment they evaluated (designed to meet less stringent emissions standards) enjoyed a 24.4% NOx advantage from PuriNOx, whereas the on-highway engines, which were designed to meet more stringent emissions standards, enjoyed only a 13.7% advantage from PuriNOx. In the present study, the discrimination between electronically- and mechanically-controlled engines is used as an indicator of engines with more sophisticated emissions controls (electronic). With the exceptions of the T444E and the L10-300, the EPA finding is reflected in the present results. We found a 13.4% benefit for electronic off-road and a 21.0% benefit for mechanical off-road. Also, excluding the T444E and L10-300, we found an 11.5% benefit for electronic on-highway and a 24.3% benefit for mechanical on-highway engines. The International T444E was an exception to the general finding of a decreased NOx benefit for electronically-controlled engines, perhaps because this vehicle was quite under-powered relative to all of the other dump trucks that were tested. The L10-300s had a much lower NOx benefit than the other mechanically-controlled engines. We also found that PuriNOx generally provides a significant advantage in the emissions of particulate matter. However, there were four exceptions to this general finding. For the mechanically-controlled Cummins 6BTA5.9 engine operating over the TxDOT Telescoping Boom Excavator Cycle, the PM advantage was only ~7%, whereas it was usually at least twice this. Also, for one of the single-axle dump trucks and one of the tandem-axle dump trucks (one mechanical, the other electronically-controlled), the difference in PM emissions was not statistically significant with 95% confidence. The final exception was a single-axle dump truck with an electronically-controlled T444E engine. In this case, the PM emissions increased by ~38% for the average hot start test and ~24% for the composite result. The literature revealed only one prior test for which PuriNOx produced increased PM, but that was for a 2-stroke diesel (Henningsen, 1994), whereas all of the engines tested in the present study were 4-stroke diesels. It is believed that the T444E produced higher PM emissions when using PuriNOx because this engine suffered more – compared to the other 7 dump trucks – from the water in the emulsion; with slower accelerations and lower cruising speeds when using PuriNOx compared to its operation on diesel fuel. As also noted in the EPA report (EPA, 2002a), our tests also showed that HC emissions increased in every case but the CO emissions increased for some engines but decreased for others. However, even though some very large increases in HC and CO emissions were found, the emissions of these species are not of significant interest because the baseline emissions (using diesel fuel) are inherently much lower than the respective standards.

3. Performance

The performance of vehicles and equipment is decreased because the water in PuriNOx does not contain any chemical energy. That is, from the perspective of the performance of the engine, PuriNOx acts much like the watered-down diesel fuel that it essentially is. This loss of performance may affect the ability of the equipment to do the required tasks or, in the extreme case, may pose a safety hazard. The ability of the equipment to perform the required tasks is discussed in this section. Safety is discussed in Section 4.B.

3.A Torque and Power Loss

Torque and power loss are discussed in detail in Appendix C. Table 3.1 is a summary of the results. Table 3.1 shows that the torque loss at peak torque speed ranges from approximately 12%-16% and the loss of torque at rated speed ranges from approximately 12%-15%. Because maximum power occurs at rated speed, this torque loss at rated speed corresponds to a loss of maximum power of approximately 12-15%. However, there is generally a peak in the torque loss at low-to-mid speed. This torque loss, plus that at peak torque speed, affects vehicle acceleration, whereas the loss of peak power is related to maximum possible cruising speed. That is, PuriNOx limits acceleration and can also decrease maximum cruising speed for on-road vehicles. For off-road equipment, the torque loss may affect productivity.

Table 3.1 Torque Loss for PuriNOx Compared to Diesel Fuel for a Variety of Engines

		Percent Torque Loss at		Max. Torque Loss	
Engine	**Control**	**Peak Torque Speed**	**Rated Speed**	**%**	**at RPM**
01 DDC Series 50	elect.	13.1	13.7	18.5	900
91 DDC Series 60	elect.	13.3	11.8	NA	
96 Cat C12	elect.	16.3	12.7	17.3	1500
00 Cummins ISB-190	elect.	12.1	13.7	19.5	1170
97 Cummins 6BTA5.9	mech	16.1	15.1	39.0	1380

The engines in Table 3.1 are used in heavy equipment, such as trucks and excavators. A small utility diesel engine was also tested as part of the present project. Such engines are used to power herbicide sprayers, traffic alerting signals, and riding mowers. These are "low tech" diesel engines, designed for production at the lowest possible cost. Thus, the effects of PuriNOx on their performance should not be expected to be more generally representative. However, a substantial torque loss was noted for this engine. This engine lost approximately 19% of its power on PuriNOx at peak engine speed. Obviously, this may affect its ability to perform the desired tasks.

3.B Operator Assessments

The objective of this section is to summarize the results of the TxDOT Houston user surveys and the double-blind operator performance assessment. In addition to these surveys, the research team interviewed representatives of 16 agencies, companies, and institutions that either verified emissions reductions associated with PuriNOx (e.g., the California Air Resources Board - CARB), tested (e.g., the City of Houston), or currently are using PuriNOx (e.g., the Port of Houston), and two engine manufacturers (Cummins and Detroit Diesel) about their experiences with PuriNOx.

3.B.1 Houston Driver Surveys

The objective of surveying PuriNOx users in Houston was to determine what the performance effects or issues associated with the use of PuriNOx-fueled vehicles/equipment were, and in which kinds of vehicles/equipment, if any, the use of PuriNOx was deemed problematic.

Survey Instrument and Approach

A survey instrument containing 18 statements about specific performance impacts was used to test the perceived effect of using PuriNOx on the operation of Houston vehicles/equipment. On a scale from 1 to 5, where 1 meant disagreement and 5 meant agreement with the statement/question, the respondents were asked to circle the option that best described how they felt The respondents were also given the opportunity to record concerns in the "any other comments" section.

Two rounds of surveys were conducted at four sites in West Harris, North Harris, Montgomery, and Fort Bend Counties during late August/early September, and November. Two rounds of surveys were conducted to determine if perceptions changed once the operators became more familiar and gained more experience with PuriNOx. Center for Transportation Research (CTR) personnel, with extensive experience in heavy equipment operations, administered the surveys.

Detailed information on the survey process concerning the development of the questionnaire and the approach is provided in Appendix D.1. This section of the document highlights the salient findings of the Houston TxDOT driver surveys.

Houston Driver Survey Responses: August/September

A total of 44 drivers/operators were surveyed in late August/early September. The responses were almost uniformly negative, although the intensity of the responses varied depending on the specific attribute tested. Some of the drivers/operators raised the following specific concerns about PuriNOx use in the comment section of the questionnaire:

- 10% to 15% loss of power;
- acceleration problems (in particular, operators felt unsafe when required to merge onto the freeway);
- required frequent shift points;
- slower hydraulic movement;
- difficulty starting vehicles/equipment in the morning;

- excessive pollution if vehicles/equipment are started only once a week;
- maximum speed that can be reached is 55 miles/hour, which impacts traffic;
- uses more fuel;
- dies when idling (e.g., when stopping at traffic lights);
- smells bad; and
- noisy.

Statistical Analyses

Because the number of responses to each statement was more than 30, a normal distribution was assumed and hypothesis tests were performed on each of them. The statistical analysis was conducted in two stages. Initially, a two-sided test was performed to test the null hypothesis that the "true" mean of the responses was 3. In other words, the null hypothesis was that the operators were neutral toward each of the statements, suggesting no perceived difference between the performance attributes of the vehicles/equipment with PuriNOx and conventional diesel fuel. If the two-sided test revealed that the null hypothesis had to be rejected for any statement — thus meaning that the operators were not neutral — a second test (a one-sided test) was performed to determine if the operators agreed or disagreed with that statement.

These tests allowed for the calculation of a confidence interval for the population mean for each of the statements (attributes). All of the tests were performed at 1% significance level (see Appendix D.1 for more details about the statistical analysis).

Two-Sided Test Results

The results of the two-sided tests are summarized in Table 3.2.

Table 3.2 Two-Sided Test Results (August/September)

Statement	Reject Null?	Confidence Interval	
		Lower limit	Upper limit
I noticed a substantial improvement in the performance of my vehicle/equipment.	Yes	1.20	1.96
I had more tasks in the past few weeks than on average.*	Yes	1.88	2.84
Even at full throttle, it took me longer than normal to perform the same task when using hydraulics.	Yes	3.46	4.42
My vehicle/equipment used more fuel than before.	Yes	3.07	4.06
I asked a mechanic to check my vehicle/equipment during the past few weeks.	Yes	3.38	4.35
I was able to do all my usual tasks faster than before.	Yes	1.28	1.99
The engine of the vehicle/equipment was noticeably noisier than before.	No	2.75	3.68
I suffered from more backaches, sore muscles, and headaches than usual.	No	2.24	3.37
I changed my driving/operating behavior over the past weeks.	Yes	3.31	4.27
I moved heavier loads over the past few weeks than normally.*	Yes	1.40	2.28
I experienced some of these symptoms: runny nose, nausea, hair loss, skin rash.	No	1.95	3.23
I noticed that my vehicle had less power than before.	Yes	4.30	4.92
I had a problem starting my vehicle/equipment early in the morning.	Yes	3.55	4.56
My vehicle was accelerating faster than before.	Yes	1.34	2.31
My vehicle/equipment smelled better than before.	Yes	1.44	2.29
I noticed more smoke coming from my vehicle/equipment.	Yes	3.60	4.62
I had to shift gears more often when doing my work.	Yes	3.06	4.23
My vehicle/equipment was vibrating more than before.	Yes	3.11	4.05

* These two questions were included to determine if the respondents' working conditions were perceived differently since switching to PuriNOx. No additional statistical analysis was performed for these questions.

As can be seen from Table 3.2, the null hypothesis was not rejected for only three of the statements (attributes): (1) The engine of the vehicle/equipment was noticeably noisier than before; (2) I suffered from more backaches, sore muscles, and headaches than usual, and (3) I experienced some of these symptoms: runny nose, nausea, hair loss, skin rash. This means that the respondents did not perceive any change in engine noise or health effects associated with the use of PuriNOx.

The fact that the null hypothesis was rejected for all of the remaining statements indicates that the Houston PuriNOx users perceived a difference in the performance of their vehicles/equipment when using PuriNOx. A one-sided test was performed on the remaining statements to determine whether the perceived impact was positive or negative.

One-Sided Test Results

The remaining statements were divided into two groups: "negative statements" and "positive statements." Table 3.3 summarizes whether the null hypothesis was rejected and the confidence intervals for the mean response of the population of PuriNOx users for each of the "negative PuriNOx statements."

Table 3.3 One-Sided Test Results: Negative PuriNOx Statements (August/September)

Statement	Reject Null?	Confidence Interval
Even at full throttle, it took me longer than normal to perform the same task when using hydraulics.	Yes	≥ 3.50
My vehicle/equipment used more fuel than before.	Yes	≥ 3.11
I asked a mechanic to check my vehicle/equipment during the past few weeks.	Yes	≥ 3.42
I noticed that my vehicle had less power than before.	Yes	≥ 4.33
I had a problem starting my vehicle/equipment early in the morning.	Yes	≥ 3.60
I noticed more smoke coming from my vehicle/equipment.	Yes	≥ 3.65
I had to shift gears more often when doing my work.	Yes	≥ 3.12
My vehicle/equipment was vibrating more than before.	Yes	≥ 3.15

Note: If the null hypothesis is rejected, then the "true" mean response is greater than 3, meaning that the respondents agreed with the statement.

It is evident that loss of power was a major concern. Other significant concerns include:

- more smoke coming from the equipment
- starting the vehicle/equipment early in the morning, and
- inability to perform tasks as quickly when using the hydraulics.

Similarly for each of the "positive PuriNOx statements," Table 3.4 summarizes whether the null hypothesis was rejected and the confidence intervals calculated.

Table 3.4 One-Sided Test Results: Positive PuriNOx Statements (August/September)

Statement	Reject Null?	Confidence Interval
I noticed a substantial improvement in the performance of my vehicle/equipment.	Yes	≤ 1.93
I was able to do all my usual tasks faster than before.	Yes	≤ 1.96
My vehicle was accelerating faster than before.	Yes	≤ 2.26
My vehicle/equipment smelled better than before.	Yes	≤ 2.25

Note: If the null hypothesis is rejected, then the "true" mean response is less than 3, meaning that the respondents disagreed with the statement.

From Table 3.4, it is evident that the respondents disagreed with the statements about increases in performance and ability to do their tasks faster than before.

Houston Driver Survey Responses: November

In late November, a total of 55 drivers/operators were surveyed in West Harris, North Harris, Montgomery, and Fort Bend Counties. The overall response from the second round of surveys was, as in the first round, uniformly negative. In addition, many more drivers/operators used the opportunity to raise their concerns about using PuriNOx in the space provided for in "any other comments." For more details about the respondents and the comments recorded, see Appendix D.1.

Similar to the first round of surveys, this section highlights the statistical results of the second round of surveys. See Appendix D.1 for more details about the frequency distribution graphs, mean sample responses, and standard deviation for all statements included in the second round of surveys.

Statistical Analyses

The same statistical tests were performed for the November survey data as for the August/September data. First, a two-sided test was performed to test the null hypothesis that the "true" mean of the responses was 3, and secondly, if the two-sided test revealed that the null hypothesis had to be rejected for any statement, a one-sided test was performed to determine if the operators agreed or disagreed with that statement. For more detailed information about the statistical tests performed, see Appendix D.1.

Two-Sided Test Results

The results of the two-sided tests are summarized in Table 3.5.

Table 3.5 Two-Sided Test Results: November

Statement	Reject Null?	Confidence Interval	
		Lower limit	Upper limit
I noticed a substantial improvement in the performance of my vehicle/equipment.	Yes	1.10	1.68
I had more tasks in the past few weeks than on average.*	Yes	1.86	2.81
Even at full throttle, it took me longer than normal to perform the same task when using hydraulics.	Yes	3.46	4.42
My vehicle/equipment used more fuel than before.	Yes	3.25	4.16
I asked a mechanic to check my vehicle/equipment during the past five months.	Yes	3.41	4.39
I was able to do all my usual tasks faster than before.	Yes	1.15	1.83
The engine of the vehicle/equipment was noticeably noisier than before.	Yes	3.24	4.17
I suffered from more backaches, sore muscles, and headaches than usual.	No	2.72	3.83
I changed my driving/operating behavior over the past five months.	Yes	3.28	4.33
I moved heavier loads over the past five months than normal.*	Yes	1.40	2.05
I experienced some of these symptoms: runny nose, nausea, hair loss, skin rash.	No	2.42	3.56
I noticed that my vehicle had less power than before.	Yes	4.28	4.90
I had a problem starting my vehicle/equipment early in the morning.	Yes	3.93	4.74
My vehicle was accelerating faster than before.	Yes	1.16	1.76
My vehicle/equipment smelled better than before.	Yes	1.25	1.95
I noticed more smoke coming from my vehicle/equipment.	Yes	3.75	4.64
I had to shift gears more often when doing my work.	Yes	3.74	4.54
My vehicle/equipment was vibrating more than before.	Yes	3.51	4.37

* These two questions were included to determine if the respondents' working conditions were perceived differently since switching to PuriNOx. Statistical analysis was performed for these questions.

As can be seen from Table 3.5, the null hypothesis was not rejected for only two of the statements (attributes): (1) I suffered from more backaches, sore muscles, and headaches than usual, and (2) I experienced some of these symptoms: runny nose, nausea, hair loss, skin rash. This means that even after 5 months the respondents did not perceive any statistically significant change in health effects associated with the use of PuriNOx.

Contrary to the analysis results of the first round of survey data that the respondents were neutral — thus they neither agreed nor disagreed — with the statement that "the engine of the vehicle/equipment was noticeably noisier than before, analysis of the November survey data indicated that the operators were not neutral. A one-sided test was thus performed to determine whether the operators agreed or disagreed with the statement.

In addition, the null hypothesis was rejected for all the remaining statements indicating that the Houston PuriNOx users continued to perceive a difference in the performance of their vehicles/equipment when using PuriNOx compared to diesel fuel. A one-sided test was performed on each remaining statement to determine whether the perceived impact was positive or negative.

One-Sided Test Results

Similar to the one-sided test results summarized for the first round of surveys, the one-sided test results for the "negative statements" and "positive statements" included in the second round of surveys are summarized in Table 3.6 and 3.7, respectively.

Table 3.6 One-Sided Test Results: Negative PuriNOx Statements (November)

Statement	Reject Null?	Confidence Interval
Even at full throttle, it took me longer than normal to perform the same task when using hydraulics.	Yes	**≥ 3.51**
My vehicle/equipment used more fuel than before.	Yes	**≥ 3.29**
I asked a mechanic to check my vehicle/equipment during the past five months.	Yes	**≥ 3.45**
The engine of the vehicle/equipment was noticeably noisier than before.	Yes	**≥ 3.28**
I noticed that my vehicle had less power than before.	Yes	**≥ 4.31**
I had a problem starting my vehicle/equipment early in the morning.	Yes	**≥ 3.97**
I noticed more smoke coming from my vehicle/equipment.	Yes	**≥ 3.79**
I had to shift gears more often when doing my work.	Yes	**≥ 3.77**
My vehicle/equipment was vibrating more than before.	Yes	**≥ 3.55**

Loss of power remained the most pressing concern, but starting the vehicles/equipment early in the morning, the need to shift gears more often, and vibration were more of a concern during the second round of surveys than the first.

Table 3.7 One-Sided Test Results: Positive PuriNOx Statements (November)

Statement	Reject Null?	Confidence Interval
I noticed a substantial improvement in the performance of my vehicle/equipment.	Yes	≤ 1.65
I was able to do all my usual tasks faster than before.	Yes	≤ 1.80
My vehicle was accelerating faster than before.	Yes	≤ 1.73
My vehicle/equipment smelled better than before.	Yes	≤ 1.92

It is evident that the operators disagree with the statements about increases in performance and faster acceleration.

Analysis of Variance

Comparing the confidence intervals calculated for each attribute for the August/September data (Table 3.3) with the confidence intervals for the November data (Table 3.6), it is evident that the interval bands are narrower overall for November. This suggests a more negative response than during the first round of surveys.

The objective of the analysis of variance (ANOVA) was to determine whether the changed perceptions were statistically significant. It was, however, found that there was not a statistically significant change (at 5% significance level) in the perceptions of the Houston PuriNOx users after a period of approximately 5 months in terms of each of the performance attributes tested. The ANOVA results are summarized and explained in Appendix D.1.

Concluding Remarks for Houston Driver Surveys

The statistical analysis (at a 1% significance level) revealed that the drivers/operators perceived performance impacts associated with the use of PuriNOx relating to a loss of power, starting problems, and more smoke. Engine noise, vibration, and the need to shift gears more often were more of a concern during the second round of surveys compared to the first. In addition, there was no evidence from the first round of surveys to suggest a perceived performance impact with respect to engine noise, but during the second round of surveys the statistical evidence suggested that the respondents agreed that the engine was noisier fueling with PuriNOx compared to conventional diesel fuel.

Specific concerns in the comment section of the questionnaire about using PuriNOx included: loss of power, poor acceleration, the inability to reach and maintain highway speeds, poor idling performance, and engine smoke. Despite numerous comments in the open-ended section of the questionnaire noting health effects, there was no statistical evidence for the perceived health effects associated with the use of PuriNOx.

Although there was some evidence to suggest that the driver/operator perceptions were more negative about the performance impacts of using PuriNOx when surveyed in November compared to August/September, the statistical analysis (ANOVA) revealed no statistically significant change in the perceptions of the Houston PuriNOx users (at a 5% significance level).

3.B.2 Operator Surveys from Double-Blind Testing ("Alternative Fuels Roadeo")

The objective of the double-blind operator assessment was to determine if drivers/operators, who have never been exposed to the PuriNOx fuel, could perceive a difference in the field performance of vehicles/equipment when performing staged activities when neither the operators nor the surveyors knew what fuel was being used. Quantitative results from data logged during the Roadeo are discussed in Section 3.C.

"Alternative Fuels Roadeo"

To generate the double-blind assessment of operator perceptions regarding the use of PuriNOx relative to conventional diesel fuel, a "Roadeo" was conducted November 13–14 at two Houston sites: Hempstead and La Marque. The following equipment was tested in the Roadeo:

- 2001 telescoping cranes/bucket trucks (Telelect with Cummins ISB engines),
- 2002 telescoping boom excavators (Gradalls with Cummins ISB-190 engines),
- 1995 loaders (Fiatallis with Fiatallis 8045T engines),
- 1999 single-axle, 6-yard dump trucks (GMC with Caterpillar 3126B engines),
- 1998 tandem-axle, 10-yard dump trucks (International with Caterpillar C10 engines), and
- 1993 forklifts (Caterpillar with Caterpillar XD3P engines).

To account for both fuel performance and vehicle performance differences, three pieces of each equipment type (identical in terms of model[7] year, engine size, etc.) were included in the Roadeo.

TxDOT employees fueled the vehicles/equipment in advance to ensure a complete double-blind test in which neither the operators nor the UT researchers knew which fuel was being used in which vehicle/equipment.

The research team, together with the Houston District, designed a series of Roadeo events, which aimed to assess the concerns raised by the Houston PuriNOx users discussed in Section 3.B.1 of this report. Appendix D.2.A contains the details of the routes and activities.

Volunteer TxDOT drivers/operators from outside the Houston District in which PuriNOx is used, were asked to participate in the Roadeo. Participating districts included: the GSD fleet, Bryan, Lufkin, Fort Worth, Pharr, Dallas, Waco, Tyler, Yoakum, and Corpus Christi.

On the days of the Roadeo, participants were assigned to two groups: (1) drivers/operators and (2) observers according to a prepared schedule in terms of the vehicles/equipment and the driver/operator qualifications. Each driver/operator was given a specific number and questionnaire at sign-in. Observers accompanied the drivers/operators during the activities to ensure that the events were undertaken in a safe manner and in an effort to control the test. The observers were tasked to note any events that might bias or influence the results, for example, slow traffic and any unusual driver behavior, such as frustration.

The research supervisor and Lenert Kurtz from the Houston District briefed all the participants on the Roadeo days. To circumvent any speculation that the performance of PuriNOx was being tested during the Roadeo, the participants were told that the performance of three alternative fuels was being tested.

In total, 50 TxDOT employees participated in the Roadeo: 30 drivers/operators and 20 observers. The performance of each equipment type was evaluated by five drivers/operators. The driver/operator performed a specified activity with all three pieces

[7] The exception was the telescoping boom excavators. Two 4-wheel drive and one 2-wheel drive excavator were available for testing during the Roadeo.

of identical equipment. Upon completing the specific events, the drivers/operators were asked to rank the performance of the three vehicles/equipment they drove/operated. The rankings were 1, 2 and 3 in terms of certain performance criteria, including power, acceleration, idling, required shift points, hydraulic movements, engine noise, etc., where "1" referred to the best and "3" to the worst of the three vehicles.

For more detailed information regarding the Roadeo site location, Roadeo equipment selection, vehicles/equipment fueled with PuriNOx and diesel, Roadeo events, Roadeo participants, Roadeo schedule, and the Roadeo questionnaires, see Appendix D.2.A.

Statistical Analysis

Kendall's coefficient of concordance (W) was calculated to determine whether the level of agreement, if any, among the rank responses of the drivers/operators for particular performance attributes (e.g., acceleration) were statistically significant. Kendall's coefficient of concordance, W, its significance and estimates of the true rank order given a significant W was calculated for each attribute (question). In terms of the rank order, 1 represents the best vehicle with respect to that particular attribute and 3 represents the worst (for more details see Appendix D.2.B).

The statistical results are summarized below for each vehicle/equipment type. The tables summarize whether the level of agreement among the operator ranking responses is statistically significant and the best estimate of the true rank order.

Telescoping Boom Excavators

The performance of the excavators seemed to be the most noticeably affected by PuriNOx. As can be seen from Table 3.8, the level of agreement among the ranking responses was statistically significant for five of the thirteen attributes evaluated during the telescoping boom excavator activity: acceleration, power, time to reach the desired/highway speed from a dead stop, ability to maintain the desired/highway speed, and overall performance.

The PuriNOx-fueled excavator A was ranked the worst and the diesel-fueled excavator B ranked the best with respect to all five of the statistically significant ranked attributes. The fact that excavator B was ranked higher than C is attributable to the fact that B was a 4-wheel drive excavator and C was a 2-wheel drive excavator. Thus, it is worth highlighting that the respondents consistently ranked the 4-wheel drive PuriNOx-fueled excavator A to be worse than the 2-wheel drive diesel-fueled excavator C in terms of acceleration, power, time it takes to reach the desired/highway speed from a dead stop, ability to maintain the desired/highway speed, and overall performance.

Table 3.8 Telescoping Boom Excavators

Attribute	W	Significance	Rank Order		
			1	2	3
Acceleration Performance	1.000	Yes	B (Diesel)	C (Diesel)	A (PuriNOx)
Level of Engine Noise	0.360	No	-	-	-
Power of Vehicle	0.760	Yes	B (Diesel)	C (Diesel)	A (PuriNOx)
Level of Vibration	0.467	No	-	-	-
Number of shift points required when negotiating a hill	0.573	No	-	-	-
Performance when lifting loads	0.360	No	-	-	-
Impact on Hydraulic Movements	0.360	No	-	-	-
Power when digging	0.650	No	-	-	-
Time it takes to reach the desired/highway speed from a dead stop	0.840	Yes	B (Diesel)	C (Diesel)	A (PuriNOx)
Performance when required to operate with a load	0.650	No	-	-	-
Ability to maintain desired/highway speeds	1.000	Yes	B (Diesel)	C (Diesel)	A (PuriNOx)
Idling Performance	0.029	No	-	-	-
Overall Performance	1.000	Yes	B (Diesel)	C (Diesel)	A (PuriNOx)

The total scores for A, B, and C are:
A: 174.5
B: 85
C: 130.5
Maximum Possible Score: 195
Minimum Possible Score: 65

Loaders

Second to the telescoping boom excavators, the loader performance seemed to be most noticeably affected when fueled with PuriNOx. The level of agreement among the operators in their ranking responses was statistically significant for four of the ten attributes evaluated: acceleration performance, power of the vehicle, power when digging, and overall performance. In terms of acceleration performance, power of the vehicle, and power when digging, the diesel-fueled loader C was consistently ranked the best and the PuriNOx-fueled vehicle A was consistently ranked the worst. An anomaly, however, exists in terms of the overall performance ranking. Given the attribute ranking it was expected that the overall performance ranking would be the same. However, from Table 3.9, it can be seen that the PuriNOx-fueled loader B was ranked best in terms of overall performance. One explanation for this anomaly is that overall performance of loader B was considered better in terms of other attributes not included in the questionnaire.

Table 3.9 Loaders

Attribute	**W**	**Significance**	**Rank Order**		
			1	**2**	**3**
Acceleration Performance	0.832	Yes	C (Diesel)	B (PuriNOx)	A (PuriNOx)
Level of Engine Noise	0.200	No	-	-	-
Power of Vehicle	0.832	Yes	C (Diesel)	B (PuriNOx)	A (PuriNOx)
Level of Vibration	0.253	No	-	-	-
Performance when lifting loads	0.150	No	-	-	-
Impact on Hydraulic Movements	0.350	No	-	-	-
Power when digging	0.832	Yes	C (Diesel)	B (PuriNOx)	A (PuriNOx)
Performance when required to operate with a load	0.200	No	-	-	-
Idling Performance	0.450	No	-	-	-
Overall Performance	0.832	Yes	B (PuriNOx)	C (Diesel)	A (PuriNOx)

The total scores for A, B, and C are:
A: 129
B: 80.5
C: 90.5
Maximum Possible Score: 150
Minimum Possible Score: 50

Telescoping Crane

As indicated in Table 3.10, statistically significant agreement in the respondents' rankings of the cranes was recorded for three attributes: acceleration, power, and overall performance. The operators consistently identified the PuriNOx-fueled vehicle A as the worst performer in terms of these attributes. Diesel-fueled crane B was ranked the best in terms of acceleration, power, and overall performance.

Table 3.10 Telescoping Crane

Attribute	W	Significance	Rank Order		
			1	**2**	**3**
Acceleration Performance	0.832	Yes	B (Diesel)	C (Diesel)	A (PuriNOx)
Level of Engine Noise	0.578	No	-	-	-
Power of Vehicle	0.744	Yes	B (Diesel)	C (Diesel)	A (PuriNOx)
Level of Vibration	0.120	No	-	-	-
Number of shift points required when negotiating a hill	0.478	No	-	-	-
Time it takes to reach the desired / highway speed from a dead stop	0.478	No	-	-	-
Ability to maintain desired / highway speeds	0.600	No	-	-	-
Idling Performance	0.600	No	-	-	-
Overall Performance	0.640	Yes	B (Diesel)	C (Diesel)	A (PuriNOx)

The total scores for A, B, and C are:
A: 120.5
B: 58
C: 91.5
Maximum Possible Score: 135
Minimum Possible Score: 45

There was, however, no statistically significant agreement in the ranking of the remaining six attributes, including: time to reach the desired/highway speed from a dead stop and ability to maintain desired/highway speed. This seems to suggest that the performance impact on the telescoping crane might be limited, although noticeable.

Forklift

Statistically significant agreement in the respondents' rankings of the forklifts was recorded for only two attributes: acceleration and impact on hydraulic movements. As can be seen from Table 3.11, the diesel-fueled forklift B was ranked the best in terms of both of these attributes and the PuriNOx-fueled forklift C was ranked the worst. No statistically significant agreement in the ranking of the remaining attributes, including power of the vehicle and performance when lifting loads, seems to suggest that the performance impact on the forklifts might be limited.

Table 3.11 Forklift

Attribute	W	Significance	Rank Order		
			1	2	3
Acceleration Performance	0.741	Yes	B Diesel	A PuriNOx	C PuriNOx
Level of Engine Noise	0.200	No	-	-	-
Power of Vehicle	0.516	No	-	-	-
Level of Vibration	0.564	No	-	-	-
Performance when lifting loads	0.411	No	-	-	-
Impact on Hydraulic Movements	0.859	Yes	B Diesel	A PuriNOx	C PuriNOx
Time it takes to reach the desired / highway speed from a dead stop	0.300	No	-	-	-
Performance when required to operate with a load	0.671	No	-	-	-
Ability to maintain desired / highway speeds	0.371	No	-	-	-
Idling Performance	0.200	No	-	-	-
Overall Performance	0.576	No	-	-	-

The total scores for A, B, and C are:
A: 111
B: 88
C: 131
Maximum Possible Score: 165
Minimum Possible Score: 55

Dump Trucks

In the case of the dump trucks, the drivers ranked the vehicles very differently in terms of each of the attributes so that no statistically significant ranking agreement was observed. Hence, there was no statistical evidence that the respondents perceived one vehicle to perform better or worse than another, which seems to indicate that PuriNOx does not significantly affect the performance of either the single-axle or tandem-axle dump trucks. The statistical evidence is presented in Appendix D.2.B.

Concluding Remarks from the Roadeo Driver Surveys

To conclude, the statistical analysis of the data recorded during the Roadeo provided evidence that supports the concerns raised by the Houston PuriNOx users regarding acceleration performance and loss of power. PuriNOx-fueled vehicles/equipment were consistently ranked worse with respect to acceleration in four of the six equipment types. Also, PuriNOx-fueled vehicles were consistently ranked worse with respect to power in three of the six equipment types. When there was a statistically significant level of agreement among the rankings of the performance attributes in terms of impact on hydraulic movements, power when digging, time taken to reach the desired/highway speed, and ability to maintain desired speeds, a diesel-fueled vehicle was rated better than the PuriNOx-fueled vehicle. The rankings of attributes like engine noise, vibration, number of shift points required when negotiating a hill, performance when lifting loads, performance when operating under load and during idling were very different among the operators (for all equipment types) providing no evidence that the PuriNOx-fueled vehicles performed better/worse than the diesel vehicles in terms of these attributes.

The perceived performance impacts of PuriNOx on specific types of equipment varied significantly. The data suggest that the excavator performance was impacted most noticeably when fueled with PuriNOx. The PuriNOx-fueled excavator was consistently ranked worse compared to the two diesel-fueled excavators with respect to five of the attributes considered. Also, the PuriNOx-fueled crane was ranked the worst performer with respect to three of the attributes tested. On the other hand, the performance of the dump trucks was ranked very differently by the 5 drivers with respect to all the attributes. Hence, there was no evidence that the PuriNOx-fueled dump trucks performed better or worse than the diesel dump trucks in terms of the tested criteria. Loaders presented an interesting case. The level of agreement among the operators in their ranking responses was statistically significant for four of the attributes evaluated: acceleration performance, power of the vehicle, power when digging, and overall performance. In terms of acceleration performance, power of the vehicle, and power when digging, the diesel-fueled loader C was consistently ranked the best and the PuriNOx-fueled vehicle A was consistently ranked the worst. The PuriNOx-fueled loader B was, however, ranked best in terms of overall performance. One explanation for this anomaly is that B's overall performance was considered better in terms of attributes not included in the questionnaire.

3.B.3 Additional PuriNOx User Interviews

During the literature review, a number of agencies, companies, and institutions were identified that either verified emissions reductions associated with PuriNOx (e.g., CARB), tested (e.g., the City of Houston), or are currently using PuriNOx (e.g., the Port of Houston). In addition, engine manufacturers looking into the use of PuriNOx in their engines (e.g., Cummins, Inc.) and emulsified diesel fuel vendors (e.g., Ramos Oil Company) were identified. Representatives from these organizations were interviewed to learn from their experiences with PuriNOx and to determine their impressions concerning using PuriNOx in their equipment (see Table 3.12 for a list of agencies, companies, and institutions interviewed). The goal was to document their experiences concerning:

- equipment adaptability,
- fuel economy,
- operational concerns (including power/efficiency loss),
- fuel separation,
- maintenance,
- health effects, and
- cost-effectiveness.

Table 3.12 List of Other PuriNOx Interviews

PuriNOx Verification/Assessments
California Air Resources Board
Environment Canada
British Columbia Ministry of Finance
Oregon Department of Environmental Quality (Portland Tax Incentive Programs)
Connecticut's Diesel Retrofit Program
National Industrial Chemicals Notification and Assessment Scheme, Australia
PuriNOx Pilots
Massachusetts Turnpike Project
Golden Gate Ferries
Teichert Construction
City of Houston
City of Sacramento
PuriNOx Users
Port of Houston
Chevron/Texaco
Ramos Oil Company, Inc.
Tri Delta Transit
Engine Manufacturers
Cummins, Inc.
Detroit Diesel

Some of the interview findings are highlighted below under the following four categories: verification/assessments, pilot projects, users, and engine manufacturers.

Verification/Assessments

CARB verified that Lubrizol's diesel emulsified fuel (PuriNOx) reduces emissions. Lubrizol funded a test conducted by SwRI in accordance with the CARB protocol on one Detroit Diesel engine (1991, 360 horsepower). The test protocol was submitted to CARB and, based on the test results, a verification letter was provided to Lubrizol.

Similarly, Lubrizol provided the British Columbia Ministry of Finance with the emissions test results demonstrated in three studies undertaken by SwRI (the Detroit Diesel engine test results referred to earlier), Environment Canada, and the Millbrook testing facility in England. Based upon the submitted test results, an initial 3-year tax exemption is available to PuriNOx users in British Columbia under the Ministry of Finance General Alternative Fuels Program. The tax exemption was only awarded for three years, because the increase in HC emissions associated with the use of PuriNOx contradics the criteria considered for exemption. Lubrizol, however, argued that the NOx reductions offset the increases in HC emissions. The Ministry is in the process of evaluating the criteria used to determine if it is too rigid. Currently, no one is marketing or using PuriNOx in British Columbia.

Approximately 3½ years ago, the State of Oregon was interested in undertaking a pilot program with PuriNOx. The pilot did not materialize because of coordination difficulties among the different state departments involved in the pilot and also a supply of the additive could not be secured. A decision was to be made in February 2003 as to whether PuriNOx can qualify for a tax credit under the Oregon Tax Incentive Program.

The State of Connecticut does not use PuriNOx, but it is an option available to contractors. The state approved the use of PuriNOx based on the CARB verification, but no one is currently using PuriNOx in Connecticut.

The National Industrial Chemicals Notification and Assessment Scheme in Australia conducted a risk assessment based on the information supplied to them by Lubrizol International. This institution referred the research team to Lubrizol for any additional information regarding PuriNOx, because it did not test the chemical itself or the fuel in which it is contained.

PuriNOx Pilots

In addition, a number of agencies and companies tested PuriNOx in their vehicles/ equipment for various periods of time. The research team interviewed the organizations that for some reason decided not to switch to PuriNOx, including the Massachusetts Turnpike Project, Golden Gate Ferries, Teichert Construction, and the City of Houston.

Massachusetts Turnpike Project

In fall 2000, a single piece of off-road construction equipment — a model year 2000 Caterpillar 311B excavator — used in the Central Artery/Tunnel project was tested using winter-blend PuriNOx. The pilot included both an emission test and a performance test. The performance test was conducted over a period of 3 weeks (16 hours a day, 5 days per week). The initial emission and opacity test results indicated NOx benefits of 24.5% to 30.5%, and smoke reductions of 93.6% to 96.8%. The only concerns noted were a slight reduction in power when required to maneuver in deep mud conditions and higher fuel consumption (Massachusetts Turnpike Authority, 2001).

Golden Gate Ferries

Golden Gate Ferries tested summer-blend PuriNOx in one of their ferries over a period of 11 weeks (summer to spring 2002).[8] According to the representative interviewed, ferry operations did not suffer from a power loss, but the ferry consumed approximately 15%-17% more fuel per week. The ferry engines ran noticeably cooler at full throttle — approximately 10 to 12 degrees — and no complaints were received about starting the ferry.

Costs incurred over the pilot period included a significant increase in the delivered fuel cost (85 to 90% per week higher compared to diesel), a minimal increase in skipper overtime attributable to more frequent fuelings, and the associated cost for adjusting the mechanic's work schedule because of the additional fuelings.

[8] The ferry has two Caterpillar 3412TA and two Scania D11 generator engines.

Teichert Construction

Teichert Construction piloted the use of summer-blend PuriNOx in their Readymix trucks for approximately 4½ months. The pilot revealed a power loss, acceleration concerns, and lower fuel economy, but it was felt that the operators could perform their tasks as quickly/efficiently as before without the need to change the equipment to counter the power loss.

The operators of the equipment complained about different fuel odors, but no complaints were received about any health effects.

Both fuel and maintenance expenditure increased. Specifically, maintenance costs increased for fuel injectors and pumps. Fuel costs increased by approximately 20%.

City of Houston

Summer-blend PuriNOx was tested as one of a number of alternative emissions abatement strategies during the City of Houston Diesel Field Demonstration Project. Emissions tests were conducted for selected City of Houston equipment (including a garbage truck, tractor mower, flatbed truck, medium dump truck, road sweeper, backhoe, Gradall, and rear loader) operating their normal activities. Fuel economy was not considered.

It was found that the power loss attributable to PuriNOx did not concern the operators. The City of Houston, however, experienced two instances where the fuel separated, in the fuel tank of a flatbed truck and in a fuel storage tank. In both cases, the fuel was not agitated for a couple of months.

At the time of the demonstration project, PuriNOx was approximately $0.35/gallon more expensive than diesel fuel. The only additional expense associated with the use of PuriNOx was the cost of the wiring required for the fuel tank pump.

In general, the City of Houston representatives felt that PuriNOx presented an interim solution for reducing NOx and particulate emissions. Over the longer term, however, the representatives indicated that exhaust aftertreatment technologies would provide superior emissions reduction benefits. The representatives expressed a concern that PuriNOx might defeat some of the aftertreatment equipment, because of the lower combustion temperature.

City of Sacramento

The City of Sacramento is currently testing (as of October 3, 2002) summer-blend PuriNOx in 20 of their vehicles: 10 side-loader refuse trucks and 10 wheeled loaders used for picking up garden waste. At the time of the interview, the City of Sacramento had been using PuriNOx for approximately 30 days.

Some concerns about power loss and acceleration were highlighted, but it was too early to determine how fuel economy was affected. Apart from the conversion costs, such as the fuel filters and the fuel labels, the only additional cost at the time of the interview was the fuel price of PuriNOx, which was approximately $0.25/gallon higher than diesel. A final determination of whether to switch to PuriNOx will be made after completing the test.

Stated Reasons for Not Adopting PuriNOx

The reasons stated by these representatives for not switching to PuriNOx included:

- higher fuel costs;
- engine manufacturer's reluctance to endorse the use of emulsified diesel fuels and the associated warranty implications;
- effects on certain engine types;
- infrastructure and logistical implications associated with using another fuel type resulting in one storage tank for gasoline, one tank for diesel, and one tank for PuriNOx;
- fuel separation concerns in vehicles that are not used regularly; and
- equal or superior emissions benefits associated with alternative abatement strategies, such as exhaust aftertreatment technologies.

PuriNOx Users

Four PuriNOx users were interviewed: the Port of Houston; Chevron/Texaco; Ramos Oil Company, Inc.; and Tri Delta Transit.

Port of Houston

The Port of Houston has been using summer-blend PuriNOx successfully for approximately 2 years in 2-yard cranes and 6-yard truck tractors. The Port of Houston initially tested PuriNOx in various types of equipment and found that, in some instances, performance was affected to the extent that it prevented the use of PuriNOx. It was concluded that PuriNOx works best in regularly used equipment in which the engine is required to run at a constant RPM (for example, where the engine is used to power a hydraulic device).

The Port of Houston reported a 20% increase in fuel usage, and PuriNOx cost approximately $0.17/gallon more than diesel in the week of July 8. No additional maintenance costs have been incurred and the additional cost to agitate the fuel is considered marginal.

The Port of Houston representative felt that operator concerns about power loss were exaggerated. According to him, the operators started complaining about power loss only after they became aware of the fact that PuriNOx resulted in a power loss.

The Port of Houston has never experienced a case of fuel separation: stored fuel is agitated for 1 hour per day and the equipment is used daily.

No complaints about health effects were recorded. Overall, the Port of Houston regards their experience with PuriNOx to be very positive.

Chevron/Texaco

Chevron/Texaco has been using summer-blend PuriNOx for approximately 8 months in 25 of their vehicles in California.

Fuel economy was noticeably affected. The Chevron representative estimated that the vehicles use approximately 15% to 17% more fuel and that PuriNOx costs approximately 20% more than diesel.

Power loss and acceleration have been somewhat of a concern. The PuriNOx-fueled vehicles were estimated to be 10% to 15% less efficient, but no changes to counter the power loss and upgrade to more powerful engines were considered.

Fuel separation is not a concern: the PuriNOx in the storage tank is agitated when fuel is dispensed and the vehicles are operated 24 hours a day.

Maintenance expenditures — specifically for fuel injectors — did increase, but they could not be attributed to the use of PuriNOx.

No complaints about health effects were noted. Overall, Chevron regards their experience with PuriNOx to be very positive.

Ramos Oil, Inc.

Ramos Oil is a vendor for PuriNOx and has been using summer-blend PuriNOx for 1.5 years in 14 trucks and trailers, ranging from 18-wheeler delivery trucks to smaller package and vacuum trucks.

Fuel economy has been affected. The representative estimated that the trucks use approximately 15% more fuel compared to diesel.

According to the representative interviewed, power loss is less of a concern and something that the operators can adjust to. Ramos Oil advises that heavy equipment operators are not told about the water in the fuel. One of the PuriNOx clients of Ramos Oil tested PuriNOx in seven of their vehicles. No complaints were received about the equipment. Once the client decided to switch its entire fleet to PuriNOx and the operators became aware of the water content of the fuel, numerous complaints about power loss were received.

Overall performance (power, acceleration, idling, etc.) is a function of the operation, the driver, the age of the equipment, and the horsepower of the engine. In some pieces of equipment, the representative noted that it takes longer to accelerate to highway speeds and in winter it is more difficult to start, but overall the representative stated minimal concerns about the performance of equipment fueled with PuriNOx.

Ramos Oil never experienced a case of fuel separation and insists that clients invest in a recirculation pump. A recirculation pump circulates approximately 20% of the volume of the fuel per day, which is adequate to prevent the fuel from layering.

Ramos Oil did not incur any additional maintenance expenses and regards its overall experience using PuriNOx to be very positive.

Tri Delta Transit

Tri Delta Transit has been using summer-blend PuriNOx for approximately 1 year in 20 of their transit buses.

Fuel economy has decreased approximately 5% since switching to PuriNOx, and the power loss is estimated at approximately 10%. In some instances, mostly in the case of older buses, the horsepower was increased to counter the power loss. The representative, however, stated that without the change operators would still have been able to do their tasks as quickly and efficiently as before.

No operator concerns were recorded about starting the equipment, acceleration, different required shift points, or engine noise, although a few mentioned different odors.

Fuel separation has never been an issue, because the fuel is agitated. Maintenance expenditure has increased slightly. Most of the increase in maintenance costs can be attributed to changing fuel filters. The only additional cost is the increase in fuel costs, which amounts to approximately 10% more than for diesel. No complaints about health effects have been received.

According to the Tri Delta representative, PuriNOx has exceeded company expectations and the company is therefore planning to convert the entire fleet of 72 buses to PuriNOx pending CARB certification.

Engine Manufacturers

Caterpillar, Inc. has approved the use of PuriNOx in some of its engines to reduce emissions based upon extensive testing in collaboration with Lubrizol (specifically, Caterpillar's older pump-line-nozzle group of engines, the 3208, 3304, 3306, 3406B, 3406C, 3408B, 3408C, 3412B, and 3412C). However, Caterpillar has not approved the use of PuriNOx in its newer electronically injected engines. For these engines, Caterpillar found the same types of injector failures as when using diesel fuel, but with a higher failure rate when using PuriNOx. Caterpillar is still studying this issue.

Two engine manufacturers were interviewed during this study — Cummins and Detroit Diesel — to determine whether using PuriNOx has any implications in terms of their engine manufacturer's warranty.

Neither engine manufacturer interviewed is endorsing or encouraging the use of PuriNOx in its equipment, and both have a "use at own risk" policy. Cummins's official position is quoted below.

"Cummins neither approves or disapproves of the use of PuriNOx diesel fuel.

Cummins is not in a position to evaluate the many variations in fuels or other additives, and their long-term effects on performance, durability and emissions compliance of Cummins products. The use of PuriNOx diesel fuel does not affect Cummins materials and workmanship warranty. Failures caused by the use of PuriNOx diesel or other fuel additives are NOT defects of workmanship and/or material as supplied by Cummins, Inc. and CANNOT be compensated under the Cummins' warranty."
(http://www.Cummins.com)

According to the Detroit Diesel representative, PuriNOx does not meet the fuel specifications specified by the company. Similar to the position of Cummins, Detroit Diesel does not approve, disapprove, or endorse the use of PuriNOx. Therefore, if a problem occurs that can be attributed to the use of PuriNOx, Detroit Diesel will not cover the concern under their warranty.

In general, manufacturers' warranties cover materials and workmanship – thus failures attributable to the use of a particular fuel is not covered. This is also evident from the warranty statement of Volvo:

> *"Volvo Trucks North America, Inc. warrants each new Volvo engine in a new Volvo truck to be free from defects in material and workmanship under normal use and service up to the periods specified, provided all Volvo Trucks North America, Inc. maintenance requirements are followed. See your local authorized Volvo Truck Dealer for recommended maintenance procedures. All warranty periods are calculated from the*

date in service of the vehicle. All coverage is 100% for parts and labor subject to the qualifications and limitations as noted"
(Volvo, North America Warranty Certificate dated May, 1999).

The International Truck and Engine Corporation stated that:

"Warranty coverage will not be voided by the installation or use of special equipment, additives or other chemicals designed to improve vehicle performance, non-International parts, or by the modifications of any part of the vehicle. However, if the use of such devices, modifications or additives causes a failure, the cost to repair or replace the failed component is not reimbursable"
(Warranty Procedures and Administrative Policies, CTS-1100 Section 3).

On the other hand, Mack Trucks does specifically approve of the use of PuriNOx in their engines:

"Mack approves PuriNOx as an emissions reduction alternative for use in Mack engines with no impact on the standard Mack warranty for workmanship and materials used in the manufacture of Mack engines. This approval is based on comprehensive testing, which Lubrizol has conducted over several years."
("An Important Message to the Mack Dealer Network, Target Fleets and Distributors of PuriNOx Fuel")

Lubrizol, however, warrants the fuel performance, including engine and system components.

The Lubrizol Warranty for PuriNOx™ Fuel

The Lubrizol Corporation warrants that the use of PuriNOx™ fuel in accordance with the PuriNOx™ Fuel Application, Storage and Usage Requirements ("Guidelines") that are available from Lubrizol or PuriNOx™ fuel distributors, will remain a stable emulsion and will not cause damage to or abnormal wear in a diesel engine due to corrosion or otherwise beyond the normal wear that would result from the use of ordinary diesel fuel. When PuriNOx™ fuel is used in accordance with the Guidelines and there is a failure in the diesel engine fuel system, which failure is due to the use of PuriNOx™ fuel instead of ordinary diesel fuel, Lubrizol will either repair or replace the damaged parts, at its option. When the claim under this warranty is for abnormal wear, Lubrizol's obligation shall be to compensate for the additional wear only, with such compensation being equal to the repair or replacement cost times the fraction of the demonstrated increased wear due to the use of PuriNOx™ fuel instead of ordinary diesel fuel. IN NO EVENT SHALL LUBRIZOL BE LIABLE FOR ANY CONSEQUENTIAL OR INDIRECT DAMAGES. THIS WARRANTY IS IN LIEU OF ANY AND ALL OTHER WARRANTIES EITHER EXPRESS OR IMPLIED, INCLUDING THE WARRANTIES OF MERCHANTIBILITY AND FITNESS FOR A PARTICULAR PURPOSE.

Lubrizol stands behind its products, and if you have questions about this warranty please contact us.

The Lubrizol Corporation
29400 Lakeland Blvd., Wickliffe, Ohio 44092-2298
Telephone: 440.943.4200, Facsimile: 440.943.5337

Concluding Remarks from Interviews with Other PuriNOx Users

The research team interviewed representatives of 16 agencies, companies, and institutions that either verified emissions reductions associated with PuriNOx (e.g., CARB), tested (e.g., City of Houston), or are currently using PuriNOx (e.g., the Port of Houston). In addition, two engine manufacturers were interviewed to determine the implications on the manufacturer's warranty, if any, of using PuriNOx.

The researchers found that a number of agencies and companies tested PuriNOx in some of their vehicles/equipment for various periods of time, such as the Massachusetts Turnpike Project, Golden Gate Ferries, Teichert Construction, and the City of Houston. The representatives reported very different experiences, although all mentioned a reduction in fuel economy and none reported health effects associated with the use of PuriNOx. The impact on power varied from no impact to noted operator concerns about power loss and acceleration. In all cases it was stated, however, that the operators were able to do their tasks as quickly/efficiently as before without any changes to the equipment to counter the power loss. The additional costs associated with the use of PuriNOx revolved mostly around the higher fuel price of PuriNOx, although one agency reported increased maintenance expenditures for fuel injectors and pumps.

Ultimately, the reasons stated for not switching to PuriNOx included:

- higher fuel costs;
- engine manufacturer's reluctance to endorse the use of diesel-emulsified fuels and the associated warranty implications;
- effects on certain engine types;
- infrastructure and logistical implications associated with using another fuel type resulting in one tank for gasoline, one tank for diesel, and one tank for PuriNOx;
- fuel separation concerns in vehicles that are not used regularly; and
- equal or superior emissions benefits associated with alternative abatement strategies, such as exhaust aftermath technologies.

The four PuriNOx users interviewed — the Port of Houston, Chevron/Texaco, Ramos Oil Company, Inc., and Tri Delta Transit — reported very positive experiences with PuriNOx.

Increases in reported fuel usage varied from 5% to 20%, and the power loss reported ranged from minimal to somewhat of a concern. Two of the representatives mentioned that operator concerns about power loss are exaggerated and became an issue only when the operators became aware that PuriNOx results in power loss. Only one of the PuriNOx users interviewed increased the horsepower of some of the older equipment to counter the power loss. It was stated, however, that without the change operators would still have been able to do their tasks as quickly and efficiently as before.

In all cases, the cost of fuel increased significantly. In two cases no additional maintenance costs have been incurred. In the other two cases maintenance expenditures did increase: (1) expenditures for fuel injectors increased noticeably, but could not be attributed to the use of PuriNOx, and (2) maintenance expenditure on fuel filters increased slightly. In all cases the additional cost to agitate the fuel is regarded marginal.

All of the representatives reported that fuel separation has never been a concern, because the equipment is used regularly and the fuel in the storage tanks is agitated. Finally, no complaints about health effects were recorded.

The two engine manufacturers interviewed (Cummins and Detroit Diesel) are not endorsing or encouraging the use of PuriNOx in their equipment and have a "use at own risk" policy. According to the Detroit Diesel representative, PuriNOx does not meet the fuel specifications of the company. Both companies do not approve, disapprove, or endorse the use of PuriNOx, and therefore a problem attributable to the use of PuriNOx will not be covered under the engine manufacturer's warranty. However, Mack Trucks does specifically endorse the use of PuriNOx in their engines.

3.C Quantitative Assessments of Vehicle Performance

PuriNOx contains 20% water in the form of an emulsion. When this fuel is used in a diesel engine with no modifications to the engine, it will result in approximately a 20% loss of power. Lubrizol acknowledges this loss of power. Nevertheless, this study made an effort to quantify the effects of the loss of power, to put the loss of power in perspective, and to make judgments about how important it is. In this section, we provide a quantitative assessment of how the loss of power from PuriNOx affects vehicle performance, as measured by the exercises done during the Roadeo.

Vehicle performance was measured at the Roadeo on six types of vehicles: single-axle dump trucks, tandem-axle dump trucks, bucket trucks, telescoping boom excavators (Gradalls), loaders, and forklifts. Two types of activities were performed to make the assessments: a driving test and/or a work activity test. On-road driving tests were performed on the single-axle dump trucks, the tandem-axle dump trucks, the bucket trucks, and the Gradalls. Work activity tests were special tests believed to be typical of the normal work performed by certain vehicle types. Work activity tests were performed on the bucket trucks, the Gradalls, the loaders, and the forklifts.

The performance for these two types of activities was measured in two ways. First, observers who were part of the project staff watched the activities. The observers could take notes and, depending on the type of vehicle and type of test, could count the number of repeated tasks over a given time period. Second, all pieces of equipment were instrumented with dataloggers to measure key vehicle and engine-operating variables including vehicle speed, engine RPM, engine load, and accelerator position on a second-by-second basis.

The detailed analyses of the quantitative assessments of vehicle performance during the Roadeo are presented in Appendix D.2.C. As part of the double-blind nature of the Roadeo, the analysis of the results presented in the appendix were made without knowledge of which vehicles were fueled with PuriNOx and which vehicles were fueled with 2D on-road ("regular") diesel fuel.

3.C.1 Single-Axle Dump Trucks

Five different drivers drove the three single-axle dump truck test vehicles from the TxDOT fleet on an 18.5 mile highway test route in the Hempstead area. The 6-yard dump trucks were filled with recycled asphalt product (RAP) to approximately 29,400 lb, near their GVWR of approximately 33,000 lb. Analysis of the second-by-second datalogger data indicated no problems with the dump trucks maintaining cruising speeds. Detailed analysis of dump truck acceleration at two locations in the route for the top three gears indicated that accelerations on the vehicles with PuriNOx were 20% slower than accelerations on the trucks with regular diesel fuel. No work activity test was performed for single-axle dump trucks.

3.C.2 Tandem-Axle Dump Trucks

Three tandem-axle dump truck test vehicles from the TxDOT fleet were driven on the same highway route as the single-axle dump trucks. However, the route was driven in the opposite direction. The 10-yard dump trucks were filled with RAP to approximately 43,500 lb (depending upon the specific truck, the GVWR is approximately 54,000 lb). Analysis of the second-by-second datalogger data indicated that the tandem-axle dump trucks had no problem maintaining cruising speeds. Detailed analyses of accelerations at three specific locations on the route showed acceleration losses of 22% to 34%, depending on the gear, with an average loss of 27% on the acceleration for the PuriNOx-fueled vehicles. Larger acceleration losses were seen for the higher gears. No work activity test was performed on the tandem-axle dump trucks.

3.C.3 Bucket Trucks

Five drivers drove the three bucket truck test vehicles from the TxDOT fleet on a 34-mile highway test route. At mile 25 of the route, the bucket trucks stopped and performed a work activity test. The test involved putting out the stabilizing legs of the truck, lifting the bucket, and moving it around in a circle. The analysis of the datalogger data indicated that there was no problem with the bucket trucks maintaining cruising speeds on the highway. Detailed analyses of acceleration at three specific locations indicated that PuriNOx produced an acceleration loss of 12% to 31% depending on the gear. Higher gears had a greater loss. The average acceleration loss was 21%. Analysis of the work activity test indicated that none of the fuels caused any loss in ability to move the bucket. Analysis of the engine load data during the test indicated that moving the bucket used, at most, 40% of the engine load. Consequently, a 20% loss of engine torque would not result in any loss of bucket-moving capability.

3.C.4 Telescoping Boom Excavators

Three Gradalls, 2 from the TxDOT fleet and one that was loaned for the Roadeo by Houston Equipment Company (the 2 wheel drive Gradall), were tested by five different drivers on the same route used by the bucket trucks. These vehicles were subjected to both an on-road test and a work activity test.

While vehicle speed data was not available from the engine computer, engine RPM data was. From the engine RPM data, with the assistance of the accelerator pedal position and engine load data, we were able to determine relative vehicle speed of the Gradalls. The analysis of the data indicated that the vehicle with the PuriNOx fuel was consistently 8% to 15% slower during open highway cruising. The reason for this is that during highway cruising Gradalls are typically operated at 100% accelerator pedal position — even for regular diesel fuel. So, for Gradalls, a loss of 20% engine power is seen as a loss in top speed on the highway. The top speed of the Gradall XL3100 is 53.4 mph on regular diesel fuel according to Gradall. This is already a speed lower than most surrounding traffic. Therefore, an additional loss of speed produced by PuriNOx is serious.

A detailed analysis of the acceleration of the test vehicles at one specific location showed that the acceleration loss was 22% to 32% with an average of 28%. When they experienced poor acceleration, in an attempt to get the vehicle up to cruising speed, two drivers of the Gradall with the PuriNOx fuel downshifted back into seventh gear after being in eighth.

The Gradalls also were given a work activity test at mile 25 of the route. This test involved digging soil from the ground and loading it into a dump truck. The data analysis indicated there were differences among the vehicles in the loads imposed on the engine during this work. The vehicle that had the most load applied to the engine was also the vehicle that demonstrated the poorest cruise speed performance and poorest acceleration performance of the three test vehicles. This vehicle had engine loads occasionally touch 100%. Thus, based on this work activity test, it appears that PuriNOx can be used in Gradalls for excavation purposes. In instances where the operator of the Gradall is more aggressive than the five drivers in this test, the power reduction of the PuriNOx fuel might cause some loss in excavating ability.

3.C.5 Wheeled Loaders

Three TxDOT loaders were evaluated in the Roadeo as they were driven by five drivers. The loaders did not undergo a highway driving test but were only subject to a work activity test in which they were to load 10-yard dump trucks from a pile of material for 30 minutes. One of the loaders (loader B) that was fueled with PuriNOx ran out of fuel during the fifth run and needed to be refueled. The number of dump trucks that were loaded was an indication of the capability of PuriNOx with respect to regular diesel fuel. While the loaders were instrumented with dataloggers, the datalogger data did not provide any information beyond that provided by the observers and their counts of the number of dump trucks filled. Statistical analysis of the number of dump trucks filled indicated that the loaders with PuriNOx loaded dump trucks about 20% slower than loaders with regular diesel fuel.

3.C.6 Forklifts

Three TxDOT fleet forklifts were tested in a work activity test by five drivers. The work activity test involved carrying pallets with 3,400 pounds of concrete mix back and forth in a paved parking lot for a distance of 50 yards. The dataloggers on the forklifts recorded vehicle speed and RPM, and were used to determine the average time for each transit. The analysis indicated that there was no significant or important difference in the amount of time required to carry the loads between the PuriNOx-fueled and the regular diesel-fueled vehicles.

3.D Conclusions Regarding Performance

Lubrizol acknowledges that PuriNOx reduces the power available to vehicles by ~20%. The question is: how does the power loss affect vehicle performance and job productivity? One way of evaluating the impact of torque loss on vehicle performance and job productivity is to determine how the vehicle/equipment is used; in other words, what engine loads are required, and the fraction of the time that the vehicle/equipment is operated at high engine loads exceeding 80% of the maximum possible load.

In this section, we combine the qualitative and quantitative results from the Roadeo to arrive at a consistent statement about the effect of PuriNOx on vehicle performance and the ability of the operators or drivers to perform their tasks. The results of the Roadeo have been discussed in Sections 3.B and 3.C of the report in terms of the qualitative observations of the Roadeo participants surveyed and in terms of the quantitative analysis of the vehicle and engine data obtained from dataloggers on the different types of equipment.

As indicated in these sections, the Roadeo was designed to determine if operators/drivers perceive a difference in the equipment/vehicle performance when performing staged activities representative of TxDOT's operations. The staged activities also specifically included events highlighted by the Houston PuriNOx users that were compromised since switching to PuriNOx. While this section focused on vehicle performance and job productivity, other issues such as vehicle maintenance, frequency of vehicle usage, safety, and cost-effectiveness will ultimately be important factors in deciding whether to use PuriNOx or not. The paragraphs below summarize the salient findings of the qualitative and quantitative analysis conducted in terms of each type of equipment/vehicle included in the Roadeo. The discussion progresses from those equipment/vehicle types that showed the greatest performance and job productivity losses to those that showed the smallest losses.

Telescoping Boom Excavators – These vehicles were significantly affected by the use of PuriNOx. Operators consistently detected differences in acceleration performance, power, time to reach cruising speed, ability to maintain cruising speed, and overall performance. In addition, the quantitative data showed a 28% loss in acceleration and loss of the ability to maintain cruise speeds above 45 mph on the open highway. The engine data obtained during the Roadeo also indicated that the PuriNOx-fueled vehicles were driven more of the time during cruising with 100% accelerator pedal positions compared to the regular diesel-fueled excavators. On the other hand, no evidence exists that the ability to excavate is affected by the use of PuriNOx.

Wheeled Loaders – The loader operators consistently saw large differences in acceleration performance, power, and power when digging among vehicles fueled with PuriNOx and regular diesel fuel. The quantitative data indicated that loaders with regular diesel fuel could load about five 10-yard dump trucks in 30 minutes while a loader fueled with PuriNOx could load only about four dump trucks in the same time. This is a substantial loss - of 20% - in job productivity for loaders.

Telescoping Cranes – PuriNOx had a relatively small effect on the performance of these vehicles. Drivers did detect slower accelerations, less power, and an overall performance effect, but they were not able to detect differences in the time required to reach cruising speed or the ability to maintain cruising speed. The quantitative data indicated approximately 21% slower accelerations, but there was no noticeable effect on ultimate cruising speeds. In addition, the fuel had no substantial effect on the ability to move the bucket.

Forklifts – The forklift drivers were able to detect differences in acceleration and hydraulic movements, but did not detect differences in other aspects of forklift operation relative to performance. In this case, the data from the dataloggers on the vehicles were not able to detect any loss of performance or job productivity related to the use of PuriNOx.

Single-Axle and Tandem-Axle Dump Trucks – The dump trucks drivers could not detect any difference in the performance of the dump trucks on the driving route. The quantitative data taken on the dump trucks, however, indicated 20% slower accelerations for single-axle dump trucks and 27% slower accelerations for tandem-axle dump trucks. The cruising speed of the dump trucks was not affected by the use of PuriNOx. That is, in the case of dump trucks, while the drivers did not perceive a difference in performance, the dataloggers indicated a performance difference. During the Roadeo the dump trucks were filled with recycled asphalt product and were required to drive a specific route. Discussions with TxDOT personnel have, however, revealed that dump trucks are frequently used to pull heavy equipment on a trailer from one site to another. This activity was not included in the Roadeo, and it is certainly possible that in these situations the performance of the dump trucks will be more noticeably affected. In such situations, much more of the driving time would be at engine conditions of greater than approximately 80% load.

To summarize, from the Roadeo data it is obvious that a loss of power attributable to the use of PuriNOx translated to significantly slower accelerations, ranging from 20% for single-axle dump trucks to 28% for telescoping boom excavators, and a productivity loss of 20% for the loaders. There is also quantitative and qualitative evidence that suggests that the power loss affected the ability of the telescoping boom excavators to maintain cruising speeds. The only anomaly that exists between the quantitative and qualitative data is the inconsistency in the perception of the dump truck drivers as to the impact of PuriNOx on vehicle acceleration.

Although the Roadeo results pertain to selected TxDOT equipment, it is safe to conclude that most vehicles/equipment will be affected by torque loss. The consequences of torque loss in terms of productivity and performance impact will, however, largely be a function of the engine load required and the time vehicles/equipment are driven/operated at engine loads exceeding ~80%. Consequently, TxDOT and contractor vehicles/equipment that are used consistently at engine loads higher than approximately 80% can, on average, expect a loss in vehicle performance and job productivity. The exact loss of productivity will depend upon the duty cycle: the fraction of time that is spent above ~80% torque and the fraction of full-load torque that is required. Taken to the other extreme, a TxDOT or contractor vehicle that spent all of its time at less than approximately 80% engine load will probably, on average, be unaffected in terms of performance and productivity when using PuriNOx. The performance of specific vehicles/equipment might, however, be affected differently depending on the age of the vehicle, usage, and maintenance history.

4. Health and Safety

Health and safety are two extremely important criteria for assessing future use of emulsified diesel fuels. Health risks are discussed in Section 4.A. Safety is discussed in Section 4.B.

4.A Health

A health risks analysis was included in this evaluation due to health complaints by TxDOT employees in the Beaumont counties that converted to PuriNOx. Because of these complaints, it was prudent to consider potential health risks in this evaluation. However, the present project was not designed to be a formal health effects study. Rather, the information for this analysis was obtained, primarily, from the Material Safety Data Sheets (MSDS) and from the results of prior studies. It must be cautioned that there are no standards for writing an MSDS. Therefore, conclusions drawn from comparing the MSDS for two fuels cannot and should not be interpreted as definitive.

Less than two months after the start of this project, the two counties in the Beaumont District that had been using PuriNOx switched back to conventional diesel fuel due to employee complaints of eye irritation, headaches, nausea, and vomiting. Specifically, 24 of 47 exposed workers in three different sections voiced these complaints, resulting in the filing of 16 Form 187s (First Report of Injury). The 24 health complaints consisted of 22 males, ranging in age from the early 20s to the late 50s, and 2 females in the mid-30s to early 40s. There was no lost time associated with these episodes. Almost all complained of illness that was believed to be due to exposure to exhaust fumes while operating equipment or being near equipment while it was being operated. Two employees were also exposed via either skin contact or to the liquid's fumes while servicing equipment.

In response to the health complaints from Beaumont, Lubrizol changed the composition of summer-grade PuriNOx, using a different base diesel fuel with a higher Cetane Number. Lubrizol believed that the problems were due to mechanical/reliability issues that resulted in poor combustion. (After the change in composition, TxDOT referred to the original formulation as "PuriNOx A" and the higher Cetane formulation as "PuriNOx B".)

Potential health risks may be associated with skin contact with the liquid fuel, inhalation of the vapors from the liquid fuel, and exposure to the exhaust emissions. Each of these is discussed in this subsection.

As noted above, the analysis of the health risks that may be associated with skin contact relied exclusively on the Material Safety Data Sheets for PuriNOx and conventional diesel fuel. This comparison is made for summer-grade PuriNOx by some of the highlights from the MSDS in Table 4.1. The table covers both skin contact and accidental ingestion. Comments in italics (e.g., *same as diesel fuel*) indicate that the same wording is used in the MSDS for diesel fuel. In fact, other than for accidental ingestion (for which PuriNOx poses a lower risk than diesel fuel), all items in the MSDS regarding exposure to the liquid are identical to the wording for diesel fuel.

Table 4.1 Selected Items from the MSDS for Summer-Grade PuriNOx Regarding Exposure to the Liquid

Principal Hazards:

Combustible liquid. (*same as diesel fuel*)
May cause chronic health effects. (*same as diesel fuel*)

Noteworthy Warnings:

No explosive properties in the liquid state, but vapors may form ignitable mixtures in air. *(same as diesel fuel)*

Acute Exposure:

Accidental ingestion: the LD50 in rats is >5,000 mg/kg, based on data from components or similar materials. *(less hazardous than diesel fuel)*
Prolonged or repeated skin contact (e.g., from clothing wet with fuel) will cause dermatitis. Symptoms may include redness, edema, drying and cracking of the skin. *(same as diesel fuel)*
Dermal toxicity: the LD50 in rabbits is >2,000 mg/kg, based on data from components or similar materials. *(same as diesel fuel)*

Chronic Exposure:

Repeated and prolonged overexposure to diesel fuel may cause degenerative changes in the liver, kidneys, and bone marrow. *(same as diesel fuel)*

Table 4.2 is a similar comparison for winter-grade PuriNOx. In this case, comments in italics compare winter-grade PuriNOx to both diesel fuel and summer-grade PuriNOx. Because of the methanol in winter-grade PuriNOx, generally the potential health risks associated with the liquid are greater than for summer-grade PuriNOx or diesel fuel. Here, it should be noted that methanol is an approved alternative fuel for use in state vehicles under Chapter 2158 of the Texas Government Code.

Table 4.2 Selected Items from the MSDS for Winter-Grade PuriNOx Regarding Exposure to the Liquid

Principal Hazards:

Flammable liquid, may create a flash fire hazard. (*stronger wording than for diesel fuel and summer-grade PuriNOx*)
Component(s) known to cause chronic human health effects. (*stronger wording than for diesel fuel and summer-grade PuriNOx*)
May be harmful if absorbed through skin. (*this "Principal Hazard" not noted for diesel fuel or summer-grade PuriNOx*)

Noteworthy Warnings:

Static ignition hazard can result from handling and use. Electrically bond and ground all containers and equipment before transfer or use of material. *(not noted for diesel fuel or summer-grade PuriNOx)*

Acute Exposure:

Accidental ingestion: the LD50 in rats is >5,000 mg/kg, based on data from components or similar materials. *(less hazardous than diesel fuel)*
Ingestion of methyl alcohol can affect the optic nerve resulting in blindness. It can also cause gastrointestinal tract irritation, mental sluggishness, nausea, severe illness and possible death. *(not noted for diesel fuel or summer-grade PuriNOx)*
Prolonged or repeated skin contact (e.g., from clothing wet with fuel) will cause dermatitis. Symptoms may include redness, edema, drying and cracking of the skin. *(same as diesel fuel and summer-grade PuriNOx)*
Dermal toxicity: the LD50 in rabbits is >2,000 mg/kg, based on data from components or similar materials. (*same as diesel fuel and summer-grade PuriNOx*) Components of this material may be absorbed through the skin. *(not noted for diesel fuel or summer-grade PuriNOx)*

Chronic Exposure:

Repeated and prolonged overexposure to methanol can cause eye, lung, spleen, kidney, brain and nervous system damage and also liver abnormalities in laboratory animals. *(not noted for diesel fuel or summer-grade PuriNOx, since these do not contain methanol)*
Repeated and prolonged overexposure to diesel fuel may cause degenerative changes in the liver, kidneys, and bone marrow. *(same as diesel fuel and summer-grade PuriNOx)*
In-vitro tests on methanol indicate limited evidence of mutagenicity. No in-vivo information. *(not noted for diesel fuel or summer-grade PuriNOx, since these do not contain methanol)*

The analysis of the health risks that may be associated with inhalation of the vapors from the liquid fuel relied upon the MSDS for PuriNOx and conventional diesel fuel. The MSDS comparison for summer-grade PuriNOx is provided in Table 4.3. Again, comments in italics (e.g., *same as diesel fuel*) indicate that the same wording is used in the MSDS for diesel fuel. In fact, other than for respiratory irritation (for which the wording for PuriNOx is slightly different than that for diesel fuel), all items in the MSDS regarding exposure to the fumes from the liquid are identical to the wording for diesel fuel.

Table 4.3 Selected Items from the MSDS for Summer-Grade PuriNOx Regarding Exposure to the Fumes from the Liquid

Principal Hazards:
Harmful if inhaled. (*same as diesel fuel*)
May cause chronic health effects. (*same as diesel fuel*)
Acute Exposure:
Not expected to cause eye irritation, based on data from components or similar materials. *(same as diesel fuel)*
Inhalation toxicity: high concentrations may cause headaches, dizziness, fatigue, nausea, vomiting, drowsiness, stupor, other central nervous system effects leading to visual impairment, respiratory failure, unconsciousness, and death. *(same as diesel fuel)*
Respiratory irritation: not expected to cause nose, throat, or lung irritation, based on data from components or similar materials. *(similar to diesel fuel)*

Table 4.4 presents similar information regarding the fumes from liquid winter-grade PuriNOx. Again, because of the methanol in winter-grade PuriNOx, generally the potential health risks associated with the fumes are greater than for summer-grade PuriNOx or diesel fuel.

Table 4.4 Selected Items from the MSDS for Winter-Grade PuriNOx Regarding Exposure to the Fumes from the Liquid

Principal Hazards:

Harmful if inhaled. (*same as diesel fuel and summer-grade PuriNOx*)
Component(s) known to cause chronic human health effects. (*stronger wording than for diesel fuel and summer-grade PuriNOx*)
May cause eye irritation. *("Principal Hazard" not noted for diesel fuel or summer-grade PuriNOx)*

Noteworthy Warnings:

Vapors from spill may form explosive mixtures with air. Immediately evacuate all personnel from danger area. *(not noted for diesel fuel or summer-grade PuriNOx)*

Acute Exposure:

Weak to moderate eye irritant. Does not meet Canadian D2B or EU R36 criteria. *(neither diesel fuel nor summer-grade PuriNOx are expected to cause eye irritation)*
Inhalation toxicity: high concentrations may cause headaches, dizziness, fatigue, nausea, vomiting, drowsiness, stupor, other central nervous system effects leading to visual impairment, respiratory failure, unconsciousness, and death. *(same as diesel fuel and summer-grade PuriNOx*)
Respiratory irritation: if material is misted or if vapors are generated from heating, exposure may cause irritation of mucous membranes and the upper respiratory tract, based on data from components or similar materials. *(stronger respiratory irritation hazard than either diesel fuel or summer-grade PuriNOx)*

Chronic Exposure:

Repeated and prolonged overexposure to methanol can cause eye, lung, spleen, kidney, brain and nervous system damage, and also liver abnormalities in laboratory animals. *(not noted for diesel fuel or summer-grade PuriNOx, since these do not contain methanol)*
Repeated and prolonged overexposure to diesel fuel may cause degenerative changes in the liver, kidneys, and bone marrow. *(same as diesel fuel and summer-grade PuriNOx)*
Methanol has been reported to cause birth defects in rats exposed to very high levels of vapor: 20,000 ppm. *(not noted for diesel fuel or summer-grade PuriNOx, since these do not contain methanol*)

As far as exposure to the exhaust is concerned, all three MSDS note the same warnings:

- Toxic fumes, gases, or vapors may evolve on burning.

- On thermal decomposition, smoke, carbon monoxide, carbon dioxide, aldehydes, and other products of incomplete combustion are formed.

Health risks associated with the exhaust emissions were analyzed based on prior studies, the results of the Rimkus study for the Texas Department of Transportation (Drysdale et al., 2002), "speciation" of the exhaust from the present project, and EPA's certification of PuriNOx (Reed, 2002). These studies are summarized in Table 4.5. More details on the results from the present study are provided in Appendix B. In the "cycle" column, TBEC and WLC stand for the TxDOT Telescoping Boom Excavator Cycle and the AGC Wheeled Loader Cycle, respectively. In this table, ND is used when a species was not detected for either fuel and means "below detection limits." When a species was measured for one fuel, but below the detection limits for the other fuel, a zero (0) is used so that a percent change may be calculated using the assumption that any species that was below the detection limit was not emitted. Also, *NA* means that no attempt was made to measure this species.

Table 4.5 Results of Studies Related to Health Risks of Exposure to Exhaust

Ref.	cycle	fuel	units	formal dehyde	acetal dehyde	propion aldehyde	acrolein	MEK	1,3-butadi ene	hexane	benzene	toluene	ethyl benzene	m&p-xylene	o-xylene	CO	sulfates	nitrates
Emissions Studies: summer-grade PuriNOx																		
1	MLTB	ULSD	mg/km	116.4	21.88	5.75	5.19	3.2	2.79	0.22	3.97	1.53	1.04	2.09	1.41	1516	*NA*	*NA*
		PuriNOx	mg/km	69.98	16.01	4.64	3.08	2.17	1.59	ND	5.15	1.74	1.01	2.34	1.39	1589	*NA*	*NA*
		change	%	-40	-27	-19	-41	-32	-43	-100	30	14	-3	12	-1	5		
2	HDD FTP	CARB ref.	mg/hp-hr	15.92	4.87	1.1	1.5	0.4	0.98	0.0	0.66	0.69	0.29	0.2	0.1	2370	1.0	*NA*
	(transient)	PuriNOx	mg/hp-hr	25.06	7.84	1.7	2.2	0.6	1.33	0.1	0.67	1.04	0.40	1.2	0.3	1283	0.6	*NA*
		change	%	57	61	55	48	37	35	200	1	50	37	467	229	-46	-38	
		95% confidence?		Y	Y	N	N	N	Y	N	N	N	N	N	N	Y	Y	
3	HDD FTP	CARB ref.	mg/hp-hr	7.6	2.8	1.0	0.9	0.3	0.4	trace	0.3	0.5	0.1	0.4	0.1	877	*NA*	*NA*
	(transient)	PuriNOx	mg/hp-hr	16.2	6.1	2.4	2.2	0.5	0.8	trace	0.5	0.8	0.0	0.5	0.1	758	*NA*	*NA*
		change	%	115	118	139	155	75	92		47	60	-67	33	103	-14		
		95% confidence?		Y	Y	Y	Y	Y	Y	N	N	Y	N	N	N	Y		
		ref. Diesel	mg/hp-hr	9.0	3.1	0.6	1.4	0.2	0.5	0.2	0.3	0.7	0.1	0.3	0.1	1012	*NA*	*NA*
		PuriNOx	mg/hp-hr	16.2	6.1	2.4	2.2	0.5	0.8	trace	0.5	0.8	0.0	0.5	0.1	758	*NA*	*NA*
		change	%	81	98	329	55	180	67		40	20	-75	99	0	-25		
		95% confidence?		Y	Y	Y	Y	Y	Y	N	N	N	N	N	N	Y		
4	TBEC	2D on-road	mg/hp-hr	9.3	3.4	1.5	1.2	0.1	ND	0.6	1.0	1.0	ND	0.6	0.1	733	3.0	0.53
		PuriNOx	mg/hp-hr	18.0	6.5	2.1	2.7	0.4	ND	0.4	1.4	1.4	0.4	1.3	0.6	1060	3.0	0.41
		change	%	93	89	42	118	217		-32	43	34	inf.	134	777	45	0	-23
		95% confidence?		Y	Y	N	Y	Y	N	N	Y	N	N	Y	Y	Y	N	Y
4	WLC	2D on-road	mg/hp-hr	5.5	1.9	1.1	0.5	ND	0.3	ND	0.7	0.7	ND	0.2	ND	567	2.0	0.49
		PuriNOx	mg/hp-hr	9.2	3.5	1.0	1.2	0.12	ND	ND	1.3	3.4	ND	0.3	0.6	531	2.4	0.45
		change	%	66	81	-1	150	inf.	-100		98	379		36	inf.	-6	18	-8
		95% confidence?		Y	Y	N	Y	Y	N	N	Y	N	N	N	Y	N	N	N
		hi S off-road	mg/hp-hr	5.8	2.2	0.8	0.7	0.05	ND	ND	1.0	2.1	0.5	1.4	0.7	598	30	0.11
		PuriNOx	mg/hp-hr	9.2	3.5	1.0	1.2	0.12	ND	ND	1.3	3.4	ND	0.3	0.6	531	2.4	0.45
		change	%	59	62	32	69	160			34	62	-100	inf.	-6	-11	-92	313
		95% confidence?		Y	Y	N	Y	Y	N	N	N	N	Y	Y	N	N	Y	Y
Health Risk Studies: summer-grade PuriNOx																		
5	bus garage			**OK**	**OK**	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	**OK**	*NA*	*NA*
6	HDD FTP			**passed EPA Tier 2 health effects tests**														
7	in-use			*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	**OK**	*NA*	*NA*

1=Bailey et al. (1999); 2=Khalek et al. (2000); 3=Fanick (2000); 4=present study; 5=Robertson & Miles (2002); 6=Reed (2002); 7=Drysdale et al. (2002)

From the present tests, it does not appear that PuriNOx poses a problem with respect to the sulfates or nitrates in comparison to 2D on-road diesel fuel. One problem with analyzing the species on the CARB and EPA lists of hazardous emissions is that no standards have been developed (except for ILEV and ULEV standards for formaldehyde of 50 and 25 mg/hp-hr, respectively). Neither the London bus study nor the Rimkus study measured many of the species in Table 4.5. The London bus garage study (Robertson and Miles, 2002) concluded that exposures to formaldehyde, acetaldehyde, and carbon monoxide were within acceptable limits (as were exposures to total inhalable dust, respirable dust, acrylaldehyde, SO_2, total hydrocarbons, and oxides of nitrogen as NO_2). Of the species in Table 4.5, the Rimkus study (Drysdale et al., 2002) only measured CO and concluded that levels were within acceptable limits (as was exposure to ammonia, hydrogen sulfide, NO, NO_2, nitric acid, SO_2, and total HCs). No health complaints were noted in the interviews with other PuriNOx users discussed in Section 3.B.3. PuriNOx has passed EPA's Tier 2 health effects analysis based upon speciated emissions tests. However, it must be noted that EPA is concerned with indirect health risks of the general population via exposure to highly diluted (by a factor of more than 1000) exhaust, whereas TxDOT is concerned about direct exposure of their workers to close-vicinity exhaust.

Thus, there is no evidence that unacceptable health risks are associated with summer-grade PuriNOx except for four factors. First, more than 20 TxDOT personnel in the Beaumont District had complaints of eye irritation, headaches, nausea, and vomiting (although none in the Houston District, and no other PuriNOx users that we interviewed, had health complaints). Second, a graduate student in the lab where UT was preparing samples of PuriNOx for separation experiments became nauseated. This was obviously due to exposure to the fumes from the liquid. Because the MSDS for PuriNOx reads exactly like that for diesel fuel ("Inhalation toxicity: high concentrations may cause headaches, dizziness, fatigue, nausea, vomiting, drowsiness, stupor, other central nervous system effects leading to visual impairment, respiratory failure, unconsciousness and death"), the nausea suffered by this graduate student poses the question of whether the concentration level for PuriNOx that causes complaints of nausea is lower than that for diesel fuel. Here, it should be noted that many have complained that the fumes from PuriNOx have a very strong odor — worse than diesel fuel — so that the composition of these fumes is not just that of watered down diesel fuel; the additive package may play an important role in the smell, and possibly in the threshold concentration that may lead to health complaints. Third, the only means available for the present report for assessing risks associated with exposure to the liquid and to the fumes from the liquid was via comparison of the MSDS for PuriNOx and conventional diesel fuel, but there are no standards for writing an MSDS. Therefore, these comparisons are not definitive. Finally, the fact that summer-grade PuriNOx passed EPA's Tier 2 health risks analysis does not indicate that there are no risks associated with direct exposure to close-vicinity exhaust.

As far as we have been able to determine, there has been only one study of the effects of winter-grade PuriNOx on emissions (SwRI, 2000). In this study, winter-grade PuriNOx was compared to CARB baseline diesel in a 1999 Detroit Diesel Series 60 via cold and hot start transient cycles. Compared to the CARB diesel fuel, winter-grade PuriNOx decreased PM by about 35% but only decreased NOx emissions ~5%. Many of the TACs were emitted at levels slightly higher than for summer-grade PuriNOx.

4.B Safety

Safety issues may be divided into two categories. Acceleration and top speed performance are discussed in the following subsection. The flash point is discussed in Subsection 4.B.2.

4.B.1 Acceleration and Speed as They Affect Safety

The quantitative assessments of vehicle performance were presented in Section 3.C and the detailed analyses are in Appendix D.2.C. In this section, we briefly discuss the differences in acceleration and speed from a safety perspective as a result of using PuriNOx compared to using regular diesel fuel. We do not believe that acceleration and speed are safety criteria for equipment that is used exclusively off the public roadways, such as loader and forklift operations. Therefore, safety will be considered only for single-axle dump trucks, tandem-axle dump trucks, bucket trucks, and telescoping boom excavators.

For the single-axle dump trucks and tandem-axle dump trucks, the driver surveys that were taken immediately after the drivers made their test runs indicated that the drivers did not perceive a difference in performance among the three test vehicles. Without even considering the datalogger data, this observation is important with respect to safety. If the performance of a vehicle meets the driver's expectation, then perhaps there is not a safety issue even if detailed quantitative measures of acceleration and speed might show a real difference in vehicle performance.

In the case of the dump trucks, the detailed analysis of second-by-second speeds and accelerations showed that the accelerations were 20% slower for single-axle dump trucks and 27% slower for tandem-axle dump trucks, and that there was no problem in ultimately reaching reasonable cruising speeds. Thus, we know from the analysis of the datalogger data that the accelerations of the dump trucks were affected by the different fuels. However, the size of the acceleration effect was small enough that the drivers could not sense it. One reason may be that the accelerations of the dump trucks are already slow (in comparison with light-duty vehicles) so if the accelerations are even 27% slower, it may be difficult for a driver to detect that difference in acceleration. Consequently, the measured loss of acceleration may not affect safety because the drivers are not aware of it, or, on the other hand, because the loss of acceleration is real, it may affect safety without the driver's knowledge.

For bucket trucks, the detailed analysis of speed and acceleration from the datalogger data indicated that accelerations were about 21% slower with PuriNOx fuel than with regular diesel fuel. In addition, the Roadeo drivers consistently ranked the PuriNOx-fueled bucket truck low in terms of acceleration and power.

In the case of the Gradalls, we believe that the loss of speed and acceleration performance is probably a safety issue. The top speed of the Gradall, as quoted by the manufacturer, is 53.4 mph on regular diesel fuel. If, on top of this, we impose the observed speed loss of 8% to 15%, the resulting top speed of the vehicle on PuriNOx will be 45 to 49 mph. The speed of the Gradall when it is going up grades on the highway will be even slower. If the Gradall is driven on highways where traffic is moving at a speed limit of 65 mph, the Gradall may seem almost motionless from the perspective of a driver in a light-duty passenger car. In terms of acceleration, the analysis indicated that accelerations for the Gradall were 28% slower than the already slow accelerations for the machine. We believe this reduced acceleration will have an important effect on the ability of the Gradall and its driver to merge into normal traffic on highways.

4.B.2 Flash Point

The National Fire Protection Association (NFPA) characterizes hydrocarbon liquids using a variety of measures of fire hazard. One measure of fire hazard is the flash point temperature of the liquid. The flash point temperature is the temperature of the liquid at which a spark generated above the liquid will result in a flash fire. Thus, the flash point temperature is related to the volatility and flammability limits of the fuel. This temperature is typically measured using an American Society for Testing and Materials (ASTM) test that depends on the viscosity of the liquid (ASTM D56, D93, D3278, D3828). NFPA characterizes liquid fuels in two broad categories (flammable and combustible liquids). Flammable liquids are those with a flash point temperature below 100 ^{o}F, while combustible liquids have flash point temperatures greater than or equal to 100 ^{o}F. The storage and handling of liquid fuels depend on ratings such as the NFPA ratings. Testing at Southwest Research Institute (SwRI) using the ASTM D93 protocol showed winter-grade PuriNOx to have a flash point of 121 ^{o}F as compared to a flash point of 171 ^{o}F for summer-grade PuriNOx. Lubrizol provides MSDS data for a winter-grade PuriNOx (20WB-CT) that indicates a flash point of 36 ^{o}C (96.8 ^{o}F). Even though the measured flash point for our sample of winter-grade PuriNOx is well above the minimum specification, the composition of all transportation fuels varies (see Appendix F) so there is no guarantee that winter-grade PuriNOx will not be sold with a flash point near the minimum specification. A concern with this fuel is that if the winter-grade PuriNOx is left in an engine's fuel tank or in any other storage container and the equipment is not used again until the ambient temperature has climbed to 100 ^{o}F or higher, there may be a safety hazard. The MSDS-rated flash point temperature of the winter-grade fuel straddles the demarcation between flammable and combustible fuels. It would be wise from a safety perspective to treat winter-grade PuriNOx more like a flammable liquid than a combustible liquid. The safety implications on storage associated with possible separation/stratification are presently unknown.

4.C Conclusions

Health and safety are important considerations for assessing any new technology or alternative fuel.

A cursory health risks analysis was added to this project, after its inception, due to health complaints from TxDOT employees from the Beaumont District (no health complaints were lodged from the Houston District or revealed by interviews with other PuriNOx users). However, this is not a formal health effects study, and should not be perceived as such. Health risks due to exposure to the liquid (e.g., skin contact) and to inhalation of the fumes (vapors) from the liquid were assessed based solely by comparing the Material Safety Data Sheets for PuriNOx and conventional diesel fuel. However, there are no standards for writing an MSDS, so any conclusions drawn from such comparisons are not definitive.

Based solely upon the information in the MSDS, it does not appear that exposure to liquid summer-grade PuriNOx poses a greater health risk than does liquid diesel fuel. However, exposure to liquid winter-grade PuriNOx does pose a greater risk. This risk probably can be managed by the use of appropriate protective clothing. Therefore, neither summer-grade nor winter-grade PuriNOx can be excluded from use based upon the available information regarding exposure to the liquid.

There is also little information available to assess the health risks associated with exposure to the fumes from the liquid, other than the MSDS. Again, the MSDS indicate that summer-grade PuriNOx poses about the same health risks as diesel fuel, and winter-grade PuriNOx presents a greater risk. However, 24 TxDOT employees in the Beaumont District complained of headaches, eye irritation, nausea, and vomiting. This may have been because of exposure to the exhaust. However, a graduate student at UT developed nausea from summer-grade PuriNOx fumes, indicating that the health complaints may be related to the fumes rather than the exhaust. It is possible that the additive package causes both the worse odor of summer-grade PuriNOx (relative to diesel fuel) and lowers the threshold concentration of the fumes that lead to health complaints. PuriNOx users should avoid breathing the fumes from the liquid – prudent practice for any liquid fuel.

Two occupational health studies of exposure to the exhaust indicate that PuriNOx does not yield products that are near or above safe limits. However, neither of these studies included the full list of Toxic Air Contaminants (TACs). Many of the TACs increase when PuriNOx is used. Neither the EPA nor CARB have established regulations for these TACs, other than formaldehyde. Summer-grade PuriNOx has passed EPA's Tier 2 health risks analysis. However, EPA is concerned with indirect exposure of the public to highly diluted exhaust, whereas TxDOT is concerned with direct exposure of employees to close-vicinity exhaust.

Thus, there is no definitive data available to support excluding summer-grade PuriNOx based upon health risks.

However, we recommend that TxDOT not use winter-grade PuriNOx for both health and safety reasons. Winter-grade PuriNOx does pose a greater health risk than diesel fuel based upon the MSDS, and the extent of this risk is uncertain. The emission of TACs when winter-grade PuriNOx is used appear to be somewhat higher than for summer-grade PuriNOx. Although these levels might prove acceptable from the perspective of exposure to highly diluted exhaust, no occupational health studies (close-vicinity exhaust) have been performed on winter-grade PuriNOx, to our knowledge. Although the flash point that we measured for winter-grade PuriNOx was higher than Lubrizol's minimum specification, the specification is low enough to be of concern as a potential fire hazard due to the possibility that commercial winter-grade PuriNOx may be delivered with a flash point near the minimum specification. Other reasons that we recommend against use of winter-grade PuriNOx are discussed later in this report.

We also do not recommend that summer-grade PuriNOx be used in telescoping boom excavators or any equipment that cannot maintain 45 mph on the highway when using PuriNOx. The safety criteria of acceptable acceleration and cruising speed for on-road driving are not relevant for off-road equipment. Therefore, use of summer-grade PuriNOx in equipment that is solely used for off-road activities is acceptable from the perspective of these safety criteria.

5. Cost-Effectiveness Analysis

The cost-effectiveness analysis performed for this study is discussed in this section. The objective and general methodology are discussed in Section 5.A. The method used to quantify the benefits of PuriNOx is discussed in Section 5.B. The costs of using PuriNOx for TxDOT's Houston District are discussed in Section 5.C. The results of the TxDOT cost-effectiveness analysis are presented in Section 5.D. The costs and cost-effectiveness analysis for AGC are presented in Section 5.E. Alternative NOx control technologies are discussed in Section 5.F.

5.A Introduction

The objective of this analysis is aimed at:

1. calculating the cost-effectiveness of using PuriNOx as an emissions reduction strategy, and
2. comparing the emissions reductions and costs of alternative abatement strategies to using PuriNOx.

All benefits and costs associated with the use of PuriNOx were estimated relative to federal 2D on-road diesel - the conventional fuel used in TxDOT's on and off-road vehicles/equipment. The study draws extensively on information captured by TxDOT, such as fuel costs, equipment maintenance costs, fuel storage costs, costs due to increased fuel consumption, etc.

The study quantified the costs of reducing emissions attributable to the adoption of PuriNOx for the Houston District and for the specific pieces of equipment included in the study: telescoping boom excavators, wheeled loaders, single-axle dump trucks, tandem-axle dump trucks, and small utility engines. This was done to determine whether it would be more cost-effective to convert only certain pieces of equipment to PuriNOx. For the remainder of TxDOT's equipment, it was assumed that, on average, the Houston off-road equipment has the same emissions reductions and incurred costs as the average of those tested, and a similar assumption was made for the on-road vehicles. This is a simplistic assumption, which will introduce some margin of error into the cost-effectiveness calculation. In practice, the quantity of emissions, for a given pollutant, from a vehicle/equipment depends on (1) the type of fuel consumed, (2) age and condition of the equipment, (3) model year, (4) weight, (5) emissions control technologies, and (6) any tampering with emissions control technologies.

The calculated cost-effectiveness of PuriNOx provides a point estimate for the costs of the achieved emissions reductions. In addition, the study identifies other alternative emission abatement strategies and summarizes the available costs of these strategies.

The data used to develop the point estimate were TxDOT's records for the 6 counties in the Houston District for fiscal year 2001 (FY01). These records include the gallons of fuel used and either miles traveled or hours used during the year for each piece of equipment. Figure 5.1 shows the total diesel fuel use by TxDOT equipment in these 6 counties over the past 10 fiscal years. As shown in Figure 5.1, diesel fuel use by TxDOT appears cyclic. The diesel used in FY01 was 10.8% below the average for this 10 year period. Therefore, our use of FY01 data will yield conservative predictions of total NOx emissions, tons of NOx removed, and gallons of PuriNOx consumed by the TxDOT fleet in Houston if our point estimates are extrapolated to future years. However, we do not believe that this has a significant impact on the cost-effectiveness calculations.

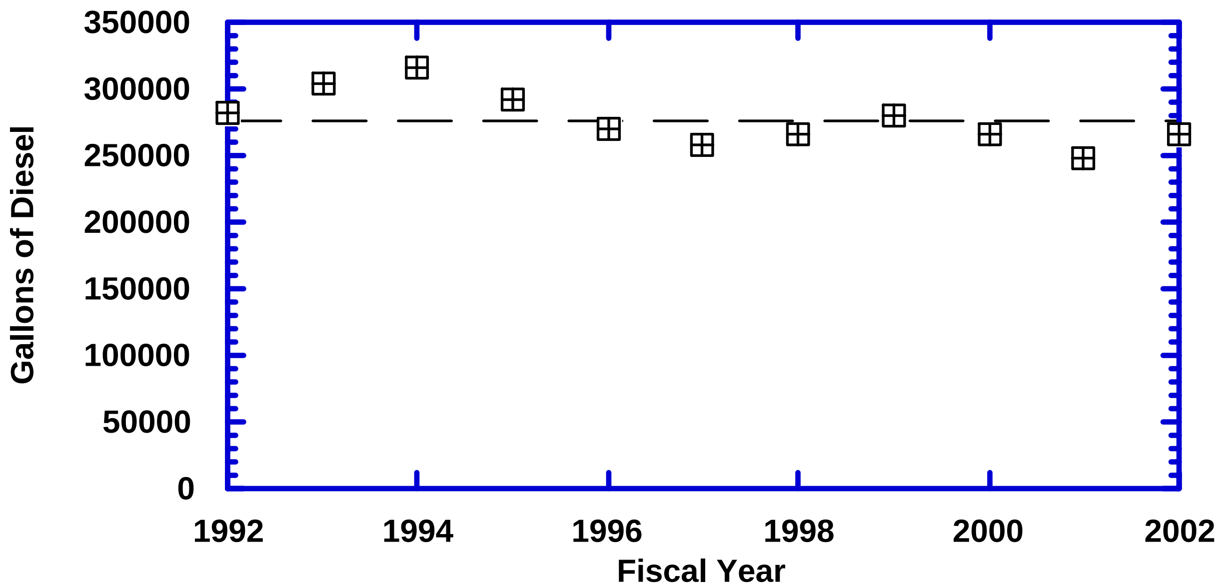

Figure 5.1. Annual diesel fuel consumption over the past 10 years by TxDOT equipment in the Houston District

5.B. Benefits

The immediate benefit of PuriNOx, from the perspective of Texas' State Implementation Plan, is decreased NOx emissions from diesel-powered vehicles and equipment. It is possible that the decrease in PM emissions from using PuriNOx will be of interest in the future. The techniques used to quantify these benefits are discussed in this subsection.

PuriNOx will decrease the atmospheric concentrations of two criteria pollutants: NOx and particulate matter. As stated earlier, NOx is a major contributor to the formation of ground-level ozone in the presence of sunlight. Ozone exposure, in turn, causes a range of human health effects, including chronic respiratory illnesses, such as emphysema, chronic bronchitis, and chronic asthma. In addition, ozone is known to reduce crop yield, increase susceptibility of plants to pests, damage a wide variety of materials, and impact visibility. Also, the secondary effects of NOx include the formation of nitrate PM, acid rain, and the reduced quality of coastal waters. Reductions in NOx emissions thus have considerable public health and environmental benefits (Environmental Protection Agency, 1997, 2000). Because PuriNOx's ability to reduce PM emissions is not of direct interest to the cost-effectiveness analyses, no further discussion is merited.

To estimate the total tons of pollutant removed per piece of equipment and also to perform the cost-effectiveness analysis, we took advantage of the TxDOT records on the amount of diesel fuel consumed annually for each piece of equipment in the 6 non-attainment counties in the Houston District. Because the water in PuriNOx does not contain any chemical energy, the rate of consumption of diesel fuel (i.e., the nonwater fraction of the PuriNOx) remains almost the same after conversion to PuriNOx. However, there is an overall fuel economy penalty: more gallons of PuriNOx must be consumed to deliver the same energy as a gallon of diesel fuel.

Given TxDOT's records of the Annual Diesel Consumption (ADC) for each piece of equipment, the calculation of the Modified Annual Diesel Mass Consumption (MADMC) for each piece of equipment depends upon whether fuel economy (mpg) or brake specific fuel consumption (bsfc in g/hp-hr) was measured. For the telescoping boom excavators, wheeled loaders, and small utility engines, the equation is:

$$\text{MADMC}\left[\frac{\text{kg}_{\text{DF}}/\text{yr}}{\text{eqpt.}}\right] = \text{ADC}\left[\frac{\text{gal}_{\text{D}}/\text{yr}}{\text{eqpt.}}\right]\cdot\rho_{\text{D}}\left[\frac{\text{kg}_{\text{D}}}{\text{gal}_{\text{D}}}\right]\cdot\frac{\text{bsfc}_{\text{P}}}{\text{bsfc}_{\text{D}}}\left[\frac{\text{kg}_{\text{P}}}{\text{kg}_{\text{D}}}\right]\cdot(1-x_{\text{H2O}})\left[\frac{\text{kg}_{\text{DF}}}{\text{kg}_{\text{P}}}\right] \quad (5.1)$$

For the dump trucks, the equation is:

$$\text{MADMC}\left[\frac{\text{kg}_{\text{DF}}/\text{yr}}{\text{vehicle}}\right] = \text{ADC}\left[\frac{\text{gal}_{\text{D}}/\text{yr}}{\text{vehicle}}\right]\cdot\frac{\text{mpg}_{\text{D}}}{\text{mpg}_{\text{P}}}\left[\frac{\text{gal}_{\text{P}}}{\text{gal}_{\text{D}}}\right]\cdot\rho_{\text{P}}\left[\frac{\text{kg}_{\text{P}}}{\text{gal}_{\text{P}}}\right]\cdot(1-x_{\text{H2O}})\left[\frac{\text{kg}_{\text{DF}}}{\text{kg}_{\text{P}}}\right] \quad (5.2)$$

In Equations 5.1 and 5.2, the units for each term are provided in square brackets, ρ is the density of the fuel, x_{H2O} is the mass fraction of water in the fuel (0.0 for diesel fuel, 0.2 for PuriNOx), subscript D refers to diesel fuel, subscript P refers to PuriNOx, and subscript DF refers to the diesel fraction of the fuel (100% for diesel fuel, 80% by mass for PuriNOx, where the additive package has been included in the diesel fraction since these additives contain chemical energy).

Equations 5.1 and 5.2 provide estimates of the mass of diesel fuel consumed annually for each piece of equipment after conversion to PuriNOx. Given this mass consumption rate, it is most convenient to convert the measured emissions rate into an Emissions Index for each pollutant species. The technique used to calculate the Emissions Index for NOx (EINOx, grams of NOx emitted per kilogram of fuel consumed) is used as an example. Calculation of the Emissions Index for other species uses the same methodology. This calculation depends upon how the emissions and fuel consumption were measured. For the telescoping boom excavators, wheeled loaders, and small utility engines, the brake specific emissions (bsNOx is the mass rate of NOx emitted per unit of power produced) and bsfc were measured. The relevant equation for these cases is:

$$\text{EINOx}\left[\frac{\text{g}_{\text{NOx}}}{\text{kg}_{\text{F}}}\right] = \frac{\text{bsNOx}\,[\text{g}_{\text{NOx}}/\text{hp-hr}]}{\text{bsfc}_{\text{F}}[\text{g}_{\text{F}}/\text{hp-hr}]}\cdot 1000\left[\frac{\text{g}_{\text{F}}}{\text{kg}_{\text{F}}}\right] \quad (5.3)$$

For the dump trucks, the emissions rate was measured (in g/mi) and the equation is:

$$\text{EINOx}\left[\frac{\text{g}_{\text{NOx}}}{\text{kg}_{\text{F}}}\right] = \dot{R}_{\text{NOx}}\left[\frac{\text{g}_{\text{NOx}}}{\text{mi}}\right]\cdot\text{mpg}\left[\frac{\text{mi}}{\text{gal}_{\text{F}}}\right]\cdot\frac{1}{\rho_{\text{F}}}\left[\frac{\text{gal}_{\text{F}}}{\text{kg}_{\text{F}}}\right] \quad (5.4)$$

In Equations 5.3 and 5.4, subscript F refers to any of the fuels tested. Because the consumption of the diesel fraction of the fuel can be estimated via Equations 5.1 and 5.2, it is convenient to modify Equations 5.3 and 5.4 to yield emissions per mass of diesel fraction consumed. The Modified Emissions Index is:

$$\mathrm{MEINOx}\left[\frac{g_{NOx}}{kg_{DF}}\right]=\mathrm{EINOx}\left[\frac{g_{NOx}}{kg_{D}}\right]\cdot\frac{1}{1-x_{H2O}}\left[\frac{kg_{D}}{kg_{DF}}\right] \tag{5.5}$$

For 2D on-road, 2D off-road, and ultra low sulfur diesel, the mass fraction of water in the fuel is 0.0 whereas it is 0.2 for PuriNOx.

The results of these calculations are shown in Table 5.1 for the heavy-duty engines (results for the small utility engines are discussed later in this subsection). In Table 5.1, identical equations to those for NOx have been used to determine the Emissions Index and Modified Emissions Index for PM.

Table 5.1. Emissions Indices Based Upon the Overall Fuel and the Diesel Fraction of the Fuel for the Heavy-Duty Engines.

Engine	Control	Fuel	EINOx g/kgF	EIPM g/kgF	MEINOx g/kgDF	MEIPM g/kgDF
TxDOT Telescoping Boom Excavator Cycle						
ISB-190	elect.	2D on-road	20.35	0.47	20.35	0.47
		PuriNOx	14.13	0.25	17.66	0.31
6BTA5.9	mech.	2D on-road	29.66	0.52	29.66	0.52
		PuriNOx	17.39	0.36	21.74	0.45
AGC Wheeled Loader Cycle						
ISB-190	elect.	2D on-road	20.66	0.42	20.66	0.42
		high S off-road	21.20	0.71	21.20	0.71
		PuriNOx	14.50	0.16	18.12	0.21
6BTA5.9	mech.	2D on-road	28.75	0.49	28.75	0.49
		low S off-road	28.16	0.82	28.16	0.82
		PuriNOx	17.98	0.25	22.47	0.32
TxDOT Single Axle Dump Truck Cycle						
3126B	elect.	2D on-road	45.83	0.29	45.83	0.29
		PuriNOx	35.28	0.26	44.10	0.33
T444E	elect.	2D on-road	19.38	0.41	19.38	0.41
		PuriNOx	11.97	0.46	14.96	0.58
7.6T-I6	mech.	2D on-road	21.42	0.78	21.42	0.78
		PuriNOx	14.13	0.31	17.66	0.39
1060	mech.	2D on-road	25.35	0.40	25.35	0.40
		PuriNOx	16.00	0.27	20.00	0.33
TxDOT Tandem Axle Dump Truck Cycle						
90 L10-300	mech.	2D on-road	24.04	1.63	24.04	1.63
		PuriNOx	18.77	1.42	23.47	1.78
C10	elect.	2D on-road	16.97	0.43	16.97	0.43
		PuriNOx	12.71	0.24	15.89	0.30
89 L10-300	mech.	2D on-road	26.17	1.60	26.17	1.60
		PuriNOx	21.91	0.99	27.39	1.23
3176	elect.	2D on-road	28.22	0.39	28.22	0.39
		PuriNOx	22.26	0.31	27.82	0.38

The change in emissions per unit mass of diesel (diesel fraction for the emulsified fuel) consumed is the difference between the Modified Emissions Index for PuriNOx and that for the baseline diesel fuel:

$$\Delta NOx\left[\frac{\Delta g_{NOx}}{kg_{DF}}\right] = MEINOx\left[\frac{g_{NOx}}{kg_{DF}}\right]_{PuriNOx} - MEINOx\left[\frac{g_{NOx}}{kg_{DF}}\right]_{diesel} \quad (5.6)$$

For the loaders, PuriNOx can be compared to both on-road and off-road diesel fuel via Equation 5.6. Additionally, on-road and off-road diesel fuel can be compared to each other. The results of these calculations are provided in Table 5.2.

Table 5.2. Changes in the Mass Emissions of NOx and PM per Unit Mass of the Diesel Fraction of the Fuel Consumed for the Heavy-Duty Engines.

Engine	Control	Fuels Compared	ΔNOx g/kgDF	ΔPM g/kgDF
TxDOT Telescoping Boom Excavator Cycle				
ISB-190	elect.	2D on-road/PuriNOx	-2.69	-0.16
6BTA5.9	mech.	2D on-road/PuriNOx	-7.92	-0.06
AGC Wheeled Loader Cycle				
ISB-190	elect.	2D on-road/PuriNOx	-2.54	-0.21
		2D high S off-road/PuriNOx	-3.08	-0.51
		2D on-road/off-road	-0.54	-0.29
6BTA5.9	mech.	2D on-road/PuriNOx	-6.28	-0.17
		2D low S off-road/PuriNOx	-5.68	-0.50
		2D on-road/off-road	NS*	-0.33
TxDOT Single Axle Dump Truck Cycle				
3126B	elect.	2D on-road/PuriNOx	-1.74	0.04
T444E	elect.	2D on-road/PuriNOx	-4.42	0.17
7.6T-I6	mech.	2D on-road/PuriNOx	-3.76	-0.40
1060	mech.	2D on-road/PuriNOx	-5.35	-0.07
TxDOT Tandem Axle Dump Truck Cycle				
90 L10-300	mech.	2D on-road/PuriNOx	-0.57	0.15
C10	elect.	2D on-road/PuriNOx	-1.08	-0.13
89 L10-300	mech.	2D on-road/PuriNOx	1.22	-0.37
3176	elect.	2D on-road/PuriNOx	-0.40	-0.01

NS - difference in EINOx not statistically significant at the 95% confidence level

The results in Table 5.2 can be used to calculate the annual change in NOx and PM emissions (as discussed below) and the cost-effectiveness for each specific type of equipment, such as telescoping boom excavators with Cummins ISB-190 engines. However, TxDOT operates excavators and dump trucks with engines that were not tested during this project. One could assume, for example, that all of the single-axle dump trucks with electronically-controlled engines behave like the average of those tested, with a similar assumption for single-axle dump trucks with mechanically-controlled engines, etc. These assumptions will introduce some error into the analysis. An easier calculation results from assuming that all single-axle dump trucks behave like the average of all of the single-axle dump trucks that were tested, with similar assumptions for the tandem-axle dump trucks, telescoping boom excavators, and wheeled loaders. These assumptions will introduce even more uncertainty into the analyses. However, this uncertainty is only important if the cost-effectiveness is near the margin of acceptability.

It is also necessary to account for all of the types of equipment that TxDOT operates that were not subjected to testing during this project. Here, a gross assumption is essential.

We assumed that the on-road equipment behaves like the average of all on-road equipment tested. A similar assumption was made for the equipment that TxDOT categorizes as off-road. Additionally, to roughly compensate for testing only two off-road engines over only one TxDOT-specific cycle, the average off-road behavior was estimated by assuming that TxDOT's wheeled loaders behave like AGC's. Here, it is noted that TxDOT uses 2D on-road diesel for all of its equipment, including off-road equipment. The results of these calculations are shown in Table 5.3.

Table 5.3 Average Changes in the Mass Emissions of NOx and PM for PuriNOx Relative to 2D On-Road Diesel

	average ΔNOx	**average ΔPM**
Equipment	g/kgDF	g/kgDF
Telescoping Boom Excavators	-5.30	-0.11
Wheeled Loaders	-4.41	-0.19
Single-Axle Dump Trucks	-3.82	-0.06
Tandem-Axle Dump Trucks	-0.21	-0.09
Average Non-Road Equipment	-4.85	-0.15
Average On-Road Equipment	-2.01	-0.08
Average On-Road with Electronic Engines	-1.91	0.02
Average On-Road with Mechanical Engines	-2.12	-0.17
Average Non-Road with Electronic Engines	-2.61	-0.19
Average Non-Road with Mechanical Engines	-7.10	-0.12

The division between electronically-controlled engines and mechanically-controlled engines in Table 5.3 reflects older engines designed to meet less stringent emissions standards and newer engines with more sophisticated emissions controls such as high pressure electronic fuel injection. In their evaluation of PuriNOx, EPA (2002a) found that the NOx improvement correlated with the baseline emissions from engines operating on diesel fuel. In other words, when PuriNOx is used in engines that meet more stringent NOx standards, the percentage benefit from PuriNOx is lower. EPA found that the off-road equipment they evaluated, which were designed to meet less stringent emissions standards, enjoyed a 24.4% advantage in NOx emissions from using PuriNOx, whereas the on-highway engines, which were designed to meet more stringent emissions standards, enjoyed only a 13.7% advantage from PuriNOx. This finding is also reflected in the present results, indirectly in Table 5.3 but directly in Tables 2.2 and 2.4 and in Figure 5.2. We found a 13.6% benefit for electronic on-highway, a 13.4% benefit for electronic off-road and a 21.0% benefit for mechanical off-road. These values are quite close to EPA's. Also, excluding he T444E and L10-300s, we found an 11.5% benefit for electronic on-highway and a 24.3% benefit for mechanical on-highway engines. Again, these values are quite close to EPA's. The International T444E in a single-axle dump truck was an exception to the general finding of a decreased NOx benefit for electronically-controlled engines, perhaps because this vehicle was quite under-powered relative to all of the other dump trucks that were tested (as discussed in Appendix B). Also, the L10-300s both had a much lower NOx benefit than the other mechanically-controlled engines. The reasons that the two L10-300s behaved differently than the other mechanically-controlled engines are unknown.

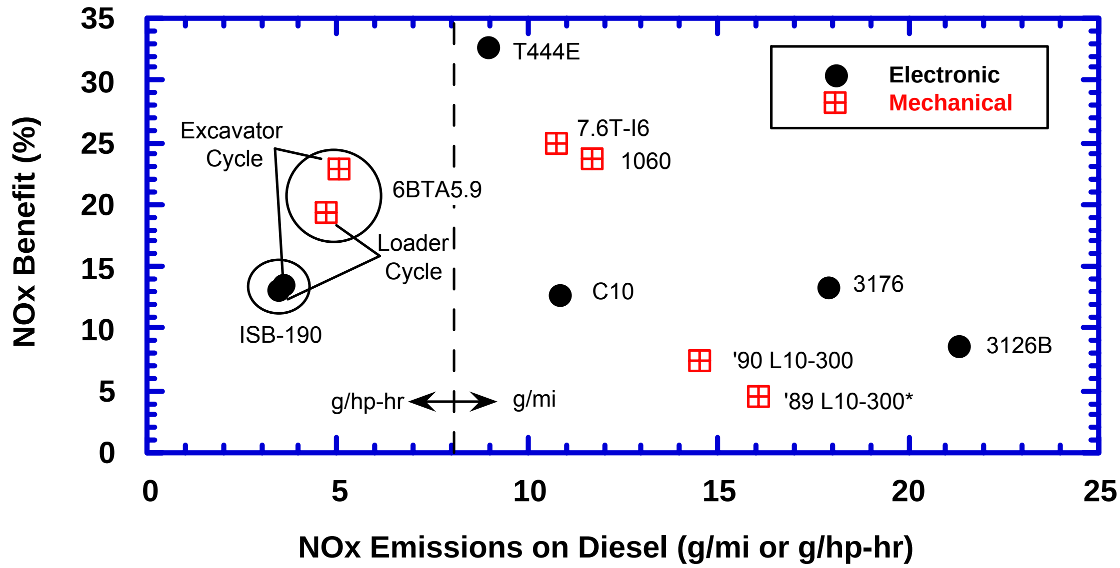

Figure 5.2. Relationship between NOx benefit due to PuriNOx and the emissions when operating on the baseline diesel fuel.

The annual changes in NOx and PM emissions for each piece of equipment (ACNOx and ACPM) can be calculated by combining Equation 5.6 with either Equation 5.1 or 5.2. For NOx, the resulting equation is:

$$\mathrm{ACNOx}\left[\frac{\mathrm{tons_{NOx}/yr}}{\mathrm{eqpt.}}\right] = \Delta\mathrm{NOx}\left[\frac{\Delta g_{\mathrm{NOx}}}{\mathrm{kg_{DF}}}\right]\cdot \mathrm{MADMC}\left[\frac{\mathrm{kg_{DF}/yr}}{\mathrm{eqpt.}}\right]\cdot 1.1023*10^{-6}\left[\frac{\mathrm{tons}}{\mathrm{g}}\right] \quad (5.7)$$

This change is the decrease in NOx emissions per year if the result is a negative number. The technique used to calculate the annual changes in emissions for PM is identical to this example for NOx. Similar calculations could be performed for the other pollutants. The results from these calculations are provided in Table 5.4.

Table 5.4. Average Changes in the Mass Emissions of NOx and PM for the Heavy-Duty Engines

	ADC	Density*	Avg. Fueling Ratio(1)	MADMC	ACNOx	ACPM
Equipment	gal/yr	kg/gal		kgDF/yr	tons/yr	tons/yr
Telescoping Boom Excavators	19478	3.187	1.28	63570	-0.372	-0.008
Wheeled Loaders	3599	3.187	1.26	11603	-0.056	-0.002
Single-Axle Dump Trucks	29035	3.240	1.14	85681	-0.361	-0.006
Tandem-Axle Dump Trucks	40504	3.240	1.13	118502	-0.027	-0.012
Other Non-Road Equipment	13299	3.187	1.27	43139	-0.231	-0.007
Other On-Road Equipment	73216	3.240	1.13	215132	-0.478	-0.018
Total, except small utility engines					**-1.525**	**-0.054**

* - diesel fuel density for the off-road equipment, PuriNOx density for the on-road equipment, as per Equations 5.1 and 5.2.

(1) units are kg PuriNOx per kg diesel for off-road equipment, gal PuriNOx per gal diesel for on-road equipment, as per Equations 5.1 and 5.2.

Table 5.4 reflects the diesel fuel used in the Houston District in 2001 by the vehicles and equipment that were eventually converted to PuriNOx. Of the total 185,048 gallons of diesel fuel used, 147,712 gallons were consumed by on-road equipment. The gallons shown for "other non-road equipment" are 37,336 gallons minus those used by the telescoping boom excavators and loaders in the Houston District, and the 601 gallons used by mowers and the 323 gallons used by traffic alerting signals. Similarly, the gallons shown for "other on-road equipment" is 147,712 gallons minus the consumption by single and tandem-axle dump trucks and the 4,957 gallons used by herbicide sprayers and the associated trucks. (Small utility engines are discussed below.) It is assumed that TxDOT's loaders operate like AGC's so that the annual emissions reductions and cost-effectiveness for TxDOT's loaders can be estimated as an individual type of equipment. In these two "other" categories in Table 5.4, the annual change in emissions was calculated with Equation 5.7 using the values for the average non-road and average on-road effects from Table 5.3.

Because emulsions separate over time, engines can become difficult or impossible to start. TxDOT has found, through trial-and-error, that they must start all engines twice each week to ensure that they will start when needed for TxDOT's operations. The emissions benefits and annual fuel consumption shown in Table 5.4 are compromised by the need to start engines fueled with PuriNOx twice each week even when not needed for normal service. The methods used to account for the emissions and fuel consumption penalties due to these extra starts are discussed in Appendix B.7. The net effects of PuriNOx on annual NOx and PM reductions and annual PuriNOx consumption is shown in Table 5.5. In this table, EAPC is the increase in annual PuriNOx consumption due to the extra starts, EACNOx and EAPM are the increases in NOx and PM emissions due to the extra starts, NAPC is the net annual PuriNOx consumption, and NACNOx and NACPM are the net annual reductions in NOx and PM emissions. The net emissions benefits shown in Table 5.5 were used in the cost-effectiveness analysis, which is discussed next.

Table 5.5. Net Effect of PuriNOx on Annual NOx and PM Benefits and PuriNOx Consumption, Including Extra Starts

	Normal Operation			**Penalty for Extra Starts**			**Net Effect**		
	APC	**ACNOx**	**ACPM**	**EAPC**	**EACNOx**	**EACPM**	**NAPC**	**NACNOx**	**NACPM**
Equipment	galP/yr	tons/yr	tons/yr	galP/yr	tons/yr	tons/yr	galP/yr	tons/yr	tons/yr
Telescoping Boom Excavat	24526	-0.372	-0.008	124	0.016	0.000	24649	-0.356	-0.008
Wheeled Loaders	4476	-0.056	-0.002	113	0.015	0.000	4589	-0.042	-0.002
Single-Axle Dump Trucks	33056	-0.361	-0.006	1092	0.141	0.001	34148	-0.220	-0.005
Tandem-Axle Dump Trucks	45719	-0.027	-0.012	498	0.064	0.000	46217	0.037	-0.011
Other Non-Road Equipmen	16643	-0.231	-0.007	924	0.119	0.001	17567	-0.112	-0.007
Other On-Road Equipment	82999	-0.478	-0.018	507	0.065	0.000	83507	-0.412	-0.018
Total, except SUEs	**207420**	**-1.525**	**-0.054**	**3258**	**0.420**	**0.002**	**210678**	**-1.104**	**-0.052**

A typical small utility diesel engine was tested at the University of Texas under a variety of conditions that allowed estimation of the effects of PuriNOx for three different applications: riding mowers, traffic alerting signals, and herbicide sprayers. Details are provided in Appendix B.6. Results for the four different fuels tested are provided in Table 5.6.

Table 5.6. Fuel Effects on Emissions for Small Utility Engines

Application	Fuel	EINOx g/kgF	EIPM g/kgF	MEINOx g/kgDF	MEIPM g/kgDF	ΔNOx g/kgDF	ΔPM g/kgDF
Mowers							
	2D on-road	28.93	6.99	28.93	6.99	0	0
	PuriNOx	20.46	4.40	25.57	5.49	-3.36	-1.49
	WG PuriNOx	18.37	3.00	22.97	3.75	-5.96	-3.24
	TxLED	28.60	3.72	28.60	3.72	-0.33	-3.27
Traffic Alerting Signals							
	2D on-road	27.19	3.99	27.19	3.99	0	0
	PuriNOx	20.26	2.22	25.32	2.78	-1.87	-1.21
	WG PuriNOx	17.29	1.38	21.61	1.73	-5.57	-2.26
	TxLED	26.30	3.79	26.30	3.79	-0.88	-0.20
Sprayers							
	2D on-road	33.79	15.35	33.79	15.35	0	0
	PuriNOx	21.08	11.19	26.36	13.99	-7.44	-1.36
	WG PuriNOx	21.43	7.57	26.79	9.46	-7.00	-5.89
	TxLED	34.97	3.534	34.97	3.53	1.17	-11.82

Table 5.7 provides the annual benefits in NOx and PM emissions for these engines before accounting for the extra starts. The TxDOT records show the diesel consumption and hours used annually for the herbicide sprayers plus the trucks used to haul them. To allow separate accounting for each, it was estimated that spraying operations account for 90% of the total time of use for the sprayers plus trucks. This provided an estimate of the hours used for spraying annually. This was multiplied by the fuel consumption rate by the sprayer engine for the typical sprayer operating conditions. In turn, this provided the estimate of the annual diesel consumption for the sprayer operations, with the remaining diesel consumed assigned to the trucks that transport the sprayers. The annual changes in NOx and PM emissions for these trucks were obtained by the assumption that they behave like the average on-road vehicles (from Table 5.3).

Table 5.7. Annual Change in NOx and PM Emissions Estimated for Use of PuriNOx in Small Utility Engines (Plus Sprayer Trucks) Before Accounting for Extra Starts

Application	ADC	Density*	Avg. Fueling Ratio(1)	MADMC	ACNOx	ACPM
Signals	359	3.187	1.29	1184	-0.002	-0.002
Mowers (including slope)						
Riding	180	3.187	1.26	577	-0.002	-0.001
Slope	421	3.187	1.27	1366	-0.007	0.000
Sprayers (including trucks)						
Sprayer engines	1233	3.187	1.15	3627	-0.030	-0.005
Sprayer trucks	3724	3.240	1.13	10942	-0.024	-0.001
Total, small utility engines					**-0.066**	**-0.009**

* - diesel fuel density for the engines, PuriNOx density for the truck, as per Equations 5.1 and 5.2.
(1) units are kg PuriNOx per kg diesel for the engines, gal PuriNOx per gal diesel for the truck, as per Equations 5.1 and 5.2.

The herbicide sprayers (with their trucks) and mowers are used seasonally. Similarly, the traffic alerting signals are not used every day. However, as for TxDOT's other PuriNOx-fueled equipment, these engines must be started twice each week to ensure that they can be started when needed. The net effect on the annual PuriNOx consumption and NOx and PM benefits are shown in Table 5.8.

Table 5.8. Net Effects of PuriNOx on Annual PuriNOx Consumption and Reductions in NOx and PM for the Small Utility Engines (Plus Sprayer Trucks)

	Normal Operation			**Penalty for Extra Starts**			**Net Effect**		
	APC	**ACNOx**	**ACPM**	**EAPC**	**EACNOx**	**EACPM**	**NAPC**	**NACNOx**	**NACPM**
Equipment	galP/yr	tons/yr	tons/yr	galP/yr	tons/yr	tons/yr	galP/yr	tons/yr	tons/yr
Signals	457	-0.002	-0.002	41	0.002	0.002	498	-0.001	0.001
Mowers									
Riding	223	-0.002	-0.001	57	0.003	0.003	280	0.001	0.002
Slope	527	-0.007	0.000	59	0.008	0.000	586	0.000	0.000
Sprayers (including trucks)									
Sprayer engines	1399	-0.030	-0.005	0	0.000	0.000	1400	-0.030	-0.005
Sprayer trucks	4221	-0.024	-0.001	3	0.000	0.000	4224	-0.024	-0.001
Total	**6827**	**-0.066**	**-0.009**	**161**	**0.013**	**0.006**	**6988**	**-0.053**	**-0.003**

5.C. Costs for TxDOT Operations in the Houston District

At the outset, TxDOT was under the impression that the only costs/impacts associated with the use of PuriNOx would be: an incremental fuel cost penalty of approximately \$0.20/gallon relative to diesel, an approximate 20 percent reduction in horsepower, and a requirement to mix the fuel at least "annually" to prevent separation (personal communication with TxDOT, 2003). However, during the PuriNOx field test, a number of additional costs were revealed. This section summarizes the costs associated with the use of PuriNOx incurred by TxDOT that were subsequently used in the cost-effectiveness analysis.

5.C.1. Implementation and Conversion Costs

In converting the Houston equipment to be fueled by PuriNOx, TxDOT was required to change fuel filters twice on each piece of equipment initially. Converting to PuriNOx thus entailed costs in terms of fuel filters and in-house labor costs. This amounted to changing a total of 766 fuel filters and 2,546 hours in labor. Vehicle labels were donated to TxDOT by the PuriNOx vendor. Since the cost of applying these labels is regarded negligible it was not considered in the cost-effectiveness calculation. Table 5.9 summarizes the implementation/conversion costs incurred.

Table 5.9 Implementation/Conversion Costs

Implementation/ Conversion Costs	Houston Equipment (Total)	Excavator	Single-Axle Dump Truck	Tandem-Axle Dump Truck	Herbicide Sprayer	Arrow Board	Mower	Loader
Number of Fuel Filters	766	140	376	104	20	22	16	29
Filter Cost ($)	5,171	945	2,538	702	135	149	108	196
Labor Cost ($)	79,333	3,178	16,671	9,535	1,589	4,736	3,895	3,988
Total ($)	**84,504**	**4,123**	**19,209**	**10,237**	**1,724**	**4,885**	**4,003**	**4,184**
Annualized ($)	**9,906**	**483**	**2,252**	**1,200**	**202**	**573**	**469**	**491**

"Arrow board" indicates traffic alerting signals

These costs are only incurred initially and should thus either be annualized if included in the cost-effectiveness analysis or considered separately as part of the up-front costs of using PuriNOx. When these costs were annualized, it was done over a period of 10 years – the time period used by TxDOT to depreciate the capital investment in TxDOT's fuel storage tanks - at an annual discount rate of 3% - the discount rate prescribed by the Texas Emissions Reduction Plan administered by the Texas Commission for Environmental Quality. The annualized cost amounts to $9,906/year for all the Houston equipment converted to PuriNOx.

5.C.2. Fuel Economy

Total fuel consumption increases when water is added to conventional diesel fuel, due to a reduction in the energy density of the fuel. As part of the SwRI tests, the fuel economy of vehicles and equipment engines was measured when operating on both diesel fuel and PuriNOx. The effect on fuel economy was calculated (via the equations in Section 5.B) and applied to the diesel gallons consumed in 2001 - excluding the diesel fuel consumed by the vehicles/equipment that were not converted to PuriNOx or that were converted back to diesel. In addition, the fuel consumed as a result of the "extra starts" required was estimated (see Section 5.C.7). These calculations provided an estimate of the increase in fuel consumption due to the use of PuriNOx in the Houston District. The estimated cost to TxDOT amounts to $40,280 per year, as shown in Table 5.10. This estimate is a proxy for the increased cost of operation due to decreased fuel economy.

Table 5.10 Fuel Economy Penalty

Fuel Economy Penalty	Houston Equipment (Total)	Excavator	Single-Axle Dump Truck	Tandem-Axle Dump Truck	Herbicide Sprayer	Arrow Board	Mower	Loader
Additional on-road PuriNOx gallons	21,784		5,113	5,713	667			
Additional off-road PuriNOx gallons	10,833	5,171				139	265	990
PuriNOx Price/gallon (2002)	1.29	1.29	1.29	1.29	1.29	1.29	1.29	1.29
Off-road PuriNOx Price/gallon, including tax rebate	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12
Total ($)	**40,280**	**5,813**	**6,596**	**7,370**	**860**	**156**	**298**	**1,113**

Note: Includes fuel consumption due to additional cold starts discussed in Section 5.C.7.

5.C.3 Fuel Cost

The increase in direct fuel costs due to the use of PuriNOx - which resulted in a higher fuel price - was estimated. The average prices for federal 2D on-road diesel (2002) and PuriNOx were estimated based on information from TxDOT's fuel records. The price differential between PuriNOx and 2D on-road diesel used in this analysis amounted to $0.27/gallon for on-road vehicles and $0.3042/gallon for off-road equipment (TxDOT uses on-road diesel in all of its equipment, but does not pay the state taxes when used in off-road equipment). This increase in the fuel price was applied to the diesel fuel consumption for 2001 - adjusted to exclude the diesel consumed by those vehicles/equipment not converted to PuriNOx or converted back to diesel. This resulted in additional costs to TxDOT of $51,240/year, as shown in Table 5.11.

Table 5.11 Fuel Cost Penalty

Fuel Cost Penalty	Houston Equipment (Total)	Excavator	Single-Axle Dump Truck	Tandem-Axle Dump Truck	Herbicide Sprayer	Arrow Board	Mower	Loader
On-road diesel (gallons) - 2001	147,712		29,035	40,504	4,957			
Off-road diesel (gallons) - 2001	37,336	19,478				359	601	3,599
#2 diesel price/gallon (2002)	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02
#2 off-road diesel price/gallon, including tax rebate (2002)	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82
PuriNOx price/gallon (2002)	1.29	1.29	1.29	1.29	1.29	1.29	1.29	1.29
Off-road PuriNOx price/gallon, including tax rebate	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12
Total ($)	**51,240**	**5,925**	**7,839**	**10,936**	**1,338**	**109**	**183**	**1,095**

5.C.4. Re-fueling Penalty

The lower fuel economy of PuriNOx fueled vehicles results in more fuel consumed given the same work output, which leads to the need to re-fuel more often and additional time to re-fuel the vehicles/equipment. The Houston TxDOT representatives estimated that it takes an additional two hours per day to fuel the Houston equipment operated on PuriNOx. At an average TxDOT labor cost of approximately $31/hour, the re-fueling penalty amounts to approximately $15,393/year. The total re-fueling cost was allocated to the different equipment types based on fuel consumption in 2001. Table 5.12 provides a summary of the total annual re-fueling cost and by equipment type.

Table 5.12 Re-fueling Penalty

Re-fueling Penalty	Houston Equipment (Total)	Excavator	Single-Axle Dump Truck	Tandem-Axle Dump Truck	Herbicide Sprayer	Arrow Board	Mower	Loader
Total ($)	**15,393**	**1,620**	**2,415**	**3,369**	**412**	**30**	**50**	**299**

5.C.5. Productivity Impacts

PuriNOx is generally associated with a loss of torque and thus a decrease in the rate at which TxDOT workers can perform their activities/tasks. This is true for at least some types of activities and equipment (see Section 3). The Houston TxDOT representatives found it very difficult to estimate how much longer it takes to complete their tasks when operating on PuriNOx. The productivity penalty was thus estimated from the data logged for the duty cycles and during the Roadeo events (see Appendix D for a discussion of the methodology used for calculating the productivity impacts). Table 5.13 provides an estimate of the costs associated with the decrease in productivity attributable to the use of PuriNOx.

Table 5.13 Productivity Penalty

Productivity Penalty	Houston Equipment (Total)	Excavator	Single-Axle Dump Truck	Tandem-Axle Dump Truck	Herbicide Sprayer	Arrow Board	Mower	Loader
Additional Time (hours)	1,319	179	109	76	Negligible	Negligible	Negligible	162
Labor Cost ($/hr)	31	31	31	31	31	31	31	31
Total ($)	**41,090**	**5,579**	**3,382**	**2,382**	**Negligible**	**Negligible**	**Negligible**	**5,034**

5.C.6. Maintenance

The TxDOT Houston maintenance personnel recorded significant increases in maintenance expenditures since switching to PuriNOx relative to diesel. The additional expenditures were related to the need to replace fuel injectors, pumps and filters – in addition to the fuel filters changed during conversion. A number of maintenance personnel also indicated the use of starting fluid to start vehicles that have not been operated for a week. After TxDOT began starting all engines at least twice per week, the use of starting fluid was abandoned, and thus it is not accounted for in the maintenance costs (however, starting twice each week results in a "fuel separation cost" as discussed in Section 5.C.7). Table 5.14 summarizes the additional maintenance costs incurred by the Houston District.

Table 5.14 Additional Maintenance Costs Incurred

Maintenance Penalty	Houston Equipment (Total)	Excavator	Single-Axle Dump Truck	Tandem-Axle Dump Truck	Herbicide Sprayer	Arrow Board	Mower	Loader
Number of fuel filters	59	16	8	5		5		5
Number of injectors	29			7				4
Number of lift pumps	8	1				2		2
Number of injector pumps	4					1		1
Average cost/fuel filter	6.75	6.75	6.75	6.75	6.75	6.75	6.75	6.75
Average cost/injector	175			175				325
Average cost/lift pump	115	122				124		514
In-house Labor costs ($)	7,229	1,433		436		2,524	405	2,088
Out-sourced labor costs ($)	5,748			1,452				581
Total ($)	**19,371**	**1,663**	**241**	**3,147**		**2,806**	**405**	**5,031**

Note: No charge was incurred for injector pumps as they were under warranty.

It is, however, unclear at this stage whether the additional replacements of fuel filters and lift pumps are part of the transition costs to PuriNOx or characteristic of the use of PuriNOx. However, as discussed in Appendix E.5, there is reason to expect that the higher rate of injector and pump failures observed by TxDOT will be a continuing issue. It was conservatively estimated that the maintenance penalty associated with the use of PuriNOx results in the following annual maintenance expenditures:

- fifteen injectors per 100 engines, and
- 2 % of the injector pumps.

The filter and lift pump replacements were assumed to be a transitional problem. Table 5.15 summarizes the estimated maintenance penalty associated with the use of PuriNOx.

Table 5.15 Maintenance Cost Penalty

Maintenance Penalty	Houston Equipment (Total)	Excavator	Single-Axle Dump Truck	Tandem-Axle Dump Truck	Herbicide Sprayer	Arrow Board	Mower	Loader
Number of injectors	58	2	12	6	1	3	2	3
Number of injector pumps	8		2	1				
Average cost/injector	175			175				325
Average cost/injector pump	514		514	514				
In-house Labor costs ($)	11,883	462	2,432	1,324	154	677	493	554
Out-sourced labor costs ($)	14,909	579	3,051	1,661	193	850	618	695
Total ($)	**40,896**	**1,195**	**6,295**	**4,556**	**398**	**1,753**	**1,275**	**2,312**

The remainder of the TxDOT maintenance expenditure was regarded part of the initial transition costs (see Table 5.16). These costs were thus – similar to the conversion/implementation costs – annualized over a period of 10 years. When annualized, the cost amounts to approximately $599 per year.

Table 5.16 Maintenance/Implementation Penalty

Maintenance/Implementation Penalty	Houston Equipment (Total)	Excavator	Single-Axle Dump Truck	Tandem-Axle Dump Truck	Herbicide Sprayer	Arrow Board	Mower	Loader
Number of fuel filters	59	16	8	5	0	5	0	5
Number of lift pumps	8	1	0	0	0	2	0	2
Average cost/fuel filter	6.75	6.75	6.75	6.75	6.75	6.75	6.75	6.75
Average cost/lift pump	115	115	115	115	115	115	115	115
In-house Labor costs ($)	1,681	385	162	101	0	223	0	223
Out-sourced labor costs ($)	2,109	483	203	127	0	280	0	280
Total ($)	**5,108**	**1,091**	**419**	**262**	**0**	**766**	**0**	**766**
Amortized ($)	**599**	**128**	**49**	**31**	**0**	**90**	**0**	**90**

5.C.7. Fuel Separation Costs

The use of PuriNOx imposes costs that are related to the potential separation of the emulsion. These costs are discussed in this subsection.

Additional Cold Starts

Maintenance personnel are starting all TxDOT engines twice per week to ensure that all engines can start when needed for normal service. The average time to start the Houston vehicles/equipment was estimated at 65 hours per week by TxDOT personnel. The researchers verified this estimate using the operating records kept by TxDOT for each piece of equipment (see Appendix B.6 for a discussion of the methodology used to calculate the hours required for the additional starts). For our calculations, it was assumed that it takes approximately 10 minutes to start and shutdown each piece of equipment. The results are summarized in Table 5.17.

Table 5.17 Starting Penalty

Starting Penalty	Houston Equipment (Total)	Excavator	Single-Axle Dump Truck	Tandem-Axle Dump Truck	Herbicide Sprayer	Arrow Board	Mower	Loader
Number of additional cold starts		624	5,718	1,966	16	1,772	1,610	1,170
Total time to re-start vehicles (hours)	3,380	104	953	328	3	295	268	195
Total ($)	**105,321**	**3,241**	**29,695**	**10,210**	**83**	**9,203**	**8,361**	**6,076**

Fuel Storage

To prevent the fuel from separating in the fuel storage tanks, TxDOT is renting skid-mounted fuel tanks with agitators from the vendor. The annual rental costs, including full maintenance, full insurance coverage, agitator, meter, hose and dispenser, of these tanks[9] amounts to $77,400 annually. The operating costs – mostly electricity – are regarded as negligible. The fuel storage cost was allocated to the specified equipment types based on fuel consumption in 2001.

Table 5.18 Fuel Storage

Fuel Storage	Houston Equipment (Total)	Excavator	Single-Axle Dump Truck	Tandem-Axle Dump Truck	Herbicide Sprayer	Arrow Board	Mower	Loader
Annual Tank rental cost	77,400	8,147	12,144	16,942	2,073	150	251	1,505
Total ($)	**77,400**	**8,147**	**12,144**	**16,942**	**2,073**	**150**	**251**	**1,505**

5.C.8. Additional Costs

This study did not attempt to quantify the following costs, if any, associated with the use of PuriNOx.

Administrative and logistics costs

Since some of TxDOT's equipment will continue to be operated on conventional diesel fuel (due either to incompatibility with PuriNOx or inability to perform the required tasks when using PuriNOx), there are some administrative and logistics costs associated with the use of two different fuels. These administrative and logistics costs were, however, regarded as negligible and therefore not considered in the cost-effectiveness calculation.

Health effects

In practice it is very difficult to estimate health costs – certain components are not measured or have large uncertainties associated with them (see text box for more information). For example, even if PuriNOx may be associated with certain skin conditions, the epidemiological studies have not been conducted to determine the health effects.

Similarly, all air pollutant concentrations have health effects, but the level of uncertainty increases once pollutant levels are below the air quality standards, or even when they are slightly above (Fernandez and Keller, 2000). In other words, the air quality standards do not provide a "magic number" below which health effects do not occur.

This study did not attempt to quantify health effects, if any, and benefits associated with the use of PuriNOx.

Reliability and durability of the engine

Long-term engine reliability and durability information concerning the use of PuriNOx is not available to ensure reasonable assumptions in the cost-effectiveness analysis. Therefore this cost category was not included in the cost-effectiveness calculations.

[9] 1 x 4,000 gallon tank and 7 x 2,000 gallon tanks

Increases in CO

CO emissions from diesel engines are less of a concern than NOx and PM emissions. Nevertheless, known health effects associated with increased levels of CO in the bloodstream include: cardiovascular strain, impaired coordination and the ability to judge time, slowed reaction time, and impaired mental abilities (Fernandez & Keller, 2000). Increased levels of CO associated with the use of PuriNOx for some engines operating over some test cycles were not considered in the cost-effectiveness analysis.

Health Cost Calculations

Estimation of the human health cost per unit of emissions emitted has generally been estimated using the damage cost method. Costs of damage to human health can relate to medical expenses, loss of work, shortened lifetimes, and reduced quality of life. The method normally involves seven steps:

- Identify the emission sources,
- Estimate the quantities of emissions,
- Simulate the air pollution in the atmosphere,
- Estimate exposure of humans to the air pollution,
- Identify and estimate physical effects of air pollution on humans, using dose-response relationships from epidemiological studies,
- Value the physical effects on humans, and
- Calculate emission values in dollars per ton (Wang, Santini, and Warrinner, 1995).

Most of these steps are fraught with uncertainties, making the results rather speculative. Researchers differ in the assumptions and simplifications they adopt to deal with the uncertainties, which often leads to a wide range of estimates. Using the damage cost approach, one study estimated that the health costs of anthropogenic air pollution ranged from a low $55 billion to a high $670 billion (1991 dollars) in the US in 1990 (Delucchi, Murphy and McCubbin; 2002).

5.D. Cost-Effectiveness Analysis for TxDOT

Table 5.19 summarizes the estimated increase in costs associated with the use of PuriNOx relative to diesel for the TxDOT Houston District.

Table 5.19 Annual PuriNOx Cost Penalty

Cost Category	Houston Equipment (Total)	Excavator	Single-Axle Dump Truck	Tandem-Axle Dump Truck	Herbicide Sprayer	Arrow Board	Mower	Loader
Implementation/Conversion	84,504	4,123	19,209	10,237	1,724	4,885	4,003	4,184
Fuel Economy	40,280	5,813	6,596	7,370	860	156	298	1,113
Fuel Price	51,240	5,925	7,839	10,936	1,338	109	183	1,095
Re-fueling	15,393	1,620	2,415	3,369	412	30	50	299
Productivity	41,090	5,579	3,382	2,382	Negligible	Negligible	Negligible	5,034
Maintenance Cost	40,896	1,195	6,295	4,556	398	1,753	1,275	2,312
Maintenance Implementation	5,108	1,091	419	262	0	766	0	766
Starting	105,321	3,241	29,695	10,210	83	9,203	8,361	6,076
Fuel Storage	77,400	8,147	12,144	16,942	2,073	150	251	1,505
Total, including implementation costs ($)	**461,231**	**36,735**	**87,996**	**66,264**	**6,890**	**17,052**	**14,421**	**22,385**
Total, excluding implementation costs ($)	**371,619**	**31,521**	**68,368**	**55,765**	**5,166**	**11,401**	**10,418**	**17,435**
Total, including annualized implementation costs ($)	**382,124**	**32,132**	**70,669**	**56,996**	**5,368**	**12,064**	**10,888**	**18,015**

As can be seen from Table 5.19, the estimated annual costs incurred by TxDOT as a result of the use of PuriNOx varies between $371,619 and $461,231, depending on how the implementation costs are accounted for. If the implementation costs are annualized over a period of ten years, the estimated costs associated with the use of PuriNOx in Houston amounts to $382,124 per year. Given the emissions benefits discussed in Section 5.B, the cost-effectiveness of using PuriNOx as a NOx emissions reduction strategy for TxDOT's Houston fleet was calculated (see Table 5.20).

Table 5.20 Cost-Effectiveness of PuriNOx to Reduce NOx Emissions (TxDOT, Houston)

Cost Category	Houston Equipment (Total)	Excavator	Single-Axle Dump Truck	Tandem-Axle Dump Truck	Herbicide Sprayer	Arrow Board	Mower	Loader
NOx Benefit (tons/year)	1.157	0.356	0.220	(0.037)	0.054	0.001	(0.001)	0.042
Total Costs, including implementation costs ($)	461,231	36,735	87,996	66,264	6,890	17,052	14,421	22,385
Total Costs, excluding implementation costs ($)	371,619	31,521	68,368	55,765	5,166	11,401	10,418	17,435
Total Costs, including annualized implementation costs ($)	382,124	32,132	70,669	56,996	5,368	12,064	10,888	18,015
Cost-Effectiveness, including implementation costs ($/ton)	**398,644**	**103,188**	**399,980**		**127,597**	**17,051,938**		**532,969**
Cost-Effectiveness, excluding implementation costs ($/ton)	**321,192**	**88,542**	**310,762**		**95,668**	**11,401,244**		**415,109**
Cost-Effectiveness, including annualized implementation costs ($/ton)	**330,272**	**90,259**	**321,221**		**99,411**	**12,063,678**		**428,926**

In the case of the tandem-axle dump trucks and mowers, the use of PuriNOx resulted in an increase in NOx emissions as opposed to a reduction. This occurred because, for these two cases, the NOx generated during the bi-weekly starts (involving an idle period of 45 minutes to ensure that the PuriNOx in the tank becomes well mixed) more than offset the NOx reduction due to use of PuriNOx during normal service.

Depending on the type of equipment, the annual cost-effectiveness of using PuriNOx to reduce NOx varied from $90,259/ton for the telescoping boom excavators to more than $12 million/ton in the case of the traffic alerting signals (arrow boards) if implementation costs are annualized. Excluding up-front implementation costs, because it has already been paid by TxDOT, the costs of reducing NOx emissions using PuriNOx ranged from $88,542/ton (for the telescoping boom excavators) to more than $11 million/ton (for the traffic alerting signals).

A number of options are potentially available to TxDOT to reduce the costs of using PuriNOx. These are briefly highlighted below.

The **largest cost burden** for TxDOT is associated with the *need to start the PuriNOx-fueled vehicles/equipment at least twice weekly*, even when not needed for normal service. This requirement results from the tendency of the emulsion to separate. TxDOT determined, via trial-and-error, that all engines must be started at least twice each week to ensure that they can be started when needed. The costs related to this are the cost of the extra fuel used during the 45 minutes of idling - to ensure that the fuel in the tank has become well mixed - and the cost of the labor. Of these two, the labor cost dominates by a large margin. For equipment used seasonally or irregularly, such as riding mowers, no options for decreasing this labor burden are apparent. For equipment that is used regularly, it seems that TxDOT has “favorites”. For example, the newer dump trucks are preferred over the older ones. Thus, it might at first appear that TxDOT could optimize the scheduling to even out the use. However, if a newer dump truck is left on the lot for a week and replaced by an older one that is used during that week, then the newer one must be started twice, exactly replacing the two starts that the older dump truck would have had. An alternative is to get rid of equipment that is not used as often, such as some of the dump trucks. However, TxDOT has a minimum utilization policy that already ensures that vehicles and equipment that are not needed are sold. That is, it does not appear that any options are available for decreasing the labor cost resulting from the need for bi-weekly starts. However, the need for “extra” starts does depend upon equipment utilization. All of our calculations are based on fuel use in the Houston District during FY01, the most recent year for which complete records were available at the beginning of this project. Over the past 10 years, fuel use in FY01 was at a low point, ~11% below the average for the 10 year period. However, increasing the NOx benefit for normal operations by 11% while decreasing the NOx and cost penalties for the extra starts by, say 50%, still yields a cost-effectiveness of more than $200,000/ton, even neglecting the additional PuriNOx consumed and other additional costs for a high utilization scenario.

The need to start the PuriNOx-fueled engines at least twice weekly also results in a NOx penalty, reducing the tons of NOx removed annually from ~1.6 tons/year for normal operation to ~1.2 tons/year after accounting for the NOx emitted during the 45 minutes of starting and warmup for each “unused” engine twice per week. In turn, this makes the cost-effectiveness of NOx removal worse. We assumed a 48% NOx benefit at idle (Musculus et al., 2002) together with data for fuel consumption and NOx emissions at idle (Lim, 2003; Storey et al., 2003) plus an assumption about how these scale with engine size. That is, there is some uncertainty in our calculations of the NOx penalty and additional uncertainty regarding whether 45 minutes is the optimum to ensure that the fuel in the tank is well mixed. A research project is required to improve these uncertainties. However, even if the result of such a project decreases the labor cost (~$105,000/year) and NOx penalties for the extra starts (~0.43 tons/year) by a factor of 2, the cost-effectiveness would still be more than $230,000 per ton.

The **second highest cost burden** is for *conversion and implementation*. This cost has already been paid by TxDOT's Houston District. As previously discussed, if this is taken to be a one-time up-front cost, the cost-effectiveness for the first year is almost $400,000/ton and in subsequent years it is ~$320,000/ton (assuming the same fuel use patterns and costs as in FY01 and FY02). Alternatively, if the conversion and implementation costs are annualized over 10 years, the cost-effectiveness is ~$330,000/ton each year. No options exist for decreasing this cost category, only perspectives on how to account for it.

The incremental cost of PuriNOx relative to diesel fuel affects both the *fuel cost category and the fuel economy* category. Taken together, these represent the **third highest cost burden**. The Lubrizol vendor has indicated lower PuriNOx fuel prices if economies of scale can be achieved in distributing the fuel to TxDOT sites, and if the fuel purchase contracts can be based on a PuriNOx Posted Price as opposed to the current practice of the base (terminal) diesel price plus a constant. As an example, if TxDOT changed its contracting procedures for purchasing fuel, JAM distributors quoted a PuriNOx price of $1.2486 for off-road PuriNOx (as opposed to $1.4059), and $1.4144 for on-road applications (as opposed to $1.5717 under the current contracting arrangement) – based upon the February 18, 2002 base diesel cost of $1.0617. (It should be noted that the base diesel cost is not what TxDOT pays for diesel fuel. TxDOT pays the terminal cost plus a constant plus tax. In 2002, the average base diesel cost was ~$0.78/gallon, and TxDOT paid ~$1.02/gallon.) At a base diesel cost of $1.0617, the fuel economy and fuel cost penalty will amount to $118,597 under the new contracting procedure as opposed to $152,836 under the existing TxDOT contracts – a saving of $34,239. The magnitude of the incremental cost is, however, highly dependent on the price of the base diesel fuel.

Another potential means for decreasing the cost burden associated with the incremental cost of PuriNOx is through the Texas Emission Reduction Plan (TERP) rebate program, which is intended to reward voluntary measures for reducing NOx emissions. The TERP, established in 2001 through the enactment of Senate Bill 5 by the 77th Texas Legislature, specifies a cost-effectiveness criterion of $13,000/ton for NOx emissions reductions. An initial study by TCEQ determined that the incremental cost – consisting of only the fuel economy and fuel cost penalties - of using PuriNOx to reduce NOx emissions justifies a fuel rebate of $0.24/gallon for off-road equipment and $0.26/gallon for on-road vehicles. The initial TCEQ estimates indicated that these rebates will allow the state to obtain the NOx emissions reductions for use of PuriNOx at $13,000/ton – the TERP cost-effectiveness criterion. A TERP grant will reduce the fuel economy and fuel cost penalties to $32,016 and $3,874, respectively. The impact on the cost-effectiveness calculations is, however, marginal as is evident from Table 5.21. It must also be noted that a TERP rebate would decrease the cost to TxDOT, but because TERP funds are also state funds, the cost-effectiveness to the State of Texas does not benefit from a TERP rebate to TxDOT.

Table 5.21 Cost-Effectiveness of PuriNOx to Reduce NOx Emissions Including TERP Grant (TxDOT, Houston)

Cost Category	**Houston Equipment (Total)**	**Excavator**	**Single-Axle Dump Truck**	**Tandem-Axle Dump Truck**	**Herbicide Sprayer**	**Arrow Board**	**Mower**	**Loader**
NOx Benefit (tons/year)	1.157	0.356	0.220	(0.037)	0.054	0.001	(0.001)	0.042
Total Costs, including implementation costs ($)	405,601	30,819	79,117	54,248	5,428	16,932	14,214	21,283
Total Costs, excluding implementation costs ($)	315,990	25,605	59,489	43,749	3,704	11,282	10,211	16,333
Total Costs, including annualized implementation costs ($)	326,495	26,216	61,790	44,979	3,906	11,944	10,680	16,914
Cost-Effectiveness, including implementation costs ($/ton)	**350,563**	**86,570**	**359,623**		**100,518**	**16,932,418**		**506,746**
Cost-Effectiveness, excluding implementation costs ($/ton)	**273,111**	**71,925**	**270,406**		**68,589**	**11,281,724**		**388,886**
Cost-Effectiveness, including annualized implementation costs ($/ton)	**282,191**	**73,624**	**280,865**		**72,332**	**11,944,158**		**402,703**

As reflected in Table 5.21, the current TERP program guarantees a rebate for use of PuriNOx of $0.26/gallon for on-road use and $0.24/gallon for off-road equipment. According to the original TCEQ estimates, this would provide NOx reductions at a cost-effectiveness of $13,000/ton. However, the results of the present study indicate that the $13,000/ton criterion justifies a rebate of only $0.095/gallon. This is shown in Table 5.22, in which the calculations consider the NOx benefits of the fuel, not accounting for the NOx penalty associated with the additional starts to prevent starting concerns, and only the incremental fuel costs – fuel economy and incremental fuel price penalties – associated with the use of PuriNOx. The TERP program is subject to change and will be re-evaluated in the near term. Thus, the present PuriNOx rebates of $0.24 and $0.26/gallon may not be available in the future. Nevertheless, the current rebates ($0.24 and $0.26 per gallon) were used to assess the effects of the TERP rebates in both Tables 5.21 and 5.23.

Table 5.22. Revised TERP Rebate Calculation (TxDOT, Houston)

Cost Category	**Houston Equipment (Total)**
NOx Benefit (tons/year)	1.591
Actual Fuel Cost-Effectiveness* ($/ton)	57,524
TERP Cost-Effectiveness ($/ton)	13,000
Potential TERP Rebate ($/year)	20,683
PuriNOx Consumption (gallons/year)	217,665
Potential TERP Rebate ($/gallon)	0.095

*Includes fuel economy and incremental fuel price penalties, but exclude NOx penalty associated with additional starts

The **fourth highest cost category** is *fuel storage*. TxDOT can consider purchasing the fuel storage tanks. The quoted cost for seven 2,000-gallon tanks and one 4,000-gallon tank, including circulation pump, delivery and installation, amounts to $165,000 (personal communication with TxDOT, 2002). If annualized over 10 years at a 3% discount rate, the fuel storage tank costs will amount to $19,343/year for 10 years – compared to $77,400/year for the rental of the skid mounted tanks. Table 5.23 summarizes the cost-effectiveness of using PuriNOx to reduce NOx emissions from the Houston TxDOT fleet, considering both the current TERP rebate and assuming that TxDOT purchases the fuel storage tanks. For the overall TxDOT fleet in the Houston District, purchase of the fuel tanks plus a TERP rebate yields a cost-effectiveness of more than $220,000/ton. Even if these are taken together with some (unknown) means of decreasing the NOx and labor penalties for the extra starts by 50% and an increase in the NOx removed by 11% for a higher equipment utilization scenario (but neglecting the additional fuel used and other factors associated with increased utilization), the cost-effectiveness is still more than $110,000/ton.

Table 5.23. Cost-Effectiveness of PuriNOx to Reduce NOx Emissions (Including TERP Grant and Fuel Storage Tank Purchase)

Cost Category	Houston Equipment (Total)	Excavator	Single-Axle Dump Truck	Tandem-Axle Dump Truck	Herbicide Sprayer	Arrow Board	Mower	Loader
NOx Benefit (tons/year)	1.157	0.356	0.220	(0.037)	0.054	0.001	(0.001)	0.042
Total Costs, including implementation costs ($)	347,544	24,708	70,008	41,540	3,873	16,820	14,025	20,154
Total Costs, excluding implementation costs ($)	257,933	19,494	50,380	31,041	2,149	11,169	10,022	15,204
Total Costs, including annualized implementation costs ($)	268,438	20,105	52,681	32,272	2,351	11,832	10,491	15,784
Cost-Effectiveness, including implementation costs ($/ton)	**300,384**	**69,404**	**318,217**		**71,718**	**16,819,786**		**479,861**
Cost-Effectiveness, excluding implementation costs ($/ton)	**222,932**	**54,759**	**228,999**		**39,789**	**11,169,092**		**362,001**
Cost-Effectiveness, including annualized implementation costs ($/ton)	**232,012**	**56,476**	**239,458**		**43,532**	**11,831,525**		**375,818**

On the other hand, the emissions reductions and cost-effectiveness of using PuriNOx in a future TxDOT fleet with only electronically-controlled engines in the single-axle dump trucks, excavators, and loaders were also analyzed. The rationale was that PuriNOx will result in fewer reductions in NOx emissions as the fleet is upgraded to cleaner electronically-controlled engines[10]. The cost-effectiveness calculation in Table 5.24, however, excludes the emissions and fuel consumption penalty associated with the additional cold starts required. A lack of data prevented the calculation of these penalties. The labor cost associated with the additional cold starts is, however, considered.

As can be seen from Table 5.24, the smaller emissions reductions associated with cleaner electronically controlled excavator and loader engines results in a worse cost-effectiveness for

[10] In the case of the tandem-axle dump trucks it was found that the use of PuriNOx in the electronically-controlled engines resulted in an increase in NOx emissions.

use of PuriNOx in these categories of equipment. The emissions benefit associated with the single-axle dump trucks is largely dominated by the significant NOx benefits associated with the electronically controlled T444E single-axle dump truck tested. (This was the only electronically-controlled engine tested that had a NOx benefit of more than 13.6% and, in fact, had a NOx benefit of 32.7%. It is believed that this unusual behavior is due to the fact that this appeared to be the most under-powered vehicle tested and, thus, suffered most from the torque loss associated with the water in the emulsion.) However, even though the cost-effectiveness for the single-axle dump trucks improved for the scenario of an all-electronic fleet, it is still very high, at almost \$230,000/ton. The best case for an all-electronic fleet is the telescoping boom excavators, at ~\$163,000 per ton of NOx removed.

Table 5.24 Cost-Effectiveness of Using PuriNOx in Electronically-Controlled Engines

	Houston Equipment			Electronically Controlled Engines		
	Excavator	**Single-Axle Dump Truck**	**Loader**	**Excavator**	**Single-Axle Dump Truck**	**Loader**
NOx Benefit (tons/year)	0.356	0.220	0.042	0.188	0.291	0.032
Total Costs, including implementation costs ($)	36,735	87,996	22,385	35,807	86,005	22,154
Total Costs, excluding implementation costs ($)	31,521	68,368	17,435	30,593	66,378	17,204
Total Costs, including annualized implementation costs ($)	32,132	70,669	18,015	31,204	68,679	17,784
Cost-Effectiveness, including implementation costs ($/ton)	**103,188**	**399,980**	**532,969**	**190,462**	**295,551**	**692,305**
Cost-Effectiveness, excluding implementation costs ($/ton)	**88,542**	**310,762**	**415,109**	**162,729**	**228,102**	**537,614**
Cost-Effectiveness, including annualized implementation costs ($/ton)	**90,259**	**321,221**	**428,926**	**165,980**	**236,009**	**555,748**

5.E. AGC Emissions and Costs

This analysis also evaluated the potential NOx reductions and costs associated with the use of PuriNOx in engines operated by AGC members under TxDOT contracts. Costs and emission reductions were estimated for both the current AGC fleet and a future fleet with 100% electronically-controlled engines.

5.E.1 Data Sources

As TxDOT contractors, AGC members operate a large number of engines in a variety of applications. In order to determine the potential benefits of PuriNOx use in this fleet, it was necessary to characterize the total population of diesel engines operated by AGC in their capacity as TxDOT contractors. This analysis relied heavily on a previous survey of AGC members performed for the Houston-Galveston Area Council (HGAC) in 2000 (Eastern Research Group, 2000). The HGAC study estimated the total number of off-road diesel construction engines greater than 25 hp operating in the 8 county ozone non-attainment area: Brazoria, Chambers, Fort Bend, Galveston, Harris, Liberty, Montgomery, and Waller counties. (Here, it should be noted that the calculations for the TxDOT fleet were only for the 6 counties in the Houston District because the 2 counties in the Beaumont District that are within the ozone nonattainment area stopped using PuriNOx due to health concerns pending the results of a study of this issue. The effect of including AGC equipment from the additional two counties is very small, as discussed in Subsection 5.E.2.) The HGAC study characterized these engines by equipment type (e.g., wheeled loaders and excavators) as well as annual activity level. Estimates of diesel fuel consumption were also provided. For this analysis, only the results for the "Heavy-Highway" sector were included, corresponding to work performed under TxDOT federal and state highway letting funds.

The HGAC study found that in 1999 AGC members in the heavy-highway sector owned and operated 988 pieces of off-road diesel construction equipment greater than 25 hp, consuming 2,038,482 gallons of off-road diesel per year. Rental equipment is not included in this evaluation because AGC representatives indicated that the fraction of rental equipment used by AGC highway contractors is quite small. The general equipment categories and their populations are summarized in Table 5.25. The current study assumed the same populations and diesel fuel consumption levels for the 2002 analysis year.

Table 5.25. Equipment Types, Population and Activity Estimates for AGC Contractors Operating in the 8 County Area (1999)

Equipment Category (> 25 hp)	# Units	Hrs/Yr/Unit
Diesel Pavers	23	625
Diesel Rollers	142	431
Diesel Paving Equipment	16	872
Diesel Surfacing Equipment	68	591
Diesel Trenchers	11	550
Diesel Bore/Drill Rigs	31	1472
Diesel Excavators	114	872
Diesel Cranes	156	1008
Diesel Graders	55	1197
Diesel Off-highway Trucks	2	7
Diesel Rough Terrain Forklifts	3	495
Diesel Rubber Tire Loaders	100	846
Diesel Rubber Tire Dozers	25	434
Diesel Tractors/Loaders/Backhoes	84	652
Diesel Crawler Tractors	132	993
Diesel Skid Steer Loaders	5	200
Diesel Other Construction Equipment	21	487
Total	**988**	

In addition to the HGAC study, this analysis relied heavily on documentation for EPA's NONROAD model and the results of the testing of the TxDOT fleet for data on NOx reductions and various cost impacts. JAM Distributing also provided critical information regarding the estimation of delivered fuel costs in the Houston area. Finally, Bob Lanham, Vice President of Williams Brothers Construction, and former President of the Association of General Contractors of Texas (Highways Branch), provided valuable input regarding the anticipated cost implications of PuriNOx use in AGC fleets.

5.E.2 Estimating Baseline Emissions for AGC

The engines representing heavy off-road applications – the ISB 190 and 6BTA5.9, tested at SwRI over the excavator and wheeled loader cycles – were certified to on-road, but not off-road, emission standards. Since on-road NOx standards are significantly cleaner than off-road standards for recent model year engines, and since engines certified to on-road standards are not typically used in off-road applications by AGC (Lanham, 2003a), it was not appropriate to use the SwRI test data to estimate baseline emissions from the AGC fleet. Therefore EPA's draft NONROAD emissions model (June 2000 version) was used to estimate baseline emissions for this fleet. NONROAD's default activity and population files were modified to reflect the characteristics of the 8 county AGC fleet, based on the HGAC study findings.

Selected load factors in the NONROAD model were also modified to reflect the wheeled loader and excavator cycles developed for this analysis. Comparing actual power output to maximum power at the same rpm levels, at each second of the cycle, the average load factor of the excavator and wheeled loader cycles were calculated at 0.35 and 0.47, respectively. However, as seen in Table 5.25 above, AGC operates a number of different equipment types, each likely to have its own typical operating cycle(s) and load factor(s). Therefore it may not be appropriate to apply the load factors for the excavator and/or wheeled loader cycles to all of the AGC equipment types.

According to NONROAD model documentation, off-road diesel equipment can be grouped into three representative "load factor assignments", corresponding to low and high transient load, and steady-state load cycles (EPA, 2002b). EPA's approach assigned excavators and wheeled loaders to the high load factor grouping. Therefore this analysis modified the load factors for all of the remaining high load factor equipment categories, leaving the default load factors for the low transient and steady-state groupings unmodified.

EPA has developed its own representative operating cycles for 7 nonroad diesel engine categories. Three of these categories are included in the high load factor assignment for diesel construction equipment – excavators, wheeled loaders, and crawler dozers. Following EPA's methodology, we averaged the load factors for the excavator and wheeled loader cycles, developed for this project, with EPA's load factor for crawler dozers (average load factor of 0.58) to determine representative load factors for the high load factor grouping as a whole (EPA, 2002b). (EPA's wheeled loader cycle agrees quite well with the AGC Wheeled Loader Cycle developed under this project in terms of average load -- 0.48 compared to 0.47, respectively. Given that EPA's excavator cycle exhibited anomalous readings above 100% load at several points in the cycle, the 0.53 factor was deemed suspect and the 0.35 factor was used for this analysis.) However, the corresponding excavator cycles did not correspond well - 0.53 for EPA's cycle vs. 0.35 for the TxDOT cycle. Averaging load factors over these three cycles results in a 0.47 value for the entire high transient group. The 0.47 value was subsequently input in the NONROAD activity file for these categories (see Table 5.26).

Table 5.26. Equipment Types in High Transient Load Factor Assignment Grouping

- Pavers
- Rollers
- Paving Equipment
- Surfacing Equipment
- Trenchers
- Excavators
- Graders
- Off-Highway Trucks
- Rough Terrain Forklifts
- Wheeled Loaders
- Wheeled Dozers
- Crawler Dozers
- Other Construction Equipment

Once the population and activity files were modified to reflect the AGC equipment population and use characteristics, NONROAD was run to determine baseline tons per year estimates for NOx in 2002 for the 8 county area. NONROAD defaults were used for temperature and diesel sulfur levels, as these factors do not influence exhaust NOx estimates for diesel engines in the model. Given this approach, **681 tons per year** of NOx are estimated for the AGC fleet using federal off-road number 2D diesel fuel.

Before comparing the baseline and subsequent NOx reduction estimates for AGC with those previously presented for TxDOT, two qualifications are in order. First, the AGC estimate is for an 8 county region that includes all of the 6 county TxDOT Houston District, plus Liberty and Chambers counties. However, using the NONROAD model's default allocation scheme, Liberty and Chambers counties only account for 0.66% and 0.36% of the total 8 county NOx emissions, respectively. Therefore the impact of including equipment operating in these two counties was deemed small, and was not adjusted for in the final analysis.

Second, the AGC emissions estimates do not account for on-road diesel use in dump trucks and related equipment. (Information on AGC's on-road fleet was not included in the HGAC report and was not readily available). According to one rough estimate (Lanham, 2003b), on-road diesel fuel use could account for around 20% of total diesel fuel consumption among AGC highway contractors. However, on-road engines typically emit 3 to 5 times less NOx than off-road engines of comparable model year and hp. For example, the 1997 and 2000 model year 190 hp engines tested at SwRI were certified to 4.0 g/mi NOx, translating to between 2 and 3 g/bhp-hr[11]. However, comparable Base and Tier 0 off-road engines are typically certified to between 8 and 11 g/bhp-hr. So if total on-road 2D fuel consumption for on-road engines were around 20% of all diesel use for AGC, the on-road contribution to total NOx emissions would be much smaller, perhaps 5

[11] The translation from g/mi to g/hp-hr requires estimates of the brake-specific fuel consumption (BSFC). For this analysis BSFC factors for on-road engines were taken from EPA document EPA420-P-98-015, for truck classes 3 to 6.

to 10%. Therefore the exclusion of on-road equipment from this analysis should not introduce large errors in the estimation of total NOx emissions and reduction potentials.

5.E.3 Potential NOx Emission Reductions

The HGAC study estimated that 2,038,482 gallons (6.50M kg) of off-road number 2D diesel were used per year for the AGC fleet in the 8 county area. Accounting for the fuel economy penalty measured in the current study, this figure translates to 2,546,542 gallons (8.25M kg) of PuriNOx per year, assuming the same hp-hrs of use. Using the Emissions Index for NOx (grams of NOx emitted per kg of fuel consumed) factors developed for the AGC Wheeled Loader Cycle, along with the above fuel consumption estimates, emission reduction factors for PuriNOx were developed for electronic and mechanical engines (13.4% and 21.0%, respectively).

The contribution of electronic and mechanical engines to total baseline emissions was determined using the "by-model-year" output option in NONROAD. This option provides emissions estimates in tons per year, along with the corresponding certification standards. Base and Tier 0 certification standards correspond to mechanically-controlled engines, while Tier 1 through Tier 3 standards correspond almost exclusively to electronically-controlled engines. Therefore the PuriNOx reduction factors were applied to the NONROAD base case emissions estimates, differentiating between the electronic and mechanical portions of the fleet. (In 2002, the off-road fleet is heavily dominated by mechanical engines, though this is changing rapidly with the recent introduction of Tier 1 engines.) Applying these factors leads to an estimate of **108.1 tons per year in NOx reductions**, assuming PuriNOx is used in 100% of all AGC diesel applications. This estimate does not include incremental emissions associated with additional starts – see Subsection 5.E.4 below. These additional emissions will occur exclusively at idle operation, which typically produces much lower NOx emissions than operation under load. Unfortunately, the NONROAD model does not provide an idle emissions estimate to allow for calculation of the NOx penalty associated with the extra starts required.

A sensitivity analysis was also performed to estimate potential emission reductions assuming the AGC fleet was comprised entirely of electronically controlled engines. This scenario will become more relevant with time, as engines meeting Tier 1 and subsequent emission standards are introduced into the fleet, and as older mechanical engines are phased out.

To estimate emissions from a 100% electronic fleet, NONROAD was run for the 2040 analysis year. Growth was factored out of the resulting emissions estimates, scaling by the increase in the number of pieces of equipment projected by the NONROAD model. Base case emissions fell from 681 tons per year of NOx to 293 tons per year. Accordingly, potential emission reductions fell significantly, **from 108 to 38 tons per year**.

5.E.4 Incremental Cost Analysis for AGC

The use of PuriNOx in the AGC fleet will incur the same types of costs discussed in Sections 5.C and 5.D for the TxDOT fleet. However, given the much higher fuel consumption rates by AGC (over an order of magnitude), absolute cost levels will increase accordingly.

Implementation and Conversion Costs

It was assumed that 2 fuel filter changes would be needed at program inception, as per the findings from the TxDOT fleet. Accordingly, parts and labor costs were applied to 2 filter changes for each of the 988 pieces of equipment in the AGC fleet. Filter costs and labor hours were assumed the same as for TxDOT. Labor cost ranges representative of AGC operations were provided by Bob Lanham. The cost calculation parameters are summarized in Table 5.27.

Table 5.27. AGC Implementation and Conversion Costs

Number of filters/unit	2
Total # units	988
Filter Cost/unit	$6.75
Total Filter Cost	$13,338
Average Loaded Wage Rate	$35.00
Avg. Install Time (hrs/unit)	3.3
Total Labor Cost	$229,871
Total Implementation Cost	**$243,209**
Annualized Cost (5 yrs @ 10%)	**$64,158**

Fuel Economy Penalty and Fuel Costs

This analysis assumed the per gallon fuel economy penalty and fuel cost increments incurred by TxDOT would also be incurred by AGC. Given the overall fuel economy penalty of 24.9% for the wheeled loaders and excavators, the fuel consumption levels noted above, and fuel costs of $1.02/gal base and $1.29/gal PuriNOx, AGC would incur an extra $574,087 per year due to fuel economy impacts, and $631,929 per year due to per gallon price differentials. The total fuel cost increase is **$1,206,016 per year if AGC pays the same base and incremental costs as TxDOT.**

Based on discussions with JAM Distributing (the PuriNOx distributor for Texas), fuel purchase contracts with AGC members will most likely be structured differently than the current TxDOT contract. AGC contracts will be based on the PuriNOx Posted Price (PPP), plus a delivery charge. The PPP will not include a fixed additive and blending cost as the current TxDOT contract does. Instead it will vary as a function of base diesel fuel cost (Goodrich, 2003). Therefore an additional fuel cost scenario was run for AGC purchasing fuel under JAM contract, based on February 18, 2003 rack prices. For off-road diesel with a rack price of $1.0617/gal, final delivered cost of PuriNOx would come to $1.1136/gal, or about a 5 cent per gallon increment. (Note that delivered costs would typically run about 12 to 15 cents per gallon lower than costs to TxDOT, due to volume discounts for AGC clients (Goodrich, 2003).) At these prices AGC would incur an extra $565,755 per year due to fuel economy impacts, and $105,797 per year due to per gallon price differentials. The total fuel cost increase is **$671,552 per year under the fuel cost scenario identified by JAM.**

Refueling Penalty

AGC will incur extra costs associated with dispensing a greater volume of fuel if PuriNOx is used. This cost includes two components – the extra time to pump the fuel, and the time associated with additional refueling events (tank turnovers). This latter cost category assumes that some fixed amount of time is required to bring the equipment to and from the pump.

The NONROAD model provides an estimate of equipment tank size in terms of average gallons per horsepower for diesel construction equipment (0.5). Given the hp distribution from the HGAC study, the average tank size of the AGC fleet was determined. Given this, the additional number of tank turnovers can be estimated. Table 5.28 summarizes the key parameters used in the cost calculation for the refueling penalty. AGC labor rate estimates were obtained from AGC representatives. Refueling rate and turnaround time are based on ERG assumptions.

Table 5.28. AGC Refueling Cost Penalty Calculation

Refuel Rate (gal/min)	10
Additional gal/yr	508,041
Additional refueling hrs/yr	847
Average Loaded Wage Rate	$16.20
Tank Size (gal/hp)	0.5
Average HP/unit	165
Average Tank Size (gal)	82
Extra refuels per yr	6,174
Extra turnaround time (mins/refueling)	10
Total Refueling Cost Penalty / yr	**$30,387**

Productivity Penalty

The PuriNOx performance analysis indicates that peak torque output is reduced by approximately 15-20% compared to diesel use. Accordingly, any diesel operating cycle that includes excursions above the ~80% torque level will have to be modified to accomplish the same task when operating on PuriNOx. Assuming that the particular piece of equipment is not replaced and upgraded with a higher hp engine, accomplishing the same amount of work will therefore require more time[12]. This finding was tentatively confirmed for the AGC wheeled loader at the Roadeo, where a 20% increase in time was found (although the Roadeo operation was designed to be especially high load, handling tightly packed material, compared to the actual AGC Wheeled Loader Cycle, which was developed for a wheeled loader handling sand and loose gravel).

To calculate the extra time needed to perform work typically performed at greater than 80% load, the AGC Wheeled Loader Cycle was evaluated on a second by second basis. The total work performed above the 80% threshold was determined. It was

[12] There may be some types of operations that cannot "subdivide" the task at hand and therefore require operation above the 80% hp threshold. In these instances a hp upgrade will be required. To determine the fraction of equipment requiring such an upgrade one would have to know how much "buffer" AGC's equipment has with respect to each work task undertaken. This analysis does not attempt to determine what fraction of the existing AGC fleet may require such upgrades.

assumed that this work would be performed "at the back end" of the cycle, at the average power level of the modified cycle (i.e., the original cycle less the excursions above 80%). The analysis found that a 4.6% increase in time would be required to perform this additional work under the AGC Wheeled Loader Cycle using PuriNOx[13].

In order to extrapolate the penalty associated with the AGC Wheeled Loader Cycle to other AGC equipment types, we first assumed that all high-load factor assignments had similar excursions above the nominal 80% threshold and would have similar operation time penalties. This assumption was refined by estimating which of these equipment categories are not likely to have excursions above the 80% level. Through engineering judgment it was determined that paving and surfacing equipment, and rough terrain forklifts were not likely to operate at very high loads for any significant period, and therefore would not incur a time penalty.

AGC representatives provided an estimate of crew sizes for each equipment type of interest in order to determine the total increase in man-hours associated with the performance penalty. Low and high estimates were developed for crew sizes and labor rates. In order to avoid project schedule delays, the high cost estimate scenario assumed labor will bill out at doubletime for this incremental time, while the low cost estimate assumed a multiplier of 1.0 (i.e., regular pay scale). The resulting low and high cost estimates for the performance penalty came to **$1,204,048** and **$5,060,965 per year**, respectively, for approximately 22,000 extra hours per year total for all pieces of equipment combined.

Maintenance

Table 5.29 summarizes the major cost elements of the maintenance analysis. Since the TxDOT and AGC fleets are not readily comparable in terms of equipment type mix, it was assumed that maintenance costs could be scaled directly from fuel use estimates. Using TxDOT's maintenance records, the incremental number of fuel filters, injectors, lift pumps, and injector pumps were calculated for the AGC fleet using total fuel consumption ratios. TxDOT records also provided an estimate of labor hours per type of repair. The filter changes listed in Table 5.29 are in addition to the two replacements required at inception, reflecting TxDOT's experience. The calculation assumes that only the fuel filter changes are handled by AGC employees (at $35/hr for skilled in-house labor), with the remaining repairs being outsourced. Finally, note that year one and annual maintenance costs are broken out, as was done for the TxDOT analysis. Year one costs are amortized over 5 years at a 10% discount rate, reflecting typical private sector practices.

[13] To the extent that a piece of equipment is oversized for a specific task in terms of hp, an operator should be able to increase the throttle to achieve this "extra" work, incurring no incremental time penalty. But again, the degree to which AGC oversizes their equipment is not known at this time.

Table 5.29. AGC Annual Maintenance Cost Projection

	Per Unit	Year 1	Annual
# Fuel Filters	-	635	0
# Injectors	-	164	148
# Lift Pumps	-	86	0
# Injector Pumps	-	23	20
Labor Hrs - Filter	0.75	477	0
Labor Hrs - Injector	8	1,314	1,184
Labor Hrs - Lift Pump	3	258	0
Labor Hrs - Inj Pump	16	369	320
Fuel Filter Cost		$4,289	$0
Injector Cost		$28,753	$25,900
Lift Pump Cost		$9,908	$0
Injector Pump Cost		$11,861	$10,280
In-house labor		$16,679	$0
Outsource Labor		$140,998	$109,190
Total $		$212,488	$145,370
Year 1 amortized		$56,054	
Total Annual Cost		**$201,424**	

Fuel Separation Costs

Consistent with the TxDOT analysis, it was assumed that all engines need to be started at least once every four days to avoid complications from fuel separation. And as with the TxDOT analysis, it was assumed that there are 10 minutes of labor time required for each start plus shutdown. The number of extra starts required to prevent fuel separation was calculated in two ways. First, it was assumed that the total hours of operation per year for each equipment type (obtained from the HGAC study) would be spread out as uniformly as possible over the year, with the one constraint that all engines are operated in 8 hour (day) increments (Lanham, 2003c). This approach leads to the minimum amount of down time and the fewest number of required extra starts. Second, it was assumed that the total hours of operation per year would all be incurred on consecutive working days. This assumption leaves the largest possible block of down time, requiring the greatest number of additional starts. Both calculations assumed a 6 day work week for AGC (Lanham, 2003c).

Given the average burdened pay rate of $16.20 per hour, the costs associated with extra starts should range between **$26,876** and **$164,921 per year**.

Fuel Storage Costs

JAM Distributing indicated that AGC members seldom purchase or even rent fuel storage equipment (Alford, 2003). JAM provides above ground tanks as part of their fuel supply contract with AGC members. It is probable that this will be true for PuriNOx as well. As such, any fuel storage costs are implicitly included in the delivered fuel costs discussed above.

Potential TERP Fuel Subsidies

Under the terms of the TERP program, certain emission control projects undertaken voluntarily are eligible for partial or complete reimbursement of incremental equipment, fuel, and infrastructure costs. These costs may be reimbursed up to the level of $13,000 per ton of NOx reduction. Note however, that this dollar per ton cutoff level does not account for many of the cost categories evaluated above, including performance, refueling, and fuel separation penalties. Therefore the $13,000 figure should not be compared directly to the more comprehensive cost-effectiveness estimates developed in this study.

Nevertheless, if AGC equipment operators were to voluntarily use PuriNOx in their TxDOT contracts, they would be eligible for TERP rebates on incremental fuel costs.[14] Assuming the current TERP rebate of $0.24/gallon, along with 2,546,542 gallons of PuriNOx consumed annually yields a potential TERP rebate of $611,170 for both the low and high fuel cost scenarios. This also assumes that TxDOT incentivizes – rather than specifies – AGC use of PuriNOx and that TCEQ does not change the per-gallon rebate amount. The remainder of the fuel cost penalty (~$60,000 under the low cost scenario and ~$595,000 under the high cost scenario) is due to the fuel economy penalty plus incremental fuel cost above $0.24/gallon. This portion would be borne by AGC and passed along to TxDOT.

AGC Cost Summary

Table 5.29 summarizes the estimated incremental costs to AGC associated with the exclusive use of PuriNOx in its off-road fleet in the 8 county area.

Table 5.30. AGC Incremental Costs Associated with PuriNOx Use

	Low	High	Comments
Implementation	64,158	64,158	(5 yr, amortized at 10%)
Maintenance	201,424	201,424	(includes year one and annualized costs)
Fuel Storage	0	0	(NA - part of Fuel Delivery Cost)
Refueling Time	30,387	30,387	
Fuel Cost	671,552	1,206,016	(high reflects same base and incr. costs as TxDOT)
Extra Starts	26,876	164,921	
Performance Penalty	1,204,048	5,060,965	
TOTAL	**$2,198,445**	**$6,727,871**	

These costs would almost certainly be passed directly on to TxDOT. If TERP funding becomes available for AGC use of PuriNOx at the full 24 cent per gallon subsidy, this would reduce overall costs to AGC (and passed through to TxDOT) by $611,170 per yea for both the low and high scenarios. In turn, this would yield annual costs approximately between $1.6 million and $6.1 million. As noted above, this requires that TxDOT incentivizes – rather than specifies – AGC use of PuriNOx and that TCEQ does not decrease the rebate amount below the current $0.24/gallon.

[14] If TxDOT were to contractually require AGC to use PuriNOx, AGC would not be eligible for TERP funds. However, TERP funding would be available if TxDOT were to merely incentivize future contracts to encourage use of low emission fuels, including but not limited to PuriNOx.

5.E.5 Cost-Effectiveness Evaluation for AGC

A range of cost-effectiveness estimates was developed for AGC use of PuriNOx, accounting for a number of different cost and emission scenarios. These findings, presented in dollars-per-ton of NOx reduction, are summarized in Table 5.31. Note that the "Low" cost scenarios assume minimal extra engine starts, low-cost performance penalty assumptions, and delivered fuel costs based on the variable PuriNOx Posted Price. "High" cost scenarios assume the maximum number of extra engine starts, high-cost performance penalty conditions, and the current TxDOT constant cost increment. Given the conjunctive nature of these different conditions, we believe it is highly unlikely that the actual cost-effectiveness will approximate either the low or high end value, but will most likely fall well in between these extremes. Therefore Table 5.31 also indicates the midpoint value for each of these scenarios, which should be more indicative of the most likely dollar-per-ton result, although the uncertainty in these estimates is expected to be large.

Table 5.31. Cost-Effectiveness Ranges for AGC Use of PuriNOx

Scenario	Low	Midpoint	High
Current Engine Mix	**$20,333**	**$41,279**	**$62,225**
All Electronic Engines	**$57,251**	**$116,228**	**$175,205**
No performance penalty, current mix	**$9,197**	**$12,307**	**$15,417**

As indicated in Table 5.31, PuriNOx will become less cost-effective with time as cleaner electronic engines come into the fleet. The final scenario – "no performance penalty, current mix" - provides an estimate of cost-effectiveness assuming that *all high load factor AGC equipment has been sufficiently oversized to allow throttle use to fully compensate for any performance penalties.* On the other hand, to the extent that new equipment must be purchased for relatively undersized equipment, one would expect total costs and dollar-per-ton values to increase above the base (current engine mix) case.

The cost-effectiveness of use of TxLED by AGC is discussed in Section 5.F.2.

5.F. Comparisons with Alternatives

The research team interviewed a number of different agencies, including representatives from the EPA's Voluntary Diesel Retrofit Program, the Diesel Technology Forum, Department of Energy, Argonne National Laboratory, Good Company Associates, AAE Technologies, and the Manufacturers of Emissions Control Association, to identify alternative emission abatement strategies for NOx in heavy-duty diesel engines. Some of the interviewees reported that, although there are a number of technologies that are in the process of being developed, currently new engine purchases are the only alternative to reduce NOx emissions. Table 5.32 summarizes available information on alternative abatement strategies with respect to emissions benefits, available cost information, fuel penalty, performance penalty, maturity of the technology and other relevant issues/comments.

The information contained in Table 5.32 was summarized from data collected by EPA, Good Company Associates, AAE Technologies, and Environment Canada to provide guidance in terms of the capabilities of available and future technologies.

The available information suggests that a number of technologies currently being researched and demonstrated would reduce NOx and/or PM emissions significantly in the future. Very few demonstrated technologies have, however, CARB or EPA verification, besides PuriNOx and replacement of older engines and vehicles with newer engines and vehicles that were designed to meet more stringent emissions standards.

Two technologies that appear to be promising are discussed in the following subsections.

Table 5.32. Alternative Emission Abatement Technologies/Fuels

Technology	Description	Emissions Reductions (%)				Cost ($)	Fuel Penalty (%)	Perfor-mance Penalty	Availability/ Maturity	Issues/Comments
		NOx	PM	HC	CO					
Re-power	Re-power with re-furbished/ new engine or upgrade emissions controls on current engine	20-55	yes	yes	Yes		Improved fuel efficiency		EPA verified	
Cooled Exhaust Gas Re-circulation (EGR)	Re-circulation of exhaust gas to a point in an engine's intake system. This dilutes the intake air and decreases the combustion temperature to a point below that at which NOx is formed.	50-70	95	70-95	70-95	12-16k plus higher ULSD costs of $0.14	0-5		Research and manufacturer's demonstrations. Research and development as retrofit.	Require major engine integration: fuel and air management system upgrades needed to counteract increased PM emissions and brake specific fuel consumption. Condensation concerns and packaging constraints. Sulfur to be < 500 ppm
Fuel Injection Rate-shaping	Precisely controlling the rate of fuel injected into the cylinder to control rate of combustion and thus peak combustion temperatures.	20	50			Fuel injection system average costs/ new engine ($1999): LHDDV ($144); MHDDV ($147); HHDDV ($160)			Used to a limited extent to meet 1998 emissions standards by manufacturers.	Potential for increased smoke emissions.

Technology	Description	Emissions Reductions (%)				Cost ($)	Fuel Penalty (%)	Perfor-mance Penalty	Availability/ Maturity	Issues/Comments
		NOx	PM	HC	CO					
Lean NOx catalysts	Facilitates HC and NOx in the exhaust stream to react to form nitrogen, CO_2 and water. Precise quantities of fuel are injected into the exhaust for these catalysts to function.	15-30	30-90	70-90	70-90	6.5 – 15K	up to 7		Commercial demonstration (10,000 hour durability data exists) Targeting CARB verification 12/02 EPA verification Spring 2003.	Primarily base metal catalysts effective at exhaust temperatures exceeding 300 ºC. Possible N_20 generation Very sulfur sensitive.
NOx absorber catalysts		80 to > 90	10-30	90	90				Research and development	Catalyst severely impacted by fuel sulfur levels. Sulfur to be reduced to < 15 ppm. Requires engine integrations, means for supplemental fuel injection
4-Way Catalyst (Lean NOx Catalyst + PM filter)		20	80	70	70	8-10K [5-10K]	4-7		Commercial demonstration	Sulfur to be < 500 ppm. Currently undergoing durability testing.
Green Plus	Non-metallic and non-mutagenic fuel combustion catalyst. Unbundles HC molecules and causes the fuel and air molecules to mix more completely and evenly in the engine, which prevents hot-spots.	20-45	30-40	30-60	50-75	$0.03/gallon	Increases fuel efficiency by 6-15%		Targeting EPA and CARB verification by 4/03.	Suited to a broad range of engines and driving cycles.
Viscon	Polymer that is added to the fuel that causes the diesel to burn more evenly and completely.	25-40		50-60	30-40	$0.03-0.04/gallon	Increases fuel efficiency by 10-20%		Targeting EPA verification 02/03.	Suited to a broad range of engines and driving cycles

Technology	Description	Emissions Reductions (%)				Cost ($)	Fuel Penalty (%)	Perfor-mance Penalty	Availability/ Maturity	Issues/Comments
		NOx	PM	HC	CO					
Clean Fuels Technology	Diesel emulsion	16-30	Up to 60		10-60	$0.05-0.15/gallon depending on volume and on- or off-road use.	2-8	Horsepower slightly affected.	Targeting CARB verification by 1/03.	Best for vehicles or equipment that does not sit for more than 30 days.
O^2 Diesel	Blend of diesel fuel, 7.7% ethanol and 0.6% proprietary additive.	2	22		11	$0.04-0.05/gallon depending on diesel price	Slightly impacted.	Slightly affected.	Submitted SwRI emissions test data to CARB for alternative diesel verification in 01/03.	Additive claimed to prevent corrosion and separation. Also restore some of lubricating loss, and minimize static electricity built-up.

Source: Compiled from EPA, 2000; Personal Communication EPA representative from Voluntary Diesel Retrofit Program, 2002; www.epa.gov/otaq/retrofit/; Personal Communication Tod Wickersham from Good Company Associates; Personal Communication Jim Peeples from AAE Technologies, Inc., MECA Independent Cost Survey for Emissions Control Retrofit Technologies, 2000; and Environment Canada, 2002

5.F.1. Selective Catalytic Reduction (SCR)

A computer controlled SCR system removes NOx from the exhaust stream by injecting ammonia into the exhaust stream over a catalyst composed of precious metals, base metals, and zeolites. NOx reductions of 50 to 90 percent have been reported, PM reductions up to 80 percent, and HC and CO reductions of between 70 and 80 percent. The up-front costs of these devices are estimated in the range of $10,000 to $20,000. The urea/water mixture, used to generate the ammonia, is usually stored in a separate tank that needs frequent replenishment. Urea consumption amounts to approximately 4 percent of the fuel use and can cost up to $0.80/gallon (EPA's Voluntary Diesel Retrofit Program, 2002).

Although these devices have been proven in stationary sources, only prototypes have been developed for mobile heavy-diesel applications. The biggest concern with this device is the control of the quantity of urea injected into the exhaust stream. Too large a quantity of urea can result in "ammonia slip", resulting in the emissions of ammonia into the atmosphere. Unresolved issues include urea refueling, tampering, ammonia slip, supply of water/urea mixtures, and the possibility of not re-filling the urea tank. One of the advantages of the SCR is that it appears to be tolerant of fuel sulfur contents up to 500 ppm (Environmental Protection Agency, 2000), although this advantage will be inconsequential once Texas Low Emission Diesel becomes the standard diesel fuel in Texas. The biggest advantage is the large (50-90%) NOx benefit, but this is accompanied by uncertainties regarding cost, durability, and emissions warranty.

5.F.2. Ultra Low Sulfur Diesel - TxLED

Texas Low Emission Diesel (TxLED) is a specially formulated, low-emission diesel fuel certified to reduce NOx emissions by 7% in off-road applications and 5.7% in on-road applications (Texas Commission on Environmental Quality)[15]. No modifications are required to existing fueling infrastructure or diesel vehicles/equipment to use TxLED. Also, no other implementation, maintenance, or performance costs are anticipated. TxLED is, however, estimated to cost between $0.12 and $0.21 more than conventional diesel in the Houston area. Given these two fuel cost scenarios, the fuel cost penalty associated with TxLED was calculated (see Table 5.33).

Table 5.33. Annual Fuel Cost Penalty of using TxLED to Reduce NOx Emissions (TxDOT, Houston)

Cost Category	Houston Equipment (Total)	Excavator	Single-Axle Dump Truck	Tandem-Axle Dump Truck	Herbicide Sprayer	Arrow Board	Mower	Loader
NOx Benefit (tons/year)	1.338	0.120	0.164	0.193	0.068	0.002	0.004	0.022
High Fuel Cost Scenario ($)	**52,723**	**4,090**	**6,156**	**8,506**	**2,646**	**75**	**126**	**756**
Low Fuel Cost Scenario ($)	**30,127**	**2,337**	**3,518**	**4,860**	**1,512**	**43**	**72**	**432**

As indicated in Table 5.33, the NOx emission reduction potential of TxLED is slightly higher than for PuriNOx (~1.3 vs ~1.1 tons/year), in spite of the 5.7-7% NOx

[15] These estimates are subject to change during the mid-course review process at TCEQ.

benefit of TxLED compared to the ~14-24% benefit for PuriNOx. The overall decrease in NOx for TxLED relative to PuriNOx occurs for two reasons: 1) TxLED does not suffer from the NOx penalty associated with the need to start engines fueled with PuriNOx at least twice each week, and 2) the ~50 vehicles and pieces of equipment in the Houston District that could not be converted to PuriNOx for various reasons can use TxLED. The calculated cost-effectiveness of using TxLED to reduce NOx emissions from TxDOT's Houston fleet is summarized in Table 5.34.

Table 5.34. Cost-Effectiveness of TxLED to Reduce NOx Emissions (TxDOT, Houston)

Cost Category	Houston Equipment (Total)	Excavator	Single-Axle Dump Truck	Tandem-Axle Dump Truck	Herbicide Sprayer	Arrow Board	Mower	Loader
NOx Benefit (tons/year)	1.338	0.120	0.164	0.193	0.068	0.002	0.004	0.022
Cost-Effectiveness; High Fuel Cost ($/ton)	**39,413**	**34,152**	**37,461**	**43,971**	**38,659**	**31,413**	**29,516**	**34,566**
Cost-Effectiveness; Low Fuel Cost ($/ton)	**22,521**	**19,515**	**21,406**	**25,127**	**22,091**	**17,950**	**16,866**	**19,752**

As is evident from Table 5.34 **TxLED is a much lower cost strategy for achieving NOx emissions reductions for TxDOT.** The available TERP rebate for TxLED is currently $0.07/gallon. Given this rebate, the annual fuel cost penalty associated with the use of TxLED will decrease to $35,149 and $12,553 under the high and low fuel cost scenarios, respectively. This results in a cost-effectiveness of $26,275 and $9,384/ton, respectively. As is the case with PuriNOx, this simply shifts all or part of the higher cost of the fuel to a different source of state funds, such that the cost-effectiveness to the State of Texas is unaffected by the TERP rebate. Additionally, TERP rebates for use of TxLED will disappear in 2005 if its use becomes mandated. Nevertheless, ~$22,000-39,000/ton for TxLED is a significantly more cost-effective than PuriNOx, at more than $200,000/ton for TxDOT.

The cost-effectiveness for AGC's use of TxLED was also estimated. According to EPA's Unified Diesel Fuel Model, diesel engines not equipped with exhaust gas recirculation (EGR) technology should experience a 6.2% reduction in NOx emissions when operating on TxLED (EPA, 2001)[16]. (At this time there are no non-road, EGR-equipped engines in service.) One current vendor of TxLED estimated an incremental cost range of 12 to 21 cents per gallon, for AGC fuel delivered to the Houston area (Hernandez, 2002). Assuming no other implementation, maintenance, or performance costs are incurred, **if adopted by AGC TxLED could provide approximately 42 tons per year of NOx reductions in the 8 county area, at a cost-effectiveness between $5,824/ton and $10,192/ton, with a midpoint value of $8,008/ton**.

[16] We anticipate that the 6.2% estimate will be officially adopted by the TCEQ during the upcoming midcourse SIP review process. This is a slight reduction from the 7% value used in the current SIPs.

6. Summary, Conclusions, and Recommendations

The present study was the most extensive study of PuriNOx to date, involving a field test of 386 diesel engines in normal service, plus emissions and fuel consumption tests of eight dump trucks, two engines used for off-road applications, and a small utility engine.

Four criteria were used to assess the use of PuriNOx: health risks (relative to conventional diesel fuel), safety hazards (fire hazards and highway safety), performance (ability of the TxDOT equipment to perform the required tasks), and cost-effectiveness. Cost-effectiveness analyses were performed separately for the TxDOT and AGC fleets in the Houston area. The results of this project, in terms of each of the four criteria, are summarized below, followed by our recommendations.

Neither summer-grade nor winter-grade PuriNOx can be excluded from use based on the available information regarding exposure to the liquid or the fumes from the liquid fuel. However, these comparisons between PuriNOx and diesel fuel were based solely upon information in the MSDS. Because there are no standards for writing an MSDS, such comparisons cannot be perceived as definitive. We recommend use of protective clothing whenever there is a risk of skin contact with the liquid fuel. Additionally, as is prudent for any liquid fuel, care should be taken to avoid breathing the fuel vapor. Two occupational health studies of exposure to the exhaust indicate that summer-grade PuriNOx does not yield products that are near or above safe limits. However, neither of these studies included the full list of Toxic Air Contaminants (TACs). The levels of many of the TACs increase when PuriNOx is used. Neither the EPA nor CARB have established regulations for these TACs, other than formaldehyde. Summer-grade PuriNOx has passed the EPA Tier 2 health risks analysis. However, EPA is concerned about exposure of the public to highly diluted exhaust whereas TxDOT is concerned about exposure of their workers to close-vicinity exhaust. It is concluded that exposure to the exhaust from vehicles using PuriNOx does not pose a significant health risk to the general public, but close-vicinity workers should take precautions to avoid breathing the exhaust.

When ambient temperatures are so low that summer-grade PuriNOx cannot be used, we recommend that TxDOT and AGC use TxLED rather than winter-grade PuriNOx. We base this recommendation on five factors. It is known that winter-grade PuriNOx poses a greater health risk than diesel fuel, but the severity of this risk is uncertain. Also, winter-grade PuriNOx has a relatively low flash point that might pose a fire hazard in some situations. The methanol in winter-grade PuriNOx is corrosive, but no durability studies have been performed so the potential effects on repair and maintenance costs cannot be assessed. Also, the NOx benefits of TxLED appear to be greater than that for winter-grade PuriNOx. Finally, in the winter months, ozone nonattainment episodes are rare.

Although the torque loss resulting from use of PuriNOx penalizes acceleration, our studies do not indicate that this poses a safety hazard. However, some of TxDOT's vehicles can barely maintain 45 mph on the highway when using PuriNOx. This poses potential risks to the driver, occupants, and other vehicles on the roadway. Telescoping boom excavators are an example of TxDOT equipment that has this problem. We recommend that PuriNOx not be used in telescoping boom excavators or any equipment that cannot maintain 45 mph on the highway when using PuriNOx.

“Performance failure” can be a result of the torque loss resulting from the water in PuriNOx. The torque loss was also analyzed as a potential safety hazard, as discussed in Section 3, and is also accounted for as a potential loss of productivity in the cost-effectiveness analysis, as discussed in Section 5. However, performance failure can also result from other factors. The performance failure criterion is simple: can the vehicle perform its required tasks when using PuriNOx? One example of a performance failure is that of the 6.5L GM engines in TxDOT’s fleet that have an optical sensor to detect water in the fuel. PuriNOx is not compatible with this sensor. Performance failure can also result from the torque loss associated with the water in the emulsion. For some pieces of equipment, this torque loss is sufficiently severe that the equipment cannot perform its required task when using PuriNOx. One example is the crane truck with the T444E engine, which TxDOT rapidly identified as being unsuitable for PuriNOx. Our study — via surveys of TxDOT drivers and operators in the Houston District, surveys and quantitative data from the “Alternative Fuels Roadeo” that we staged for this project, and interviews with other PuriNOx users — did not identify any performance failures that TxDOT had not already identified. If it is decided that TxDOT will continue using PuriNOx and that AGC will begin using it, we recommend that TxDOT continue its own determinations of performance failures, on a case-by-case basis, and that AGC should make a similar determination of what equipment cannot use PuriNOx due to inability to perform the required tasks.

All of the Houston TxDOT PuriNOx users and Roadeo participants perceived one or more differences in the performance of their vehicles/equipment when using PuriNOx. The Houston PuriNOx user responses were almost uniformly negative, although the intensity of the responses varied depending on the specific attribute tested. The statistical analysis revealed that the drivers/operators perceived performance impacts associated with the use of PuriNOx relating to a loss of power, starting problems, and more smoke. Specific concerns in the comment section of the questionnaire about using PuriNOx included: loss of power, the inability to reach and maintain highway speeds, poor idling performance, and engine smoke (however, the tests at SwRI revealed only one combination of engine/vehicle and cycle for which PuriNOx increased the emissions of PM).

The statistical analysis of the data recorded during the Roadeo provided evidence that supports the concerns raised by the Houston PuriNOx users regarding acceleration performance and loss of power. However, the rankings of other attributes - like engine noise, vibration, number of shift points required when negotiating a hill, performance when lifting loads, performance when operating under load and during idling - were very different among the operators (for all equipment types) providing no evidence that the PuriNOx-fueled vehicles performed better/worse than the diesel vehicles in terms of these attributes.

The statistical analysis of the Roadeo suggests that the performance of the excavator and loader were impacted most noticeably when fueled with PuriNOx. Also, the PuriNOx-fueled bucket trucks and forklifts were somewhat impacted by the use of PuriNOx. On the other hand, there was no evidence that the PuriNOx-fueled dump trucks performed better or worse than the diesel dump trucks in terms of the tested criteria. From the Roadeo data it can be concluded that contractor vehicles/equipment that are used consistently at engine loads higher than approximately 80% can, on average, expect a loss in vehicle performance and job productivity. Taken to the other extreme, a TxDOT or contractor vehicle that spends all of its time at less than approximately 80% engine load will probably, on average, be unaffected in terms of performance and productivity when using PuriNOx. The performance of specific vehicles/equipment might, however, be affected differently depending on the age of the vehicle, usage, and maintenance history.

The TxDOT PuriNOx user surveys also revealed that the TxDOT drivers/operators did not change their attitude toward the fuel after a period of approximately four months. In fact, the comments suggested that the driver/operator perceptions were more negative about the performance impacts of using PuriNOx when surveyed in November compared to August/September, but the statistical analysis revealed no statistically significant change in the perceptions of the Houston PuriNOx users (at a 5% significance level).

From the perspectives of health, safety, and ability to perform the required tasks, summer-grade PuriNOx is suitable for use – and offers a NOx benefit - in most diesel vehicles and types of equipment. However, the NOx benefit must be weighed against the costs of using PuriNOx. That is, for both the TxDOT and AGC fleets, the primary criterion for use of PuriNOx is cost-effectiveness. This analysis includes the costs of converting to PuriNOx and implementing its use, fuel economy effects, the higher cost of PuriNOx, the cost of refueling more often owing to the PuriNOx fuel consumption penalty, the cost of lower equipment productivity owing to the loss of torque, increased maintenance, and various costs associated with the tendency of the emulsion to separate.

As an example of the productivity loss, at the Roadeo we found that wheeled loaders fueled with conventional diesel fuel could fill 5 dump trucks in 30 minutes, whereas loaders fueled with PuriNOx could only fill 4 dump trucks. Our analysis revealed that vehicles and equipment that are used with engine loads of about 80% or higher will experience a productivity loss. Thus, loss of productivity will depend upon the specific duty cycle for a given type of equipment: whether or not it performs work at more than ~80% torque and, if so, the percent torque and percent time it is required to work at these conditions. Any loss of productivity means that it will take longer and cost more to perform some jobs, for both TxDOT and AGC.

The tendency of emulsions to separate results in several problems. Examples are the emissions and fuel consumption penalties associated with the need to start PuriNOx-fueled engines twice weekly even when the equipment is not needed and the more frequent failure rates of injectors and fuel pumps. We performed fundamental studies of these cost-related issues, as discussed in the following paragraphs.

Our studies show that the fuel separates faster at higher temperatures, and in a non-linear manner (the separation rate is much higher at 130 ºF than at 35 or 73 ºF). During normal engine operation, the fuel in the fuel delivery system is heated via conduction from the engine and by the relatively high underhood air temperature. Heated fuel then returns to the fuel tank, where it heats the fuel in the tank. Hotter fuel is then delivered to the engine. The result is that the temperatures in both the tank and the fuel delivery system are higher than ambient during normal operation. However, the emulsion is probably well-mixed via agitation from the fuel that returns to the tank. When the engine is turned off, many of the components of the fuel delivery system hot soak to near coolant temperature (approximately 200 ºF). Also, radiation from the asphalt or concrete surface that the truck is parked on can elevate the tank temperature. Thus, separation may occur relatively rapidly after engine shut down.

Our tests revealed that corrosion does not occur in 2D diesel fuel for our test conditions, nor in a well-mixed emulsion, nor in the milky-white portion of the fuel after separation has occurred. Rather, corrosion only occurs in the transparent portion of the fuel after separation. Even though this upper portion has the appearance of diesel fuel, the fact that it corrodes whereas diesel fuel does not is strong indication that it contains one or more components that are not present in diesel fuel (possibly the additives) or is enriched in some diesel component(s) that may be corrosive. The upper portion of the separated fuel has a lower specific gravity than either PuriNOx or pure diesel fuel. This is additional evidence that the upper portion of the separated emulsion is enriched in light components. It is not known what these components are, but they must be responsible for the corrosive nature of the emulsion once it separates. In turn, this could lead to corrosion of the tanks, injectors, and injection pumps. No complaints of tank corrosion have been noted during the period of this study, but that is undoubtedly a longer-term problem compared to the duration over which TxDOT has been using PuriNOx. However, TxDOT has noted increased failures of injectors and pumps. The present results may explain these failures as possibly resulting from separation within these components at elevated temperature.

Also, separation within the fuel delivery system, after engine shut down, may be the cause of hard starting. Our studies of the fuel that is injected after a shut down, hot soak, and 5 day period of non-use revealed evidence of separation in the fuel lines that can affect starting and idling.

TxDOT suffers a cost burden due to the need for starting each engine twice per week, even when not needed for normal service. There are also NOx and fuel consumption penalties associated with these extra starts. TxDOT also suffers a cost burden due to more frequent injector and pump failures, possibly due to corrosion. AGC will suffer from similar cost burdens. These factors were accounted for in the cost-effectiveness analyses for TxDOT and AGC.

The TxDOT cost-effectiveness calculations – a point estimate for the costs incurred by TxDOT in 2002 using PuriNOx – revealed that PuriNOx is a relatively high cost strategy for TxDOT to reduce NOx emissions. Depending on how the up-front conversion and implementation costs are accounted for, the costs of reducing NOx ranged from almost $400,000/ton (all up-front costs are counted in 2002) to about $330,000/ton (up-front costs are annualized over a period of 10 years) to approximately $320,000/ton (Year 2 cost with all up-front implementation costs absorbed during Year 1, assuming the same fuel use patterns and costs for Year 2 as in Year 1). The need to restart the engines twice per week is a significant burden that costs TxDOT approximately $105,000 in labor every year. Even in the scenario where TxDOT purchases the fuel storage tanks – a significant cost factor in the current calculation – and applies for TERP funding (which only shifts the cost to a different source of state funds), the costs of reducing NOx ranged from ~$300,000/ton to ~$223,000/ton. Even if these are taken together with some (unknown) means of decreasing the NOx and labor penalties for the extra starts by 50% and an increase in the NOx removed by 11% for a higher equipment utilization scenario (but neglecting the additional fuel used and other factors associated with increased utilization), the cost-effectiveness is still more than $110,000/ton.

TxLED, on the other hand, is a much lower cost strategy available to TxDOT for reducing NOx emissions. Additionally, the NOx emission reduction potential of TxLED is slightly higher than for PuriNOx (1.338 vs 1.157 tons), in spite of the 5.7-7% NOx benefit of TxLED relative to the ~12-23% benefit for PuriNOx. The overall decrease in NOx for TxLED relative to PuriNOx occurs for two reasons: 1) TxLED does not suffer from the NOx penalty associated with the need to start engines fueled with PuriNOx at least twice each week, and 2) the ~50 vehicles and pieces of equipment in the Houston District that could not be converted to PuriNOx for various reasons can use TxLED. The only penalty associated with the use of TxLED for TxDOT is a higher fuel price. The cost-effectiveness of TxLED to reduce NOx emissions was estimated to range between ~$23,000/ton and ~$39,000/ton given an incremental cost range of $0.12 and $0.21/gallon relative to diesel, respectively. Given the TERP rebate of $0.07/gallon for TxLED, the cost-effectiveness improves to between ~$9,000/ton and ~$26,000/ton, respectively. However, as is also true regarding TERP rebates for PuriNOx, this simply shifts part of the higher cost of the fuel to a different source of state funds, such that the cost-effectiveness to the State of Texas is unaffected by the TERP rebate. Additionally, TERP rebates for use of TxLED will disappear in 2005 if its use becomes mandated. Nevertheless, $23,000-$39,000/ton for TxLED is an improvement over the cost-effectiveness of PuriNOx, at more than $200,000/ton for TxDOT.

The AGC cost-effectiveness evaluation also found that TxLED is more cost-effective than the use of PuriNOx in the AGC contractor fleet. Taking the midpoint of the dollar-per-ton ranges, TxLED reductions would cost approximately $8,000 per ton of NOx, while PuriNOx reductions would cost about $41,000 (for the current engine mix scenario). However, in terms of absolute NOx reductions, PuriNOx use could generate about 108 tons per year of NOx reductions, compared to only 42 tons per year of reductions from TxLED use. Therefore, the "first" 42 tons of reductions could be obtained at the relatively low cost of about $8,000 per ton. However, the *marginal cost-effectiveness* of the remaining 66 tons of reduction potential is even higher than the average cost-effectiveness for PuriNOx reported above, at about $62,000 per ton, using the midpoint value for incremental TxLED costs.[17] To the extent that cost-effectiveness is an important decision criterion, it is instructive to look at marginal as well as average cost-effectiveness levels.[18]

Note that these cost-effectiveness values are static estimates, only applicable to the current AGC fleet mix. As discussed in Section 5.F, as electronic engines penetrate the fleet more and more, potential NOx reductions will fall and dollar-per-ton values will increase. This trend may be accelerated to the extent that AGC contractors participate in the TERP program through re-engining and early retirement of mechanical engines. Such a trend will tend to increase dollar-per-ton estimates for TxLED as well as PuriNOx.

The cost-effectiveness of control options will also change as baseline fuels change. Most notably, if TxLED use becomes mandated in 2005, TxLED will become the new baseline fuel. Accordingly, PuriNOx use will lead to significantly lower NOx reductions from 2005 onward, simply due to the cleaner baseline fuel. In other words, the marginal cost-effectiveness of PuriNOx ($62,000/ton) will become the *average* cost-effectiveness once TxLED is adopted region wide.

In all cases, the cost-effectiveness of PuriNOx use is expected to increase above the current estimates over time for both TxDOT and AGC. Given these findings, we do not

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[17] Here marginal cost-effectiveness attributes the entire cost of PuriNOx adoption, net of the higher baseline cost of TxLED, only to the incremental reductions over and above those obtainable from TxLED (i.e., about $4.1M/66 tpy).
[18] Note that the Clean Air Act Amendments do not consider cost-effectiveness in the determination of compliance with the Act's requirements.

anticipate that PuriNOx will meet the cost-effectiveness level obtainable through the use of TxLED. Based on this criterion alone, we cannot recommend that either TxDOT or the AGC contractors use PuriNOx in their current operations. As discussed above, the cost-effectiveness of PuriNOx is likely to get even worse as older equipment is replaced with newer equipment that has improved NOx emissions.

However, we must acknowledge that PuriNOx is capable of generating substantially larger NOx reductions than TxLED (approximately 66 tons per year in 2002 for the AGC operations in the Houston area). Since NOx reductions are critical to the ultimate attainment of the NAAQS in the Houston area, and since the Clean Air Act Amendments do not permit emission reduction strategies to be rejected solely on the basis of cost, the use of PuriNOx in the AGC fleet may require further evaluation.

In this light, two additional questions should be answered. 1) Will the Houston area require an additional 66 tons or more per year of NOx reductions in order to meet the NAAQS standards?[19] 2) If so, are there other NOx control strategies that can obtain similar or greater reductions at a lower dollar-per-ton value?

The answer to the first question is almost certainly "yes." However, the answer to the second question is not immediately clear. Based on this analysis, it is not known whether or not PuriNOx is more cost-effective than retrofitting engines with EGR or SCR, for example. For this reason, it may be necessary to refine the current cost-effectiveness estimates for PuriNOx use in the AGC fleet.

The following additional steps would be needed to more accurately quantify potential emission reductions and costs for the AGC fleet.

1. Develop representative operating cycles for key high-load equipment types to refine the potential performance penalty of PuriNOx, and assess the need for engine upgrades.
2. Measure emissions and PuriNOx benefits over other cycles (beyond the AGC Wheeled Loader Cycle).
3. Measure fuel economy impacts for specific cycles.
4. Re-evaluate equipment type groupings based on new cycle information to refine extrapolation of costs and emissions to the AGC fleet as a whole.
5. Evaluate impacts for the on-road portion of the AGC fleet (which may include cycle development and emissions measurements).
6. Measure impacts for Tier 2 and Tier 3 engines as they become available. Extrapolate these findings to future analysis years.

Although we believe that PuriNOx is not preferred for either the TxDOT or AGC fleets, we are certain that there are fleet operations for which PuriNOx is an excellent method for NOx reductions. The main problem for the TxDOT operations is that they have too much equipment that is not used at least twice per week, resulting in the "extra starts" penalties for labor, fuel consumption, and NOx emissions. The main difficulty for AGC is that a portion of their equipment will suffer a performance penalty that results in additional time required to perform the necessary tasks. Our results indicate that vehicles and equipment with engines that spend little time above ~80% torque will not have a notable performance penalty. From the interviews we conducted with other PuriNOx users and testers, it is obvious that PuriNOx works well for

[19] The NAAQS must be met by the 2007 attainment deadline. The actual reductions obtainable from PuriNOx use in 2007 are likely to be somewhat less than 66 tons due to the penetration of electronic engines into the fleet, although industry growth would temper this trend somewhat.

some fleets. Centrally fueled bus fleets and the Port of Houston's crane applications are two examples where PuriNOx seems very appropriate.

In summary, the major recommendations resulting from this study are:

- TxDOT should continue to take a leading role in decreasing emissions. Because maintaining this leading role involves use of public funds, cost-effectiveness should be a primary criterion in choosing between alternatives. In this regard, TxLED is a much more cost-effective strategy for reducing emissions from the TxDOT fleet than is PuriNOx.
- AGC should follow TxDOT's lead in using TxLED, for both its off-road and on-road equipment. If TxDOT specifies the use of TxLED by its contractors, they will not be eligible for TERP rebates. TxDOT should consider the costs of a requirement that its contractors use TxLED.
- Both TxDOT and AGC should begin using TxLED as soon as possible.
- AGC should not be required to use PuriNOx in absence of an in-depth study focused upon AGC operations, similar to the present study for TxDOT's Houston District.
- We encourage exploration of the use of PuriNOx in fleets that lack the characteristics that make TxDOT and AGC poor candidates for its use.

If it is decided that AGC must begin using PuriNOx, it is likely that TxDOT will continue using it as well. In this case, we recommend:

- Use protective clothing whenever there is a risk of skin contact with the liquid fuel.
- Take actions to minimize the possibility of inhaling fumes from the liquid (prudent practice for any liquid fuel).
- Take precautions to avoid breathing the exhaust.
- Use conventional diesel fuel (especially TxLED) rather than PuriNOx when ambient temperatures are so low that summer-grade PuriNOx cannot be used. This recommendation is based upon the 5 factors discussed above.
- Do not use PuriNOx in telescoping boom excavators or any other equipment that cannot maintain at least 45 mph when traveling on public roadways.
- Do not use PuriNOx in small utility engines. Because these are small engines, the NOx emissions rate is small and, therefore, the NOx benefit of using PuriNOx is smaller still. However, even if these engines are used regularly, the other costs of using PuriNOx are high relative to the NOx reduction. Therefore, the cost-effectiveness of using PuriNOx in these engines can be quite high, such as the >$11,000,000/ton for TxDOT's traffic alerting signals.
- Determine, on a case-by-case basis, which specific pieces of equipment cannot use PuriNOx because the torque loss is sufficiently severe that the required tasks cannot be performed.

Appendix A. Test Cycles

The test cycles developed for this project are discussed in this appendix. The development of these cycles is discussed in Appendix A.1. Where possible, these cycles are compared with those developed by EPA for similar equipment in Appendix A.2.

A.1. Cycle Development

The equipment selected for testing (and thus cycle development) is discussed in Subsection A.1.A. The methods used to log the data required for cycle development for the selected equipment are discussed in Subsection A.1.B. The analysis of these data and the final cycles that were generated are discussed in Subsection A.1.C.

A.1.A. Equipment Selection

The equipment selected for emissions and fuel consumption testing (and therefore cycle development) was based on TxDOT's records of fuel use in FY01 for 12 of Texas' 16 nonattainment counties (excluding the 3 county Galveston NAA and the 1 county El Paso NAA). The equipment falls into the 2 normal categories: on-road and off-road. The categories assigned are those designated by TxDOT, which may not always agree with EPA's.

In FY01, these 12 counties used 673,392 gallons of diesel fuel, of which 16% was used by off-road equipment. Off-road equipment consumes fuel while moving and also while stationary. Thus, the engines from off-road equipment must be tested on an engine dynamometer to capture the emissions and fuel consumption for all of their activities. Figure A.1.1 shows the fuel use by the TxDOT off-road equipment in the 12 nonattainment counties in FY01. Slightly more than 79% of the diesel fuel used by off-road equipment was consumed by 4 general types of equipment: 26% by telescoping boom excavators, 23% by "total" loaders (mostly wheeled loaders, but also some crawlers), 16% by motor graders, and 14% by "total" tractors (both pneumatic tired and crawlers, but not truck tractors, which are on-road). Because telescoping boom excavators consume more fuel than any other individual type of off-road equipment, they were selected for cycle development and testing.

At the kick-off meeting for this project, AGC noted that they do not use telescoping boom excavators. Instead, they use loaders for excavation. In response, and with funding from AGC, we developed the AGC Wheeled Loader Cycle, as discussed later in this section. Additionally, for the TxDOT cost-effectiveness analyses, we assumed that TxDOT's loaders behave like AGC's. As noted above, loaders consume the second most fuel among TxDOT's off-road equipment.

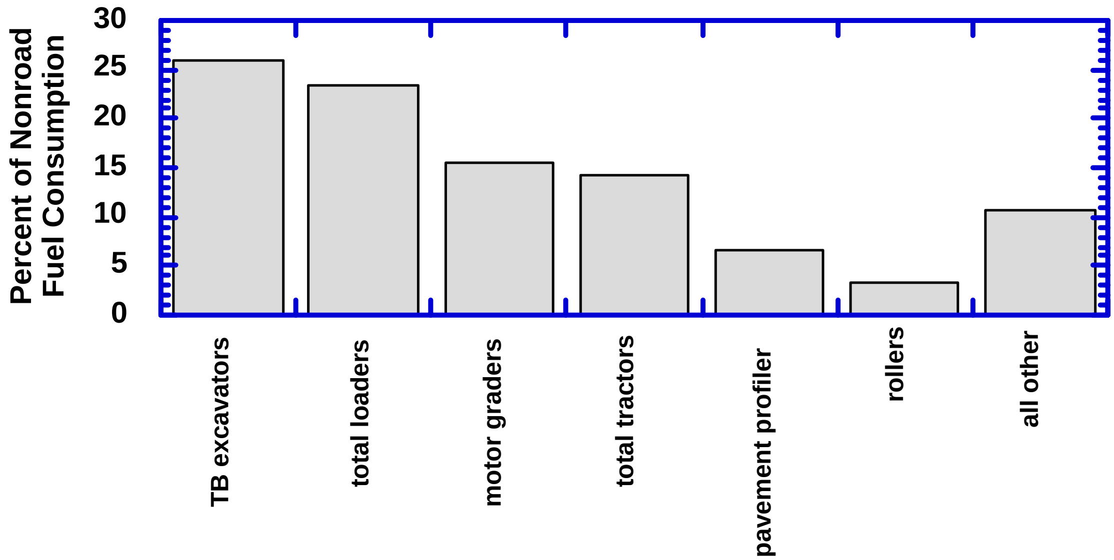


Figure A.1.1. Fuel consumption by TxDOT off-road equipment in Texas' 12 major nonattainment counties in FY01

Figure A.1.2 shows the fuel use by TxDOT's on-road equipment in Texas' 12 major nonattainment counties in FY01. Slightly more than 78% of the diesel fuel used by the on-road equipment was consumed by 4 general types of equipment: 24% by tandem-axle dump trucks, 19% by the combination of light-duty and medium-duty trucks, 18% by aerial personnel devices, and 17% by single-axle dump trucks. Because the light- and medium-duty trucks are different (but are difficult to separate in TxDOT's records) and because the aerial personnel devices (APCs) do some work while stationary, the single-axle and tandem-axle dump trucks were selected for testing and cycle development. Together, the single- and tandem-axle dump trucks consumed 41% of the diesel fuel used by TxDOT's on-road trucks in these 12 noinattainment counties in FY01.

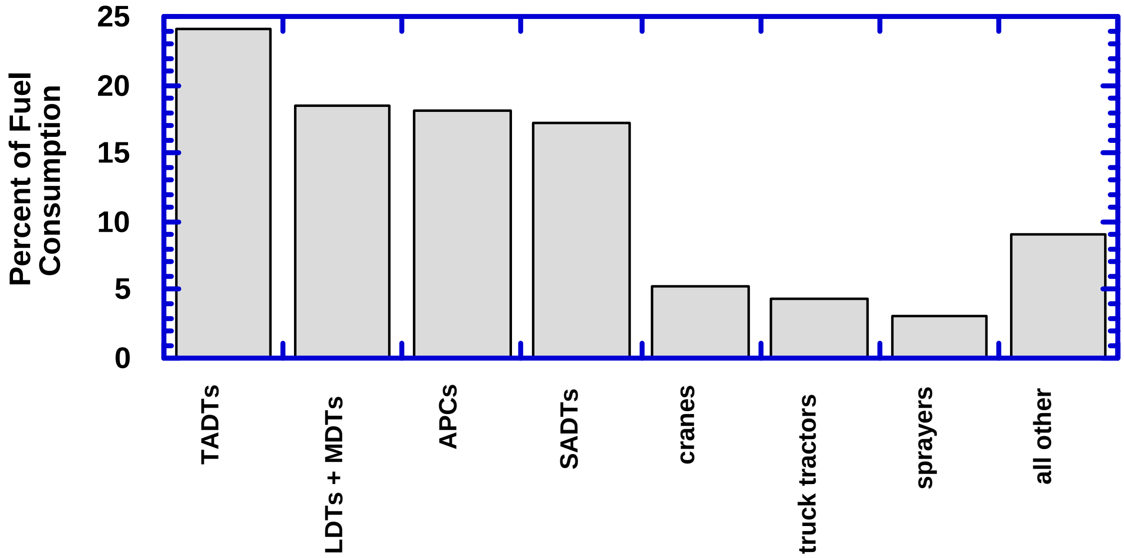


Figure A.1.2. Fuel consumption by TxDOT on-road equipment in Texas' 12 major nonattainment counties in FY01

A.1.B. Datalogging Methods to Acquire Vehicle and Engine Operating Data

Dataloggers were used in this project to log second-by-second vehicle and engine operating parameters on the vehicles that were involved in testing. Three types of datalogging systems were used during different phases of the project:

- the Autologger;
- the datalogger based on Cummins QuickCheck; and
- the datalogger based on Caterpillar Electronic Technician.

The Autologgers, which had been used in the 1992 EPA Federal Test Procedure revision project, were used to collect speed and RPM data on mechanically controlled diesel engines on selected Roadeo test vehicles. The Autologger was also modified to collect sound power level measurements during the chassis dynamometer tests at Southwest Research Institute (SwRI).

The QuickCheck-based datalogger was used to collect field data on TxDOT vehicles under normal TxDOT working conditions to generate TxDOT-specific dynamometer test cycles for single-axle dump truck chassis dynamometer testing, tandem-axle dump truck chassis dynamometer testing, and Gradall engine dynamometer testing. The QuickCheck datalogger was also used to collect data on TxDOT vehicles with electronic engines during the Roadeo tests. Finally, the QuickCheck datalogger was used to collect engine operating data on vehicles with electronic engines that were tested on chassis dynamometers at SwRI and on electronically controlled diesel engines that were tested on engine dynamometers at SwRI.

The Caterpillar datalogging system was used to instrument the Caterpillar 980G wheeled loader owned by Capital Aggregates for the purpose of developing an engine dynamometer test cycle specific to a loader as used by AGC.

Heavy-duty trucks and off-road vehicles with electronically controlled engines are typically equipped with a data port conforming to two SAE (Society of Automotive Engineers) protocols. SAE Standard J1708, "Serial Data Communications Between Microcomputer Systems in Heavy-Duty Vehicle Applications," describes the hardware level protocol for a low-speed, differential, multipoint data bus that is similar in some ways to the RS-232 serial protocol found on most computers. In addition, SAE Standard J1587, "Electronic Data Interchange Between Microcomputer Systems in Heavy-Duty Vehicle Applications," describes the content and formatting of data transmitted over the data bus.

Both Cummins and Caterpillar have adopted the SAE J1587/J1708 standards on most heavy-duty on-road vehicles and some off-road vehicles equipped with electronically controlled engines. Using these data ports, real-time engine and vehicle operating parameters such as engine speed (RPM), vehicle speed, and percent engine load are available. To collect this data, an SAE J1587/J1708 compliant datalogger was required. In addition to being SAE J1587/J1708 compliant, the datalogger needed to collect second-by-second data over a 1-week period with little or no operator input or servicing. Owing to the need to collect most of the data over a 2-week period, at least 6 dataloggers were required. Twelve dataloggers were used to support the Roadeo event.

No SAE J1587/J1708 datalogger was available at the time this study was conducted. However, engine manufacturers Cummins and Caterpillar both have SAE J1587/J1708 monitors (the Cummins QuickCheck and the Caterpillar Electronic Technician) that work with handheld computers using the Palm OS™. Neither product supports datalogging, but with the support of Cummins, which provided detailed technical information on the operation of the QuickCheck, the decision was made to write a custom datalogging application for the Palm handheld computer and QuickCheck monitor.

The QuickCheck Datalogging System

Datalogging Equipment – The Cummins QuickCheck product connects to the Palm handheld computer in the same fashion as modems and other communication adapters. The unit snaps onto the bottom of the handheld computer and communicates via the HotSync™ connector. A HandEra 330 handheld computer was used, because of the HandEra 330's support for the Compact Flash data storage that was needed to collect a full week of data without the need to service the unit. 64 MB Compact Flash cards were used.

The complete datalogger system consists of the HandEra 330 computer running the custom datalogging application, the Cummins QuickCheck, a 12 V, 7.2 amp per hour sealed-lead-acid (SLA) battery and a custom-made harness and voltage regulator to provide SLA power to the HandEra 330 and QuickCheck. The HandEra 330 accepts the external 12 VDC directly, but the QuickCheck requires about 3 VDC, which is typically supplied by 2 AAA batteries. Therefore, the 12 V battery voltage was regulated down to 3.3 VDC using an LM2937ET-3.3. This regulator is capable of supplying much more power than is required by the QuickCheck, but it was selected because its TO-220 package eliminated any need for a heatsink and because it was relatively easy to hand solder to the battery harness and mount to the case of the QuickCheck. The QuickCheck batteries are not used, and the SLA battery harness is soldered directly to the QuickCheck printed circuit board.

DataLogger Software – Custom datalogging software was generated for the HandEra 330 running the Palm OS. The software is written in C and was developed within the Metrowerks CodeWarrior™ integrated development environment (IDE). The shell for the datalogger software was generated by the CodeWarrior "wizard." The wizard creates the Palm OS compatible shell with an event loop as the starting point for the application. For the datalogger application, the event loop simply executes the code every 100 ms.

Logged data is stored on the Compact Flash in a file. A new file is created each time the application is run and is given a filename that contains the current date/time and a unique vehicle number. Each datalogger uses a different vehicle number so that data files can be identified by the filename if the datalogger vehicle number is recorded when the datalogger is installed on a vehicle. For example, the file "2-8-30@10-14-7V01.txt" was created by the datalogger with vehicle number V01 on August 30, 2002 (2-8-30) at 10:14:07AM (10-14-7).

When the datalogger application is first launched by tapping on the "DATALOGGER" con, it will display the following banner for a few seconds:

SAE J1587/1708 Datalogger
Emerald Electronic Design
August 2002

DATALOGGER RUNNING
Vehicle ID: V01

If the Compact Flash card is not installed or the serial port fails to open, the program will not continue, and the "DATALOGGER RUNNING" line will read "File create failed" or "Serial open failed." Otherwise, the program will then display several logged parameters as they are updated (see below). This display will be updated each second for the first minute and will then remain static with the 60th second's data. This permits initial verification of the connection and data collection process but does not require the continuous overhead associated with the display of data. The data is displayed in raw decimal units to minimize the software overhead needed to convert to engineering units; for example:

Status: 7000
ThrottlePos: 65535
RoadSpeed: 0
PcntAccelPos: 0
PcntEgnLoad: 5
OutputTorque: 65535
EgnCoolantTemp: 97
EgnSpeed: 3204

At the beginning of each 100 ms period, the software checks the serial buffer for any data that has arrived via the QuickCheck. All of the serial data present is then parsed using a finite-state-machine (FSM) to decode the SAE J1587 formatted packets. The FSM is implemented as a switch/case statement in function ReceivePacketData(). The FSM compares each engine parameter received using a lookup table to determine if the parameter is one that is being logged. If the parameter is being logged, it is copied to a buffer using an index from the lookup table. If a logged parameter is received more than once per second, the parameter in the buffer is overwritten so that the buffer always contains the most recent value of the parameter when it is recorded to the Compact Flash. Once per second the buffer of parameters is written to Compact Flash, and each location in the buffer is initialized to the default value of 65535.

The datalogging software writes a date/time stamp at the beginning of the data file and every 60 seconds while datalogging is occurring. If the parameter values for vehicle speed, percent engine load, engine coolant temperature, and engine RPM are not updated for 15 consecutive sampling intervals (i.e., 15 seconds) the data recording is suspended until 1 or more of these 4 parameter values are updated. The message "Engine off, log disabled" is written to the data file when data recording is suspended. Once data recording is resumed, a date/time stamp corresponding to the next data record is written to the data file. Therefore, 15 data records with invalid data will be recorded each time the engine is turned off.

The data is written to the file as ASCII formatted decimals without conversion to engineering units. Each parameter value is separated by a comma (comma-delimited format), and each second of data is terminated by a CR-LF. Every 60 seconds a date/time stamp is written to the file on a separate line. The following is an example of 2 seconds of data with a date/time stamp in between.

```
7000,65535,102,159,50,65535,190,5684,65535,...,65535
2002-8-30@8-51-52V06
6000,65535,103,166,62,65535,190,5744,65535,...,65535
```

The 28 parameters that were logged are shown in Table A.1. The parameter selection is hard-coded into the program and can be changed only within the CodeWarrior IDE. They are written to the file in the order shown. On the vehicles used in the study, only the parameters with an asterisk were typically available. The status parameter was for debugging only.

Table A.1 Parameters Logged by the QuickCheck Datalogger

Parameter	PID No. (per SAE J1587)	Conversion Factor (LSB=Least Significant Bit)
Status	-	
TrottlePosition	51	
RoadSpeed*	84	1LSB=0.5MPH
PrcntAcclPosition1*	91	1LSB=0.4%
PrcntEngnLoad*	92	1LSB=0.5%
OutputTorque	93	
EgnCoolantTemp*	110	1LSB=1.0degF
EngineSpeed*	190	1LSB = 0.25RPM
VehicleAccel	383	
Axle1LiftPressure	7	
PrcntAcclPosition3	28	
PrcntAcclPosition2	29	
TrnsmssnPosition	31	
TrqLimitFactor	68	
PTOstatus	89	
WaterInFuel	97	
TurboSpeed	103	
PrcntEgnRetarder	122	
AvgFuelRate	133	
PTOengagementStatus	150	
TrnsmsnRangeSelected	162	
TrnsmsnRangeAttained	163	
EgnOilTemp*	175	1LSB=0.25degF
FrntAxleWght	178	
RearAxleWght	179	
CargoWght	181	
PTOSpeed	186	
PTOsetSpeed	187	
VehWghtChange	413	

Datalogger Installation – The loggers were placed in vehicles in a plastic container with 2 inches of foam surrounding the datalogger and batteries. On the dump trucks the logger was attached with tie-wraps to the rear cabin wall just behind the driver's seat, as is shown in Figure A.1.3. The data ports were located to the left of the steering columns under the dashboard. On the tandem-axle dump trucks the data port was a standard 6-pin Deutsch style connector that matched the connectors on the cables supplied with the Cummins QuickCheck, as is shown in Figure A.1.4. The cable was routed under the door threshold plate to prevent snagging or crushing the cable during normal vehicle operation.

Figure A.1.3 QuickCheck Datalogger installation location in dump truck

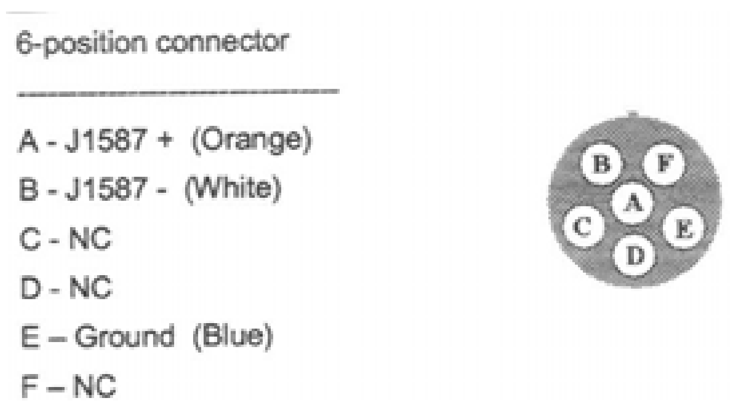


Figure A.1.4 6-Pin Deutsch connector (cable end view)

The single-axle dump trucks with Caterpillar engines had nonstandard 16-pin data port connectors supplied by Caterpillar. To make the connection to the QuickCheck, insulation displacement "T-taps" were clamped onto the wires at the back of the connector, and individual wires with small banana plugs were used to connect the wires to the 6-pin Deutsch style connector. The Caterpillar connector pin-out and its mapping onto the 6-pin Deutsch connector are shown in Table A.2. Figure A.1.5 shows the 16-pin connector and the 6-pin Deutsch connector in a typical wiring set-up.

Table A.2 Mapping from Caterpillar Connector to Deutsch Connector

Caterpillar 16-pin connector pin number	Signal	Wire color	6-pin Deutsch pin number
7	J1587+	WHT/BLK	A
15	J1587-	BRN/BLK	B
5	Ground	BLK/WHT	E
16	+12V	ORG	Not used

Figure A.1.5 Typical wiring of Deutsch and Caterpillar connectors

On the Gradalls the logger was placed beneath the driver's seat in the forward cab. The drawer beneath the seat was removed. The 6-pin Deutsch connector is located on the bottom surface of the dash left of the steering column, as is shown in Figure A.1.6, and the cable was routed under the rubber floor mats.

Figure A.1.6 Typical wiring set-up in a Gradall

The data collected by the logger must be retrieved at least once per week, and the battery replaced or recharged. Data files can be transferred to the PC using any Compact Flash reader. Some digital cameras can be used for this purpose. After the data is transferred to a PC and archived, the data file should be erased on the Compact Flash card before it is used for additional data collection.

The Autologger Datalogging System

The Autologger was designed, built, tested, and used to collect data for the 1992 U.S. EPA Federal Test Procedure revision project. The datalogger was used to collect second-by-second operating data on approximately 400 privately owned vehicles in Spokane, Baltimore, and Atlanta (DeFries and Kishan, 1992). The Autologger was designed to collect second-by-second vehicle speed, RPM, and manifold absolute pressure data on light-duty gasoline engines. In this TxDOT project on diesel engines, the datalogger was used to collect speed data, RPM data, or sound pressure level data. The speed and RPM data were collected separately by 2 different dataloggers in this project.

The speed input on the datalogger counts pulses produced by a magnet on a rotating shaft inducing current in a magnet pick-up coil. The pulses correspond to the distance that the vehicle moves. When forklifts were instrumented in this project, the datalogger received 1 pulse for approximately every foot of distance traveled. For wheeled loaders, the datalogger received approximately 3 pulses for every foot that the loader moved.

The datalogger contains software that allows the datalogger to be calibrated after it is installed on a given vehicle so that the number of pulses can be used to measure the distance traveled. The datalogger uses the rate of the pulses to calculate the speed of the vehicle.

The Autologgers were designed also to measure the RPM of gasoline engines by acquiring a signal from the ignition coil. Because in this project we needed to know the RPM of diesel engines, which have no ignition coils, a different approach was used. We chose to measure second-by-second diesel engine speed by using the speed input of a separate datalogger. Accordingly, we attached a single magnet to a rotating pulley on each diesel engine that was to be instrumented. We fabricated a bracket to hold the magnetic induction pick-up coil approximately 0.375 inches away from the path of the magnet. The pulses produced by the magnet and inductive coil were calibrated on the speed channel of this second autologger by counting the number of pulses for a 1-minute period while the diesel engine idled. The RPM of the diesel engine was measured during this calibration period by a handheld photo-tachometer, which uses a light beam reflected from a piece of reflective tape attached to the vibration damper of the diesel engine.

This method was used to install 2 dataloggers on each loader and forklift in the Roadeo. Each of these vehicles had 1 datalogger to measure vehicle speed and 1 datalogger to measure RPM. At the end of the datalogging period the Autologgers were removed from the equipment, and the data was downloaded onto a PC for data analysis.

The Caterpillar Electronic Technician Datalogging System

We wanted to instrument a non-TxDOT off-road vehicle owned by an AGC member company to develop a test cycle that could be used to test the emissions effects of PuriNOx on an engine dynamometer. Capital Aggregates volunteered to let us instrument their new Caterpillar 980G loader for 1 week to collect typical operating data. This loader is used constantly to load dump trucks with aggregate.

Although this loader has an electronic engine, its data bus is not compatible with the Cummins QuickCheck. This vehicle uses the Caterpillar Cat DataLink data bus. We worked with Holt Cat, the local Caterpillar dealer in Austin, to instrument the loader. Holt Cat provided a PC that was running Caterpillar proprietary software called Electronic Technician. We purchased a Caterpillar 171-4400 Communications Adapter II to connect the loader's Cat DataLink bus to the PC. The Electronic Technician software understands the Communication Adaptor's protocol, and it also has datalogging capabilities. The auxiliary power outlet on the loader was used with a power inverter to power the PC.

Unfortunately, each time the PC started logging data, it crashed after 107 minutes. When it crashed, it corrupted the data that had already been collected. We found that Caterpillar could recover the corrupted files for us. Accordingly, we acquired one data file in the morning and one in the afternoon for a week and sent the files to Caterpillar for recovery. The resulting data files were analyzed in SAS to build a wheeled loader engine dynamometer test cycle.

<u>A.1.C. Analysis of Data for Cycle Generation</u> – The determination of the emission rates of different vehicle types as they are used by TxDOT or its contractors was made by testing engines or vehicles over dynamometer test cycles that were representative of typical vehicle operation. Separate test cycles were developed for single-axle dump trucks, tandem-axle dump trucks, telescoping boom excavators, and wheeled loaders. The collection of data used to build these cycles was made under conditions of normal in-use vehicle operation in the field. The following subsections describe the vehicles used to generate the data, the method used to characterize the operation of each vehicle type, and the designation of microtrips in preparation for cycle building.

Dump Truck Operating Data

Data analysis for the single-axle and tandem-axle dump trucks consisted of preprocessing the raw data collected from dataloggers attached to dump trucks in the field and designating microtrips. There were 2 single-axle dump trucks (#3489 and #3490) and 2 tandem-axle dump trucks (#3871 and #5577). Tables A.3 and A.4 give specific descriptions of these trucks. The data was collected with a QuickCheck datalogger during the weeks of August 12–16, 2002 and August 19–23, 2002. The exception is dump truck #3490, for which we have data only for August 13–16.

Table A.3 Single-Axle Dump Trucks for TxDOT Cycle Generation Data

TxDOT Designation	#14-3489-H	#14-3490-H
Vehicle Make	Chevrolet	Chevrolet
Vehicle Model Year	2001	2001
Vehicle model	C7500	C7500
Axle type	Single	Single
VIN	1GBM7H1CXYJ528451	1GBM7H2C41J500781
Gross vehicle weight rating	33,000 lb	33,000 lb
Engine Manufacturer	Caterpillar	Caterpillar
Engine Model Year	2000	2000
Engine model	3126B	3126B
Serial No.	8YL78498	
No. of cylinders	6	6
Displacement	7.2L	7.2L
No. of gears	6	6
Engine Family	YCPXH0442HRK	YCPXH0442HRK
Engine configuration	In-Line	In-Line
Max. advertised power	210 HP	210 HP
Rated speed	2400 RPM	2400 RPM
Low idle speed	800 RPM	800 RPM
Fuel rate @ max KW (mm-sq/stroke)	152	152
Odometer before test (mi)	25179.9	23847
Odometer after test (mi)	25523	23979.1
Datalogger serial number	V03	V04

Table A.4 Tandem-Axle Dump Trucks for TxDOT Cycle Generation Data

TxDOT Designation	#14-5577-F	#14-3871-G
Vehicle Make	Ford	Volvo
Vehicle Model Year	1995/1996	1997
Vehicle model	L9000	
Axle type	Tandem	Tandem
VIN	1FDYU90S1TVA03604	4VHJCAPE4VR858340
Gross vehicle weight rating	54,400 lb	54,400 lb
Engine Manufacturer	Caterpillar	Cummins
Engine Model Year	1995	1997
Engine model	3176	M11-310E+
Serial No.	9CK24760	34855917
Displacement	10.3L	10.8L
No. of gears	9	9
Engine Family	SCP629EZDARK	VCE661EJDARB
Max. advertised power	300 HP	310 HP @ 1800 RPM
Rated speed	1800 RPM	
Low idle speed	700 RPM	600-800 RPM
Fuel rate @ max KW (mm-sq/stroke)	162	
Peak torque		1150 ft-lb @ 1200 RPM
Odometer before test (mi)		70492.8
Odometer after test (mi)		70975
Datalogger serial number	V02	V01

The raw data output from the datalogger consisted of text files that were first converted to a SAS dataset for further processing. Because the datalogger assigned a date and time stamp only once every minute, we assigned a date and time stamp to each second-by-second observation. We also removed blank data from the end of each trip to account for the fact that the datalogger continued recording data for approximately 15 seconds after the dump truck engine was turned off. The raw data was then transformed from datalogger units to engineering units using the following correction factors:

Speed (mph) = 0.5 * Datalogger Speed
Pedal Position (percent) = 0.4 * Datalogger Pedal Position
Load (percent) = 0.5 * Datalogger Load
RPM = 0.25 * Datalogger RPM
Oil Temperature (F) = 0.25 * Datalogger Oil Temperature

The transformed data reveals that the daily routine of the dump trucks involves speeds ranging from 0-65 miles per hour with an average around 15 miles per hour and periods of idle. Engine loads and accelerator positions range from 0-100% with averages around 15-20%. The drivers probably accelerated at close to 100% pedal position when starting from zero speed on the highway, but were able to let off of the accelerator once they achieved a cruising speed. Looking at the raw data, we realized that we could assign a gear position for each second by using the ratio of speed to rpm. Table A.5 gives the ratio ranges used.

Table A.5 Vehicle Speed/RPM Ratio Tolerances for Dump Truck Gear Assignments

	Truck #5577		**Truck #3871**		**Truck #3489**		**Truck #3490**	
Gear	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**
1	0.00215	0.00285	0.002	0.00325	0.00225	0.00375	0.00255	0.0036
2	0.0038	0.0045	0.00325	0.00465	0.00475	0.00585	0.0048	0.00585
3	0.0053	0.006	0.00465	0.0065	0.0083	0.0093	0.0083	0.00935
4	0.00735	0.00805	0.007	0.0081	0.01365	0.0145	0.01355	0.0146
5	0.0101	0.0108	0.0096	0.0108	0.0206	0.0215	0.0207	0.0216
6	0.01415	0.01485	0.0137	0.0148	0.0286	0.0291	0.0285	0.0293
7	0.0193	0.02	0.0196	0.0206				
8	0.0264	0.0271	0.0268	0.02795				
9	0.0357	0.0364	0.0363	0.03725				

The primary activity of a dump truck is to transport material or equipment on a trailer. The purpose of developing a dump truck cycle was to characterize the performance of a dump truck using a new fuel while performing high load tasks. Therefore, we wanted to eliminate field data that represented typical low load situations from inclusion in the cycle development algorithm. The high-load situations were defined as time periods when the dump truck was traveling with a full bed or pulling a heavy trailer. While we knew the speed and the full and empty weights of the dump trucks, we did not know a dump truck's load during its daily activity while we were recording field data. This part of the data processing involved estimating periods of high or low loads and isolating these periods for cycle generation.

To estimate the weight of the dump truck at each second, we related the engine power directly to an increase in the vehicle's kinetic energy. In applying this relationship, we made the simplifying assumptions that the effects due to aerodynamic drag, rolling resistance, and grade are zero. The relative effective weight of the dump truck can then be calculated for each accelerating second of operation from the following equation:

Relative Effective Weight

$$= \frac{2 * \text{Torque} * \text{RPM}}{v_f^2 - v_i^2} * \frac{(32.17\ \text{ft}/\text{s}^2)\,(3600\ \text{s}/\text{hr})^2\ (2\pi\ \text{rad}/\text{rev})}{(5280\ \text{ft}/\text{mile})^2\,(60\ \text{s}/\text{min})}$$

where: Torque is in lb-ft
RPM is in rev/min, and
v_f and v_i are in mile/hr

v_i represents the speed at the current second and v_f represents the speed at the following second. The raw data included the vehicle speed and engine RPM, but we had to compute the torque using a rough approximation to the maximum achievable power curve for the dump trucks.

$$\text{Torque} = 500 \text{ lbft} * \% \text{ load} * \frac{\text{RPM}}{1400 \text{ rpm}},$$
$$\text{if RPM} < 1400 \text{ rpm}$$
$$= 500 \text{ lbft} * \% \text{ Load},$$
$$\text{if RPM} \geq 1400 \text{ rpm}$$

This relationship assumes that maximum torque for the engine is 500 lb-ft above 1,400 rpm, and it is proportional to RPM below 1,400 rpm. Also, we only calculated the relative effective weight for positive accelerations because the relative effective weight equation applies only to increases in kinetic energy.

In reality, the weight of a dump truck does not change substantially when it is in transit. Since a dump truck would have the opportunity to change cargo only at 0 or low speed, we chose a cutpoint of 10 miles per hour. The weight of the dump truck was estimated to be the average of its relative effective weight for time periods when it moved faster than 10 miles per hour. For example, whenever the data reported the dump truck as moving less than 10 miles per hour, we did not record a weight for the truck because the weight could be changing. When the dump truck reached a speed of 10 miles per hour we averaged its second by second relative effective weight until the speed fell below 10 miles per hour and assigned this as the weight of the truck throughout the same time period.

The last step in preprocessing the data was to divide the data into microtrips that could be input into the cycle generation algorithm and to eliminate the units that were considered low load. The microtrips were determined by vehicle speed alone. The beginning of a new microtrip was marked by a change in vehicle speed from non-0 to 0.

Each microtrip was designated as 1 of 4 types: high load, low load, idle, or non-idle. Microtrips that had average effective weights above the cutpoints in Table A.6 were designated as high load. Microtrips that had average effective weights below the cutpoints were designated as low load. Microtrips with all speeds at 0 mph were designated as idle. Microtrips with all speeds less than 10 mph but having at least 1 non-0 speed were designated as non-idle.

Table A.6 Cutpoints Used to Separate Low and High Effective Mass Dump Truck Observations

Truck No.	**Relative Effective Weight Cutpoint (lbs)**
3489	22500
3490	22000
3871	24700
5577	25000

The cutpoints in Table A.7 were determined by dividing the high load and low load microtrips approximately in half and attempting to avoid having average effective weight data points fall on the cutpoint value.

Once all of the microtrips were designated, only high load, idle, and non-idle microtrips were retained for consideration by the cycle development algorithm. Low load microtrips were deleted from consideration by the algorithm.

Gradall Operating Data

About 17 hours of second-by-second data was collected on a TxDOT telescoping boom excavator from August 14-23, 2002 with a QuickCheck datalogger. Table A.7 gives a description of the vehicle used.

Table A.7 Telescoping Boom Excavator for TxDOT Cycle Generation Data

Vehicle Description	Gradall TxDOT #9823
Engine Manufacturer	Cummins
Year	2000-2001
Engine No.	46048303
Vehicle model	XL 3100
Engine model	ISB-190
No. of cylinders	6
Displacement	5.9L
No. of gears	9
Engine configuration	INLINE
Max. advertised power	190 hp
Rated speed	2600 RPM

The data included the date, time, accelerator position, engine load, engine speed, coolant temperature, PTO status, and PTO speed setting. To convert these values to engineering units, we used the same factors as given above for the dump trucks.

The data shows that the Gradall is characterized by two modes of operation according to the 2 tasks it performs. The primary task of the Gradall is excavation, but these vehicles are generally driven from the TxDOT facility to the excavating site. For example, this Gradall was based in Taylor, Texas so the data includes sections of the Gradall driving to and from the site as well as periods of excavation. The driving and excavation modes of operation are quite distinct. The major differences that distinguish the 2 modes of operation are accelerator position, engine speed, and engine load. On-road driving is characterized by non-0 accelerator position, rapid changes in RPM and load during shifting, and slow changes in RPM and load during cruising. On the other hand, excavation is characterized by 0 accelerator position, engine RPM at either 800 rpm or 1,900 rpm, and rapid fluctuations in engine load between 0% and 80%. The difference in accelerator behavior clearly identifies the periods of driving and excavation in the data as shown in Figure A.1.7 for a single day of activity.

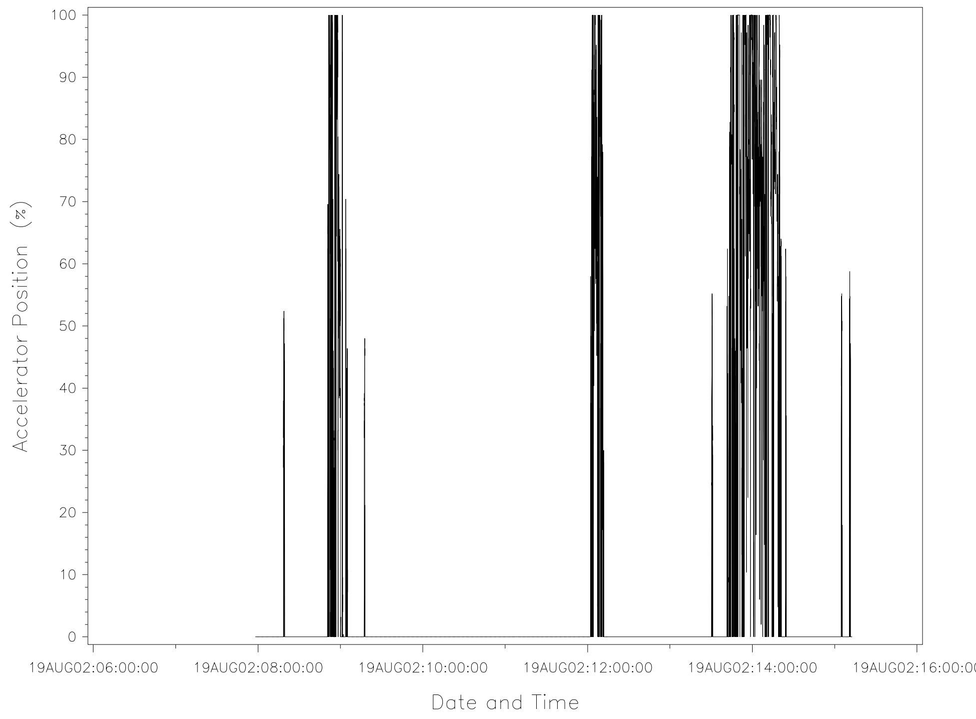


Figure A.1.7 Accelerator position for Gradall on August 19

From the data, we can also see that engine speed is not constant except at idle for on-road driving, but for excavation the engine speed is usually constant at either 800 rpm or 1,900 rpm. Figures A.1.8. and A.1.9 show portions of this typical RPM data for on-road driving and excavation, respectively.

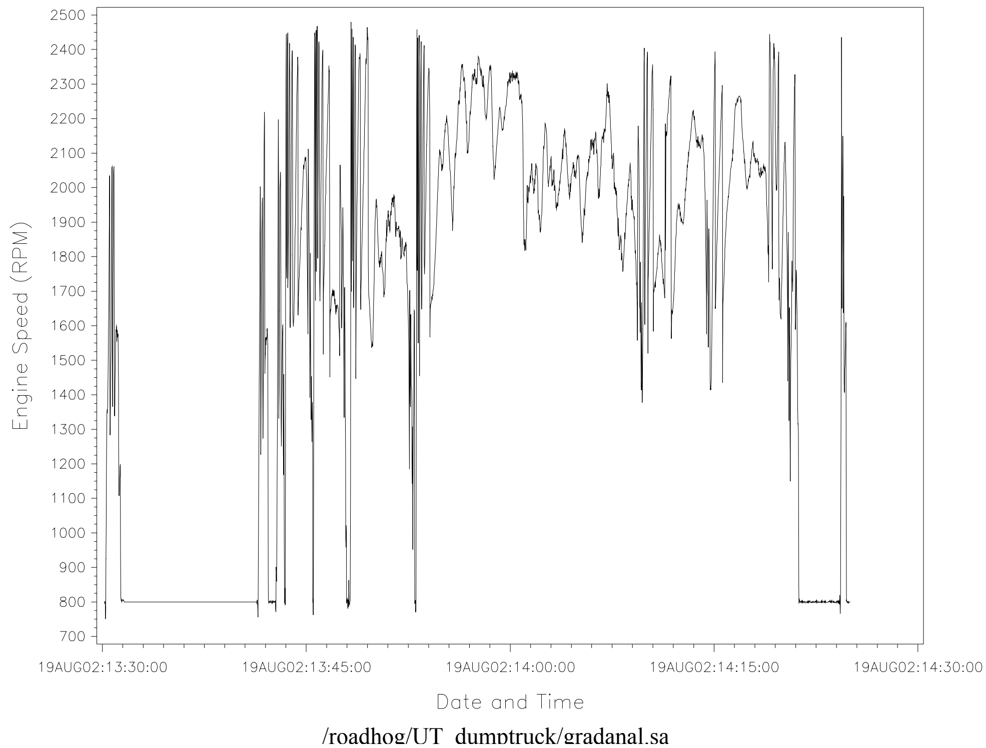


Figure A.1.8 Engine speed during driving on August 19

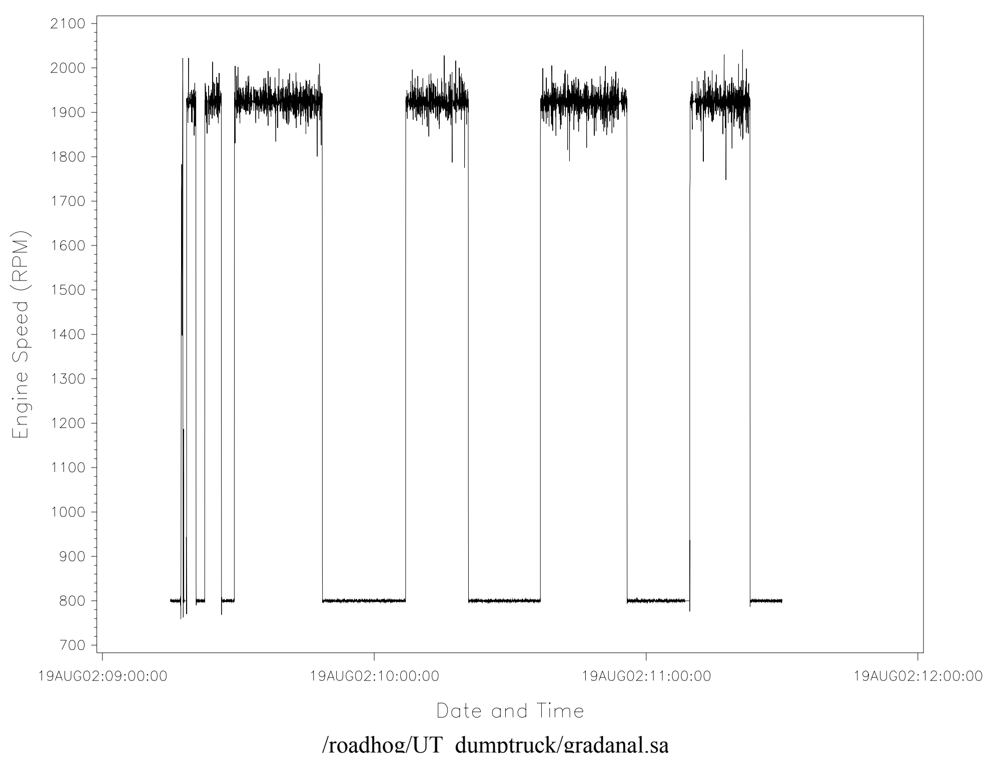


Figure A.1.9 Engine speed during excavating on August 19

As can be seen from Figure A.1.10, engine loads for on-road driving are frequently 100%. Figure A.1.11 shows that engine loads for excavation are either low when the engine is idling at 800 rpm or they vary rapidly between 0% and 80% for higher speeds around 1,900 rpm.

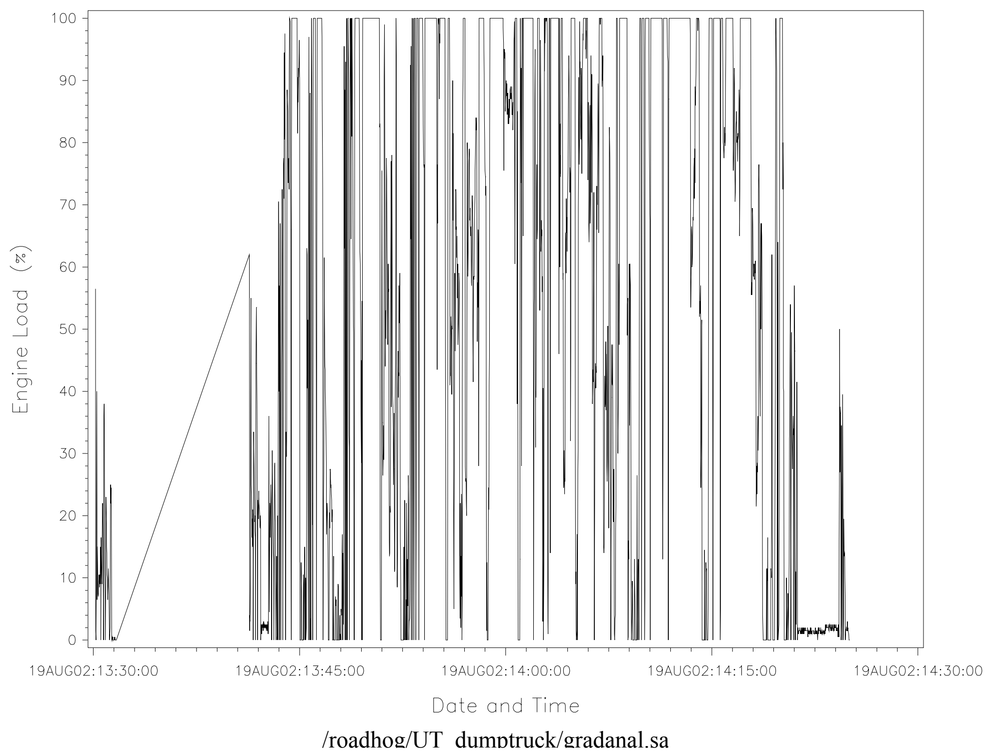


Figure A.1.10 Engine loads during driving on August 19

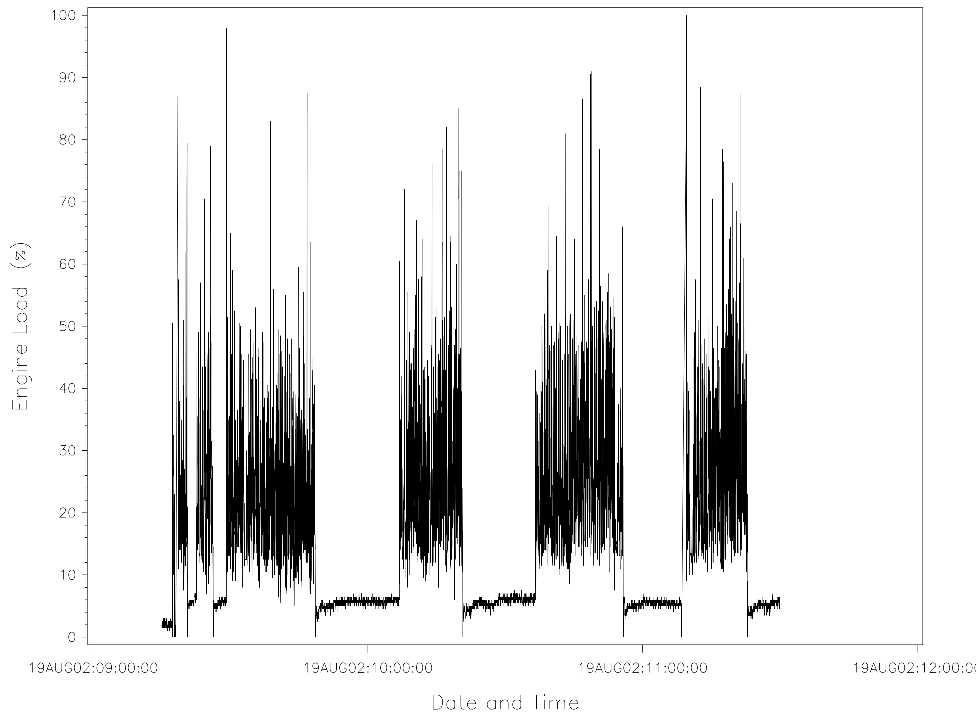


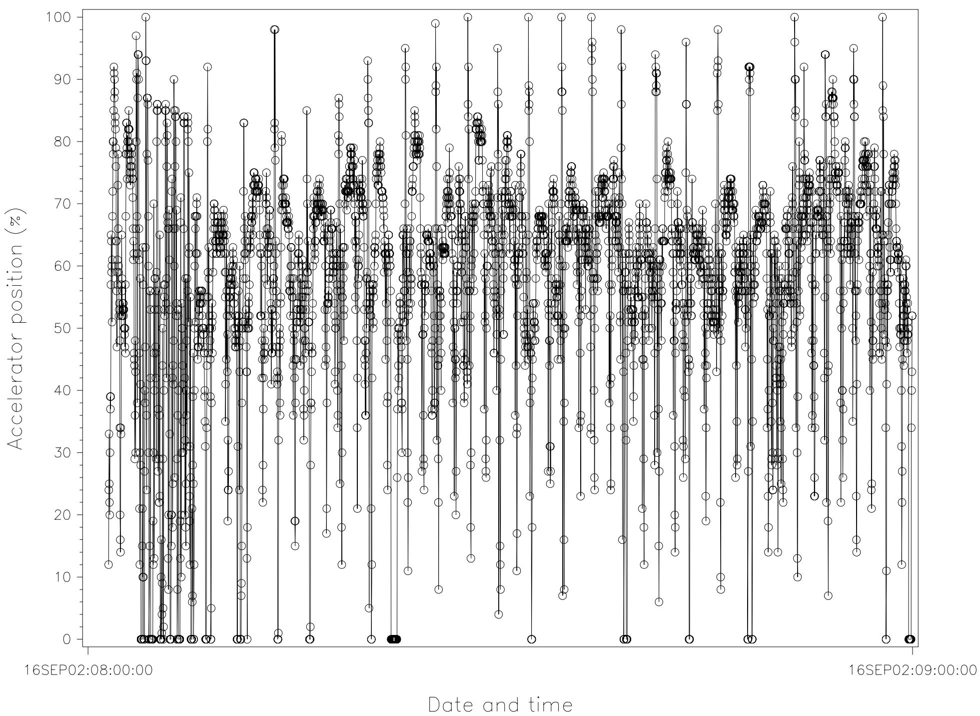
Figure A.1.11 Engine loads during excavating on August 19

It should be noted that Gradalls are underpowered for operation on the road. With a maximum speed of approximately 53 mph, accelerator position and engine load are consistently 100% when driving on the road. Unlike dump trucks, which see a reduction in these numbers at cruising speeds, Gradalls must maintain full throttle and load to maintain speed.

Preparation of the Gradall data for the cycle generation algorithm included converting engine load percentages to torque using the measured torque curve for the Cummins ISB-190 engine. We determined the idling periods by first flagging each second with 0% pedal position, with less than 12% engine load, and with RPM less than 850 RPM. We improved the result by hand and trimmed the idle periods to last no longer than 60 seconds. The entire dataset was divided into microtrips by assigning a new microtrip to every period beginning with an idle and ending with a non-idle. All Gradall microtrips were considered by the cycle generation algorithm.

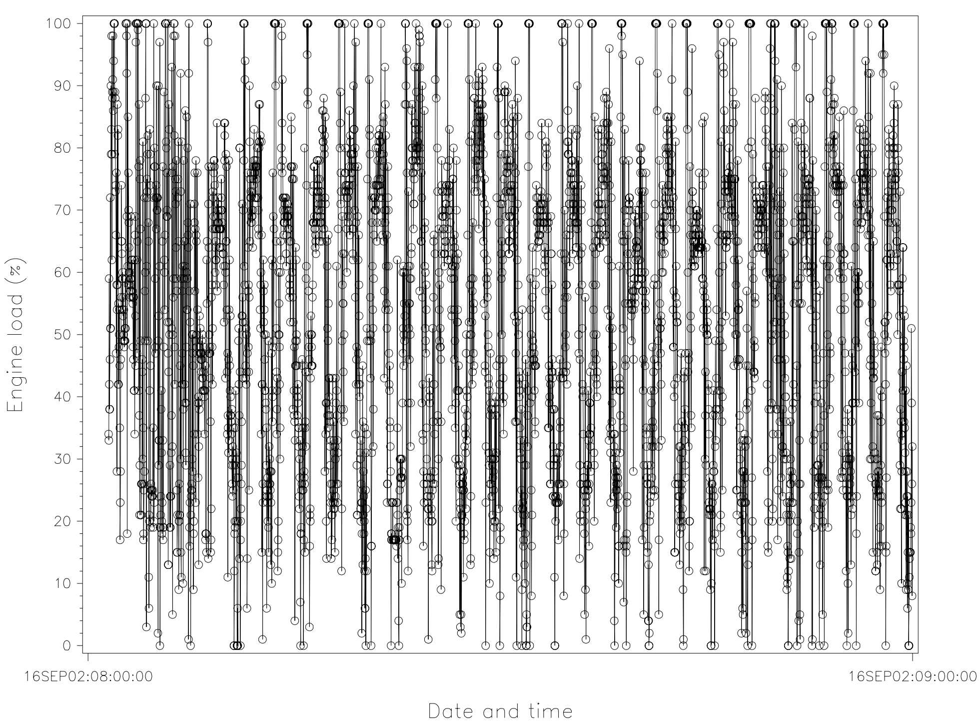
Wheeled Loader Operating Data

Field data was collected from a Caterpillar 980G loader owned by Capital Aggregates from September 16-20, 2002 with the Electronic Technician datalogger. The raw data was a text file downloaded from the datalogger and included the date, time, engine speed, throttle position, engine load, and fuel position. Because the primary task of a loader involves scooping material and moving it short distances to fill the bed of a dump truck, the structure of the data is rather random. Figures A.1.12, A.1.13, and A.1.14 exhibit this random structure as well as some particular characteristics of the data.



/roadhog/UT_dumptruck/capagg980g.sas &sysdate &systim

Figure A.1.12 Sample accelerator positions for the wheeled loader



/roadhog/UT_dumptruck/capagg980g.sas &sysdate &systim

Figure A.1.13 Sample engine loads for the wheeled loader

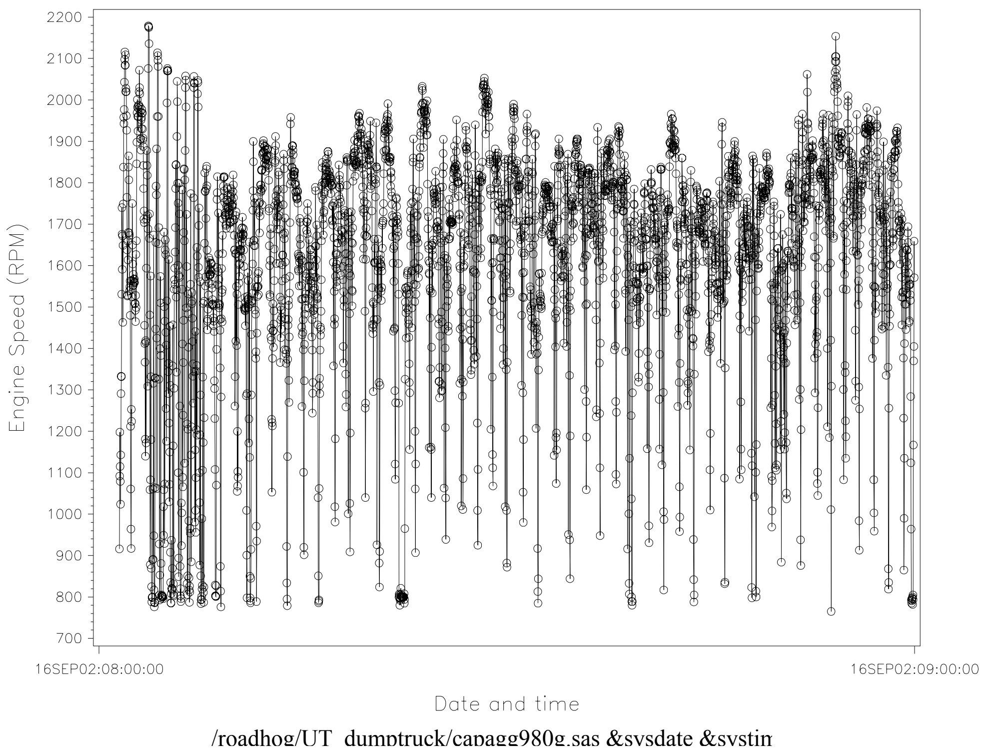


Figure A.1.14 Sample engine speed for the wheeled loader

The accelerator position generally ranges between 40% and 80% or is 0%, probably because the loader makes many stops and starts. The engine load ranges consistently from 0% to 100%, and the engine often idles around 900 RPM or ranges from 1,400 RPM to 1,900 RPM.

Similarly to the Gradall, we preprocessed loader data for the cycle generation algorithm by flagging idling periods and designating microtrips. During a first pass, we marked each second with RPM less than 900 RPM, 0% accelerator position, and engine load less than 30% as idle. We also designated seconds with engine speed less than 900 RPM and pedal position less than 6% to be idling seconds. Finally, we edited the data by hand to obtain the most accurate representation of the idling characteristics of the loader. Microtrips were designated as beginning with a new idling period and ending at the end of the following contiguous non-idle period. All of the microtrips were considered by the cycle generation algorithm.

Cycle Generation

The data collected in the field on TxDOT equipment were used to develop TxDOT specific test cycles:

- the TxDOT Single-Axle Dump Truck Cycle;
- the TxDOT Tandem-Axle Dump Truck Cycle; and
- the TxDOT Telescoping Boom Excavator Cycle

The data collected on the Caterpillar 980G loader at Capital Aggregates were used to develop a fourth test cycle:

- the AGC Wheeled Loader Cycle.

The test cycles were developed by using pieces (microtrips) of real vehicle or engine operating data from the vehicle operation datasets. The main objective of this task was to develop dynamometer test cycles lasting approximately 20 minutes that would be expected to have an emissions behavior similar to that produced by vehicles under normal use. The test cycles were built around vehicle and engine operating parameters known to be important to exhaust emissions.

Engine operation cycles were considered for the operation of the Gradall and loader because the engines of these vehicles would be tested on engine dynamometers. The final cycles were developed as second-by-second traces of engine torque versus time and engine RPM versus time. The key parameters considered during the development of the engine cycles were torque, RPM, and the change of the torque and RPM at each second of vehicle operation. These 4 parameters have been found to be necessary and sufficient to model the emissions behavior of heavy-duty diesel engines. The engine operation data were divided into small microtrips, which begin with an engine idle, include non-idle operation, and end just before the next engine idle. As mentioned before, these microtrips were the basic building blocks for the cycle. (This was done in the SAS program makemicrga.sas.)

Vehicle driving cycles were generated for the single- and tandem-axle dump trucks. The final driving cycle was developed as a second-by-second trace of vehicle speed versus time. The key parameters considered for the development of the driving cycle were vehicle speed, vehicle acceleration, and vehicle weight. The vehicle driving data was divided into microtrips, in which each microtrip was a contiguous speed trace of vehicle driving made up of an idle period followed by all non-idle driving until the next idle began.

A strategy based on a least squares comparison of 2 matrices was used to select microtrips for inclusion into the test cycle. Each microtrip was represented by a matrix whose dimensions were speed and acceleration for the vehicle cycle, and RPM, torque, change of RPM in a second, and change of torque in a second for the engine cycle. The matrix of the entire driving or engine operation dataset was used as the reference matrix. The continuous values for each of the selected variables were converted into a frequency distribution through the use of bins, where each observation from the dataset was placed in a particular bin based on upper and lower boundaries of the bins. The elements of the frequency distribution were the number of observations in each bin. The microtrips were represented by the microtrip frequency distribution matrix, M, and the entire database was represented by the target frequency distribution matrix, T. As the microtrips were sequentially selected to build up the test cycle, a new cycle frequency distribution matrix, C, was developed. In addition, the microtrip and the reference matrix included bins or elements, which represented the number of seconds of operation at each point in the multidimensional matrix. Before these matrices were compared they were converted to a cumulative form, where any (λ+1) bin included all the seconds of operation from 0 to λ. This was done in all dimensions of the 2 matrices and allowed us to include the proximity of bins in addition to specific location of the bin.

The goal of building the cycle was to select microtrips in such a way that when their frequencies are added together, the bins or elements of the resulting cycle frequency distribution, C, would be as similar as possible to the bins of the reference or target frequency distribution, T. Each element of the cycle frequency distribution, C, is the sum of the two selected microtrips, M1 and M2. The cycle frequency distribution was then compared to the target frequency, T, so that the difference between the elements of the 2 matrices is minimized. This was done by selecting microtrips that minimize the sum of squares of the cumulative frequency matrices, T and C, as given by

$$s^2 = \sum_{i}^{n} \left(Y_{T_i} - Y_{C_i} \right)^2$$

The final test cycle is made up of the microtrips selected from the target dataset. Each microtrip is considered in the development of the cycle distribution in order to minimize the difference in the sum of squares between the cycle matrix and the target matrix. The first microtrip was selected from the group of all microtrips. This microtrip represented the smallest sum of squares difference between the target and itself. A second microtrip is then added to the first microtrip so that the combined frequency distribution results in the smallest sum of squares among all remaining microtrips. This iterative process is continued until the duration of the cycle is about 20 minutes. Many iterations are tried to select the best set of microtrips to represent the cycle. After the microtrip matrices are selected to represent the cycle, the second-by-second vehicle or engine operation for those microtrips are extracted from the driving database to develop the final driving trace for the cycle. (This was done in a SAS program makecyclega.sas.)

The final test cycles of speed versus time for the single-axle and tandem-axle dump trucks are shown in Figures A.1.15 and A.1.16.

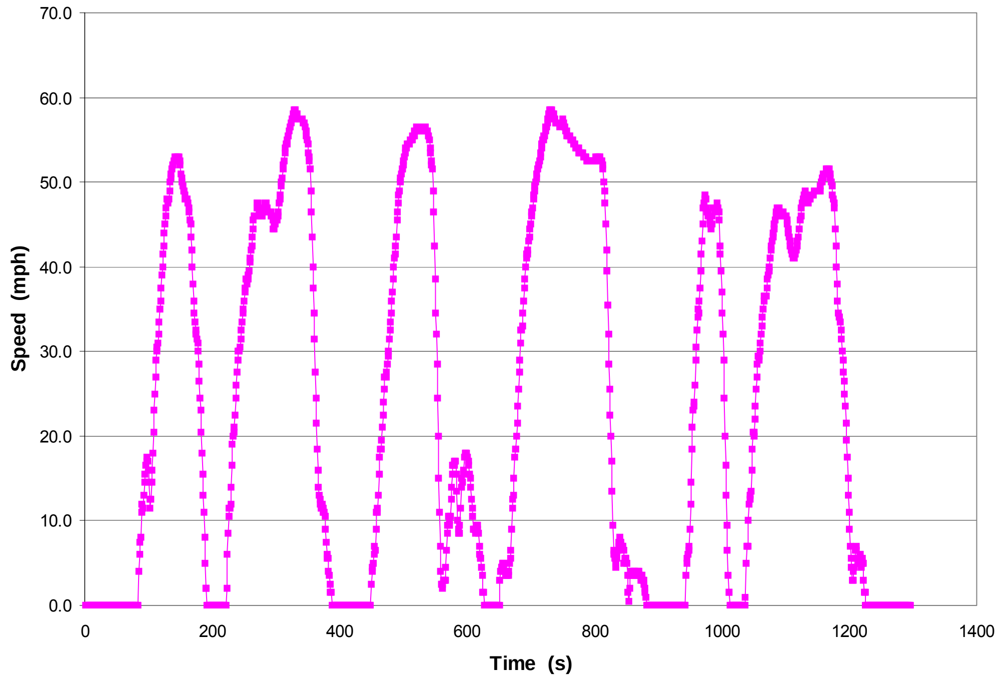


Figure A.1.15 TxDOT Single-Axle Dump Truck Test Cycle

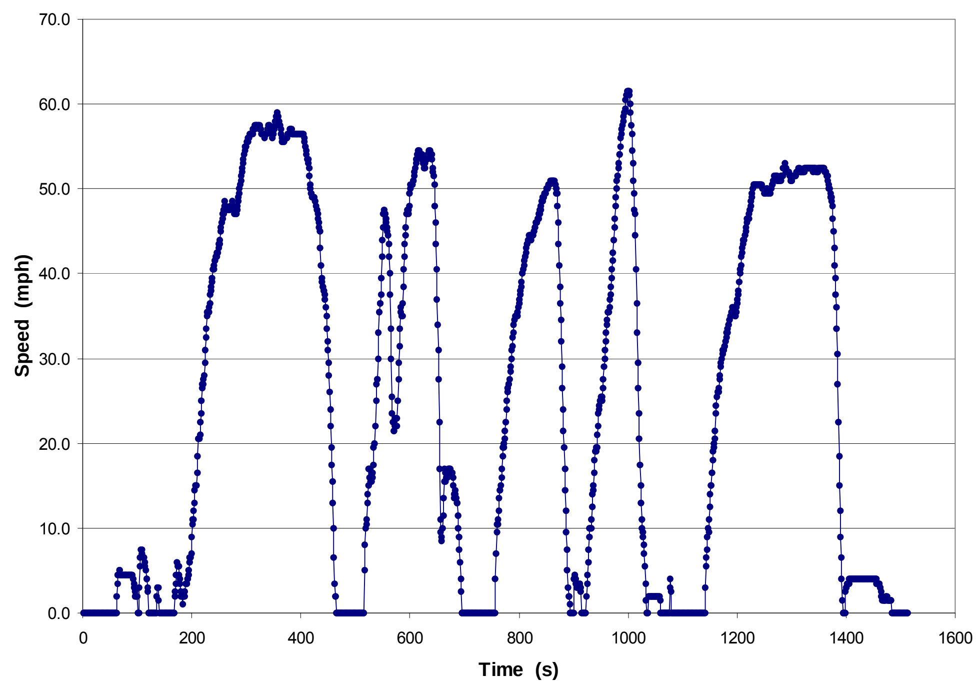


Figure A.1.16 TxDOT Tandem-Axle Dump Truck Test Cycle

The final test cycles of percent torque and percent RPM versus time, as is customary in EPA engine test cycles, for the wheeled loader and the telescoping boom excavator are shown in Figures A.1.17 and A.1.18. The percent torque uses 0% and 100% reference values that correspond to zero torque and the maximum engine torque at the corresponding RPM on the lug curve. The percent RPM uses 0% and 100% reference values that correspond to curb idle RPM and engine maximum RPM.

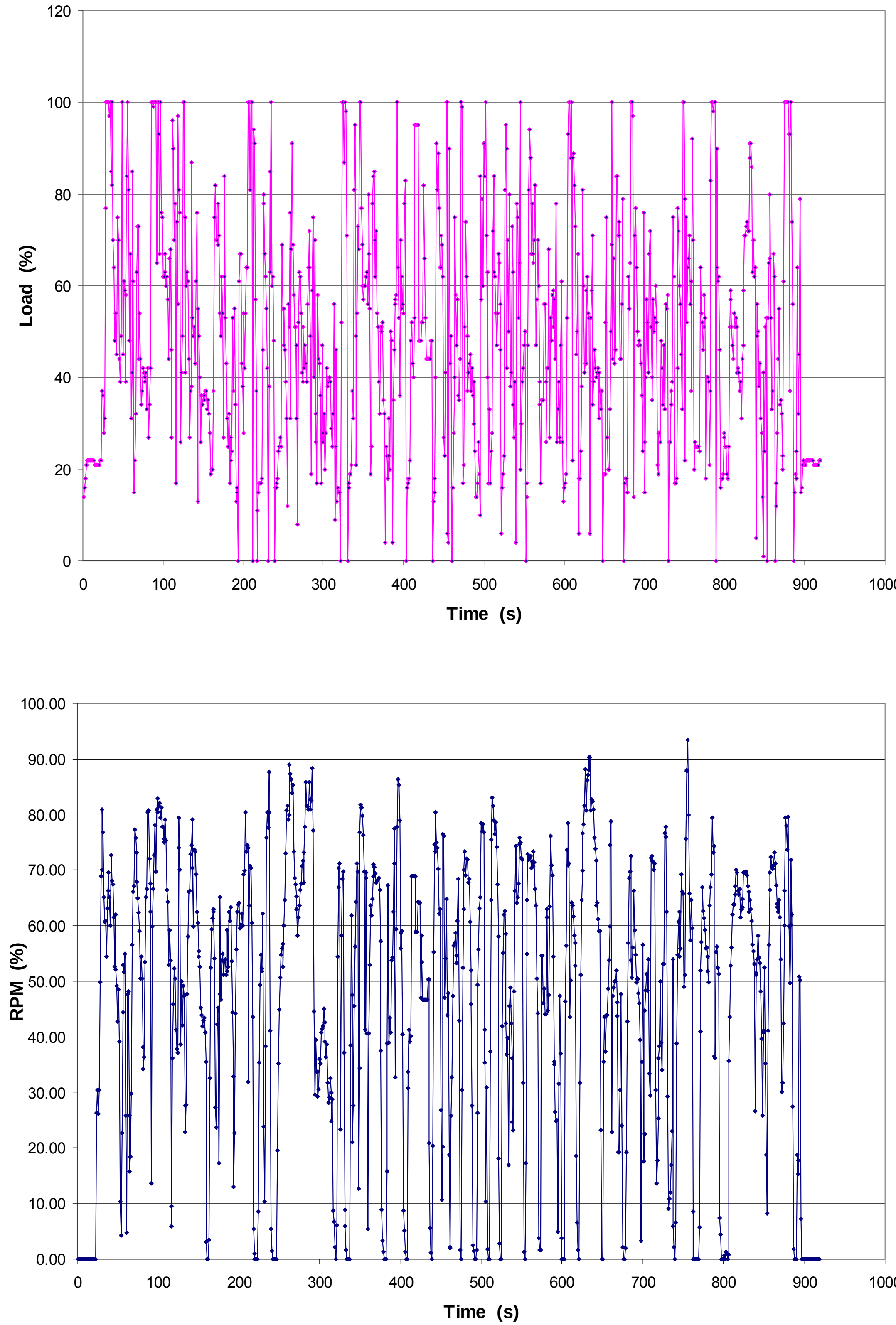


Figure A.1.17 AGC Wheeled Loader Test Cycle

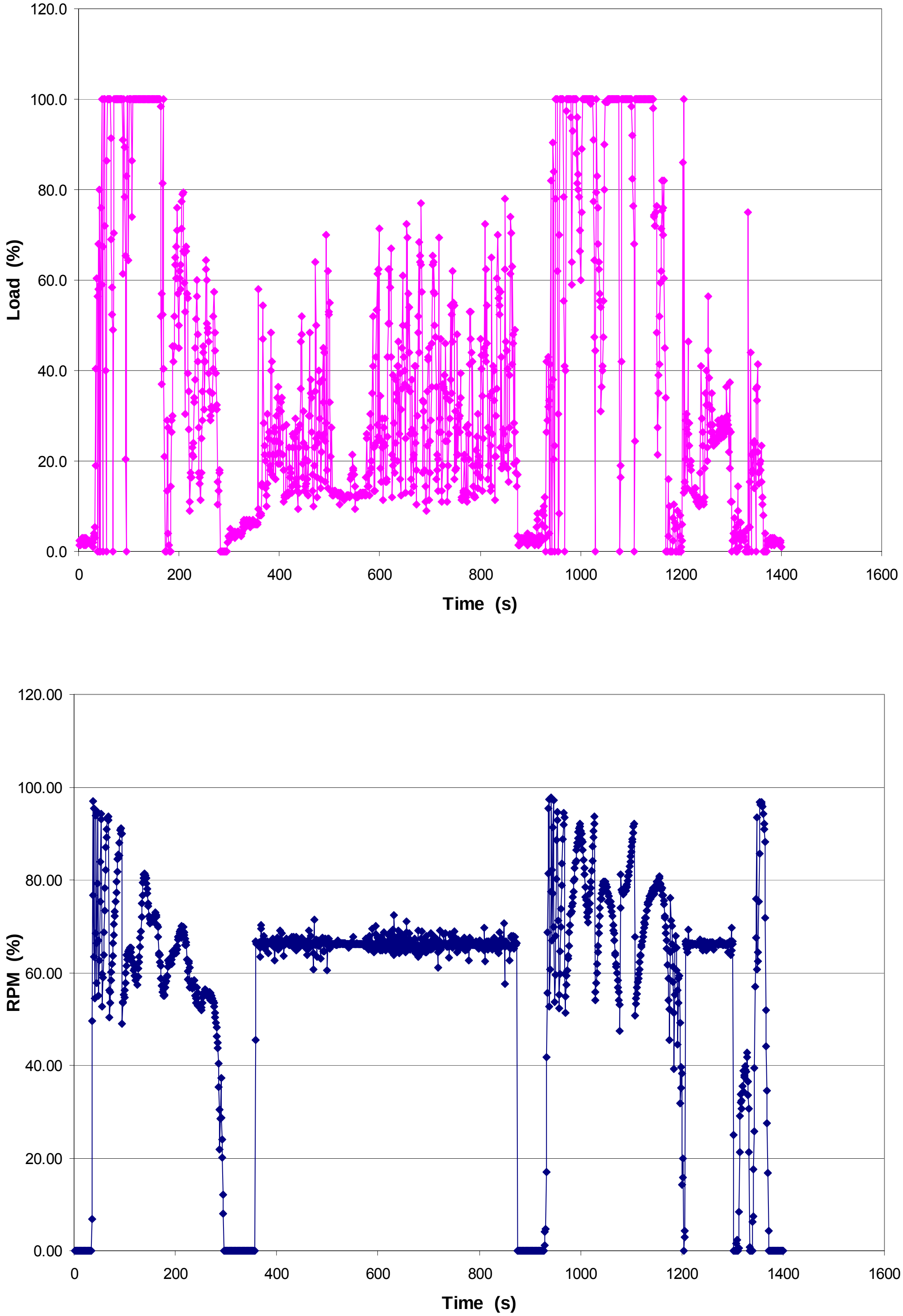


Figure A.1.18 TxDOT Telescoping Boom Excavator Cycle

Approaches to Application of Test Cycles

In the last section, test cycles that are representative of actual operating behaviors for the vehicles and engines under consideration were developed. In this section we describe how these cycles can be used to evaluate engines or fuels. In particular, if fuels used in engines lead to a reduction in power so that the engine cannot follow the cycle, we consider the options that can be used to apply the test cycles in these situations so that the emissions performance of fuels are compared on an equal basis.

Test cycles for single-axle dump trucks, tandem-axle dump trucks, loaders, and telescoping boom excavators were developed with considerable effort to make dynamometer testing as representative of operation in Texas as possible. While it is important that a test cycle represents the typical operation of the engine or vehicle, it is just as important that the fuels be tested on a cycle that represents the changes in machine use that will actually occur when the use of the new fuel is implemented. To represent the emissions effect of a department-wide switch to a new, low-emissions (and low-performance) fuel, chassis dynamometer or engine dynamometer tests need to apply test cycles in a manner that includes the requirement that a vehicle must go the same distance or that an engine must do the same amount of work as that which is achieved with the standard fuel.

Specifically, consider the case of the chassis dynamometer testing. Dump trucks need to operate from here to there; they must go a specific distance to do their jobs. If the new fuel produces such a loss of full load torque that the prescribed speeds on the trace cannot be achieved, the shortened distance of the achieved speed versus time profile translates into a situation in which the truck does not reach its destination. With new fuel usage, vehicles will not be able to accelerate as quickly, yet they must go the same distance. Failure to correct for this distance effect will bias the measured emissions in favor of a low-performance fuel.

In a similar manner, consider the case of engine dynamometer testing. The main job of off-road vehicles is to perform a certain amount of work. If the new fuel produces such a loss of power (torque*RPM) that the needed amount of work cannot be done in the usual amount of time, the machine will need to take a longer time to accomplish the assigned task. With new fuel usage, machines will not be able to get the work done as quickly, yet they must do the same amount of work. Failure to correct for this time effect will bias the measured emissions in favor of the low-performance fuel.

It is important to differentiate and measure the emissions effect of simple loss of performance owing to a fuel from the separate effect of fuel composition. Specifically, Lubrizol tells us that use of the new fuel will reduce high-load performance because the fuel contains 20% water. Available power is also reduced at low and medium loads, but because the operator can simply push the throttle further down to do the job required, operators can still get jobs done that require only low or medium loads. There may be emissions reductions at low and medium loads that are a consequence of the water in the fuel. However, emissions reductions at those portions of a test cycle that call for high loads depend on whether the high load is achieved or not, as well as the chemical effect of the water in the fuel. If we compare the emissions of the standard fuel, which can produce the highest loads demanded by the trace, with the emissions of the new fuel, which cannot achieve those loads, the measured emissions changes of the new fuel with respect to the standard fuel will be biased because the comparison is made on a different basis.

A hockey puck taped to the back of the accelerator pedal would also reduce peak power and emissions. We call this the hockey puck effect. One question is, how much lower are emissions when the new fuel is used than when the hockey puck and the standard fuel is used? If the emissions are the same, then TxDOT may as well equip every vehicle with a roll of duct tape and a hockey puck. This approach saves a lot of fuel distribution headaches.

On the other hand, we also need to answer a second question: How much will emissions actually be reduced when the fuel is changed from the standard fuel to a new fuel? The complication is that machine operation will change in response to engine performance changes. To answer this question, the test cycle needs to be adaptable.

Dump Truck Chassis Dyno Cycles – Traditional (U.S. EPA) chassis cycles (at least for light-duty vehicles) are speed versus time cycles. However, when vehicles are not able to achieve the required accelerations, the vehicles do not go the associated total cycle distance. This is a problem for the testing of dump trucks.

One solution is to use a speed versus distance cycle. This makes sense because it reflects how vehicles in the field would be used with both fuels. We can generate a test cycle that is typical of dump truck operation and express it as a speed versus distance trace. A portion of a hypothetical test cycle is shown in Figure A.1.19 by the solid curve. This trace represents driving from one stop sign to the next stop sign.

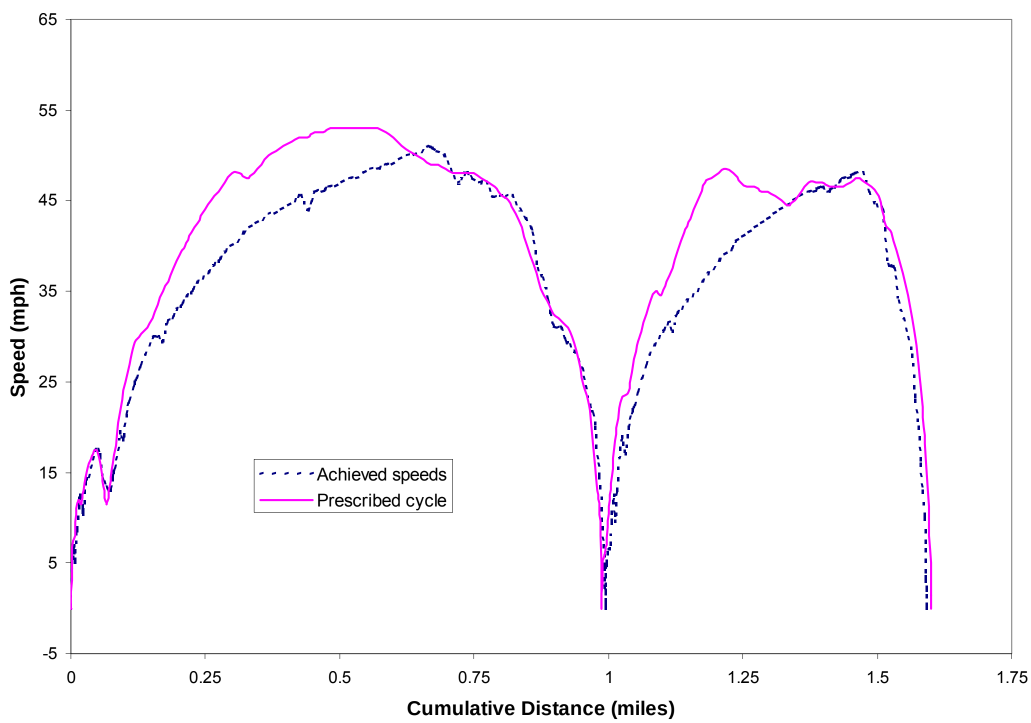


Figure A.1.19 Hypothetical distance-based test cycle

The first test ("Chassis 1" in Table A.8) would be with the standard fuel. It would follow the solid curve trace. The second test (Chassis 2) would be with the test fuel.

Because the vehicle will have lower peak power, it will not be able to accelerate as quickly but would ultimately be able to achieve the same cruise speed that the standard fuel provided. The test with the new fuel would have a trace similar to the dashed curve in the figure. Nevertheless, the distance cycle will require that the vehicle go the same distance. Of course, the vehicle with the test fuel will take longer to travel the prescribed distance.

The "results" of these tests (Chassis 1 and Chassis 2) are shown as the first 2 lines in Table A.8. Clearly, for Chassis 2 the NOx is lower, and the duration of the trip is longer. These results directly illustrate the effects of the new fuel versus the standard fuel when fuels are switched in the field. They show the emissions and duration trade-offs between the fuels, but they do not measure the effect of the new fuel on an equal operational basis. In other words, it is possible that simply taping a hockey puck under the accelerator might produce these effects on emissions and trip duration. How do we measure the emissions effect of the new fuel on an equal operational basis?

Table A.8 Hypothetical Dynamometer Truck Cycle Testing

Test	Fuel	Trace Achieved	NOx Result	Trace Duration
Chassis 1	Standard	Solid	100	17 minutes
Chassis 2	New	Dashed	60	20 minutes
Chassis 3	Standard	Dashed	70	20 minutes

If we perform a third test (Chassis 3) with the vehicle using the standard fuel following the dashed trace, which was achieved by the new fuel, we can compare emissions on an equal operational basis. The "results" for this test are also shown in Table A.8. If the emissions results for Chassis 3 are equal to the results for Chassis 2, then there is no need to use the new fuel — just issue hockey pucks! If Chassis 3 has higher emissions than Chassis 2, the new fuel is beneficial.

Using the Chassis 1 and Chassis 2 numbers in the table, it could be said that the benefit of the new fuel over the standard fuel is a NOx reduction of 40. However, because the duration of the trip increases, that statement would not be entirely appropriate. The Chassis 2 and Chassis 3 numbers indicate that after correcting for trip duration, the NOx reduction is only 10. Overall, to get a better measure of the benefits of the new fuel beyond the emissions reductions associated with loss of torque, all three tests need to be performed.

Off-Road Engine Dyno Cycles – When off-road machines in the field experience lower peak power with a new fuel, we expect that the operators will need to modify their approach to the job to get it done. For example, an excavator might need to take shallower cuts of the material. By doing this, the machine is performing approximately the same amount of total work for the job, but it takes longer to do the job. We saw above that for dump trucks the quantity that was crucial to do the job was the total distance traveled. Analogously, the quantity that is crucial for off-road vehicles to do the job is the total amount of work done.

Traditional engine cycles use dual curves of relative torque versus time and relative RPM versus time. The situation in which torque or RPM is not achievable when using the standard fuel is not encountered because the absolute torques and RPMs of the cycle are calculated from the maximum engine RPM and torque for standard fuel. However, when the fuel is changed, then the test will dictate absolute torque and/or RPM conditions that cannot be achieved with the new fuel. In these situations the engine will not be able to perform the amount of work required by the test cycle for each second of the cycle. Thus, when engines are not able to achieve the required torque/RPM conditions, the engines do not perform the same amount of total work. This is a problem for emissions testing the engines of off-road vehicles.

Just as for chassis dyno testing of dump trucks, the engines of off-road vehicles should be tested to determine (1) the trade-off between emissions and duration of a job as would occur in the field when the fuels are switched and (2) the emissions benefit of the new fuel over the standard fuel when the fuels are tested at the same operational conditions.

From a technical, fundamental point of view, the solution is to use a cycle made up of torque**cumulative work* and RPM**cumulative work* curves. This is analogous to the speed**distance* cycle for dump trucks. However, implementation of a versus-work trace may not be easily compatible with the engine dynamometer control system. Practical implementation of the approach is made in four steps:

- An Original cycle of torque*time and RPM*time cycle from the field operating data would be developed.
- A dyno test using the Original cycle would be made on the new fuel solely to determine those conditions under which the new fuel cannot achieve that high load torque required by the Original cycle.
- The achieved torque, RPM, and power achieved for that Original cycle test would be post-processed off line to derive a Derivative torque*time and RPM*time cycle that could be achieved by that fuel and would have the same torque*cumulative work and RPM*cumulative work curve as the designed cycle. Postprocessing would simply extend the duration of those portions of the Original cycle where the engine on the new fuel is at full load torque until the same total work is done.
- The Derivative cycle could be used in the test program where desired.

The first test ("Stand 1" in Table A.9) would be with the standard fuel. It would follow the Original cycle. The second test (Stand 2) would be with the test fuel using the Derivative cycle. Although the Stand 2 test will have a longer duration, the same amount of total work will be done as with Stand 1.

The "results" of these tests are shown as the first 2 lines in Table A.9. Clearly, the NOx is lower and the duration of the trip is longer for Stand 2. These results directly estimate the effects of the new fuel versus the standard fuel when fuels are switched in the field. They show the emissions and duration trade-offs between the fuels. But they do not measure the effect of the new fuel on an equal operational basis. In other words, it is possible that simply taping a hockey puck under the accelerator might produce these effects on emissions and job duration. How do we measure the emissions effect of the new fuel on an equal operational basis?

Table A.9 Hypothetical Off-Road Engine Dyno Cycle Testing

Test	Fuel	Cycle	NOx Result	Work Done	Trace Time
Stand 1	Standard	Original	100	10	10
Stand 2	New	Derivative	85	10	12
Stand 3	Standard	Derivative	90	10	12

If we perform a third test (Stand 3) with the engine following the Derivative cycle, we can compare emissions on an equal operational basis. The "results" for this test are also shown in the table. If the emissions results for Stand 3 are equal to the results for Stand 2, then there is no need to use the new fuel. If Stand 3 has higher emissions than Stand 2, the new fuel is beneficial.

Using the Stand 1 and Stand 2 numbers in the table, it could be said that the benefit of the new fuel over the standard fuel is a NOx reduction of 15. However, because the duration of the job increases, that statement would not be entirely appropriate. The Stand 2 and Stand 3 numbers indicate that after correcting for job duration, the NOx reduction is only 5. Overall, to get a better measure of the benefits of the new fuel beyond the emissions reductions associated with loss of peak power, all three tests need to be performed.

Another possible method is to attempt to test the engine with the new fuel on the Original cycle as shown in Table A.10. We call the achieved torque*time and RPM*time curves for this test the Not Original cycle because the engine using the new fuel would not be able to achieve the desired torque and/or RPM. Stand 5 would then be made by testing the engine with the standard fuel over the Not Original cycle achieved in the Stand 4 test. The Stands 4 and 5 tests will have the same duration as the Original cycle, but the full amount of work of the Original cycle will not have been done. Therefore, comparison of Stands 4 and 5 results with Stand 1 results reflects the trade-off between emissions reductions and work done. This method would compare the two fuels on the same basis but would result in less work being done, as compared with the intent of the original cycle with the original fuel. This would be an acceptable but a less desirable method than the method outlined in Table A.9.

Table A.10 Alternate Hypothetical Off-Road Engine Dyno Cycle Testing

Test	Fuel	Cycle	NOx Result	Work Done	Trace Time
Stand 1	Standard	Original	100	10	10
Stand 4	New	Not Original	78	8	10
Stand 5	Standard	Not Original	80	8	10

A.2. Comparison with EPA Cycles

Currently, the only available EPA cycles for off-road vehicles that coincide with the vehicles used in the TxDOT study are the telescoping boom excavator and the wheeled loader, dated August 29, 1999. We developed transient cycles for these 2 vehicles as well as for tandem- and single-axle dump trucks, but EPA cycles for the dump trucks were not available for comparison. Analysis of the TxDOT cycles can be found in the previous section; in this section we focus on a comparison with the EPA cycles.

EPA has 4 cycles available for wheeled loaders: a high-speed cycle, a high-torque cycle, and 2 cycles representing typical vehicle use. The major difference among the EPA cycles is that the typical cycles have significantly longer periods of idle. Figures A.2.1 to A.2.4 show engine load versus engine speed for the EPA cycles. Figure A.2.5 shows the same characteristics for the loader cycle developed in this project.

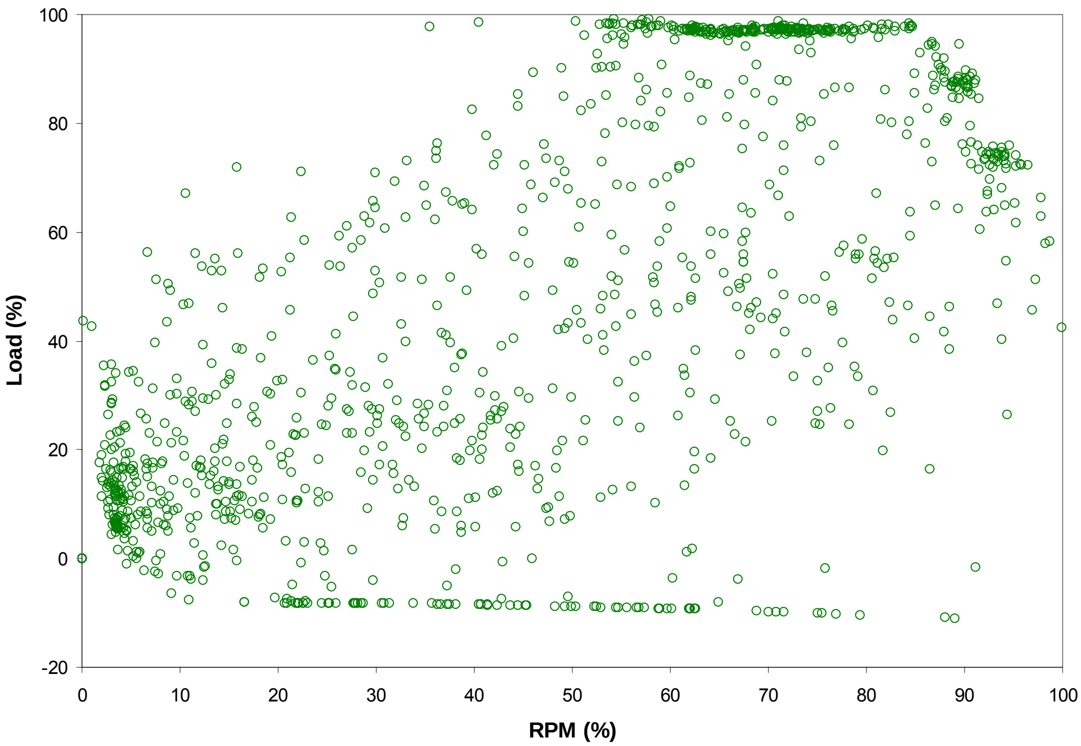


Figure A.2.1 EPA High-Speed Loader Cycle Characteristics

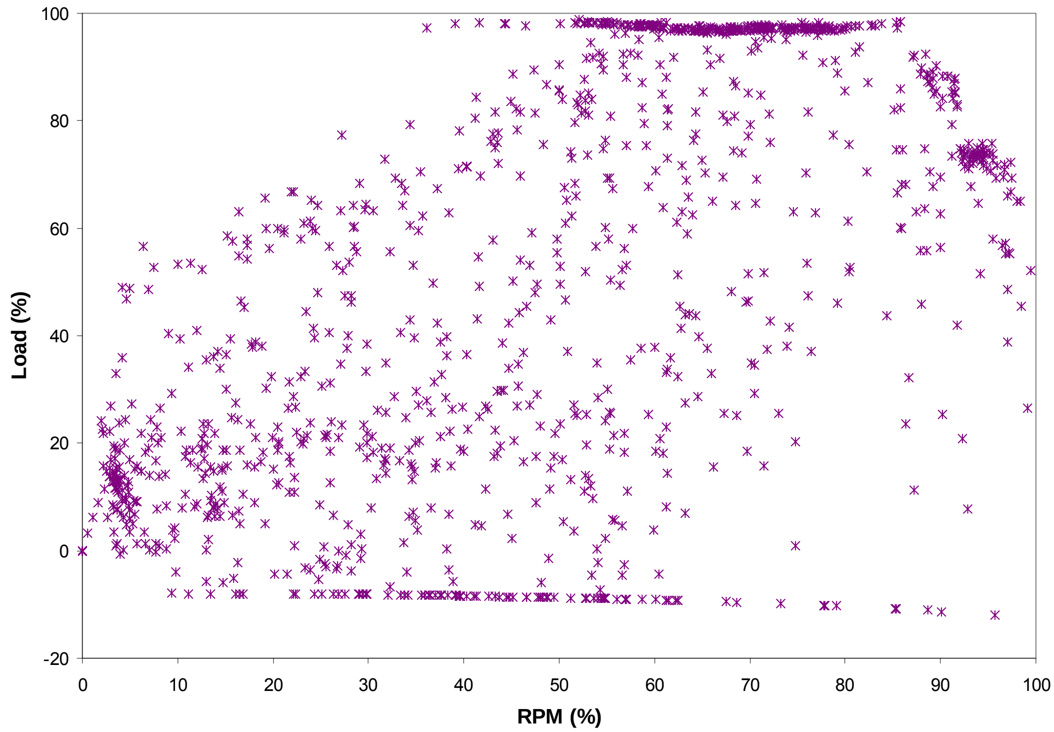


Figure A.2.2 EPA High-Torque Loader Cycle Characteristics

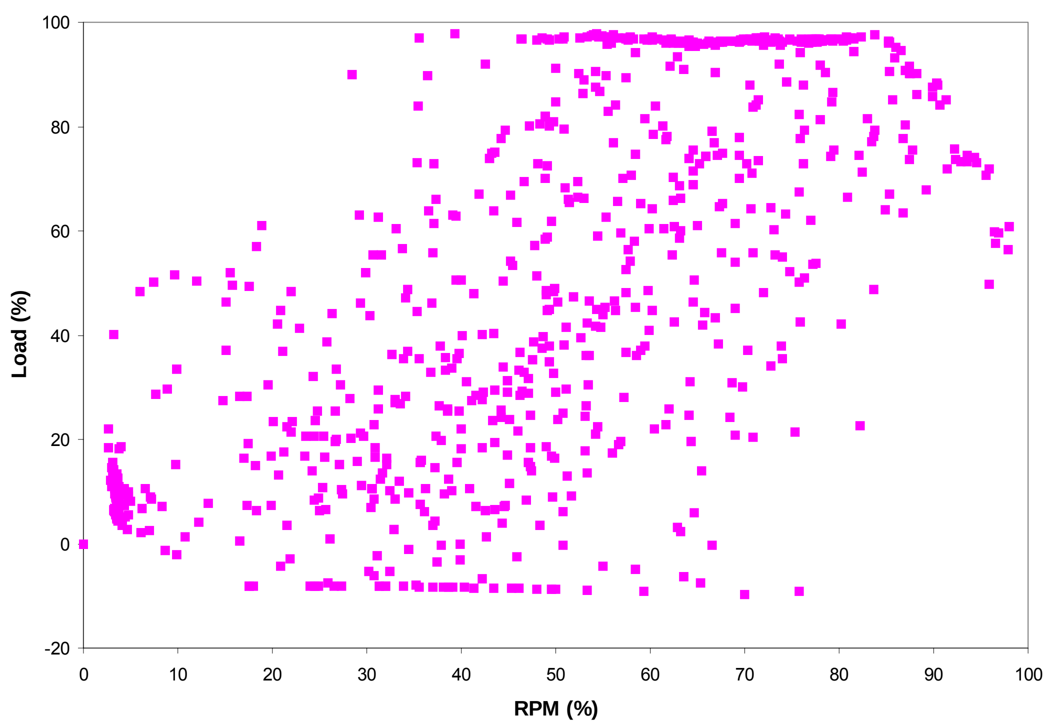


Figure A.2.3 EPA Typical 1 Loader Cycle Characteristics

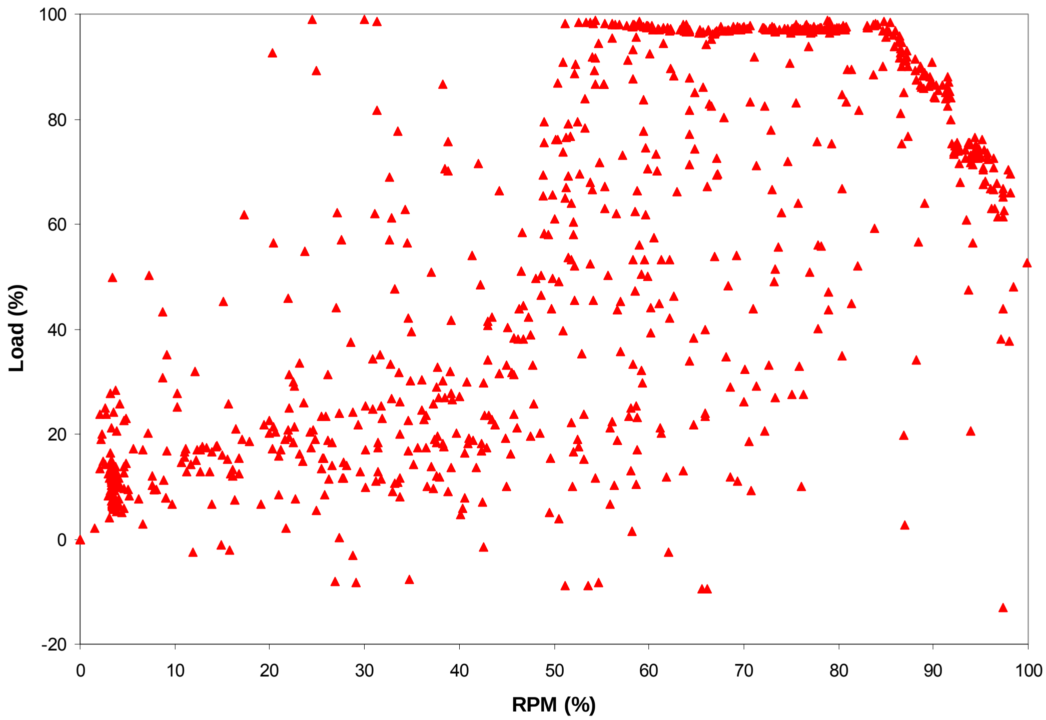


Figure A.2.4 EPA Typical 2 Loader Cycle Characteristics

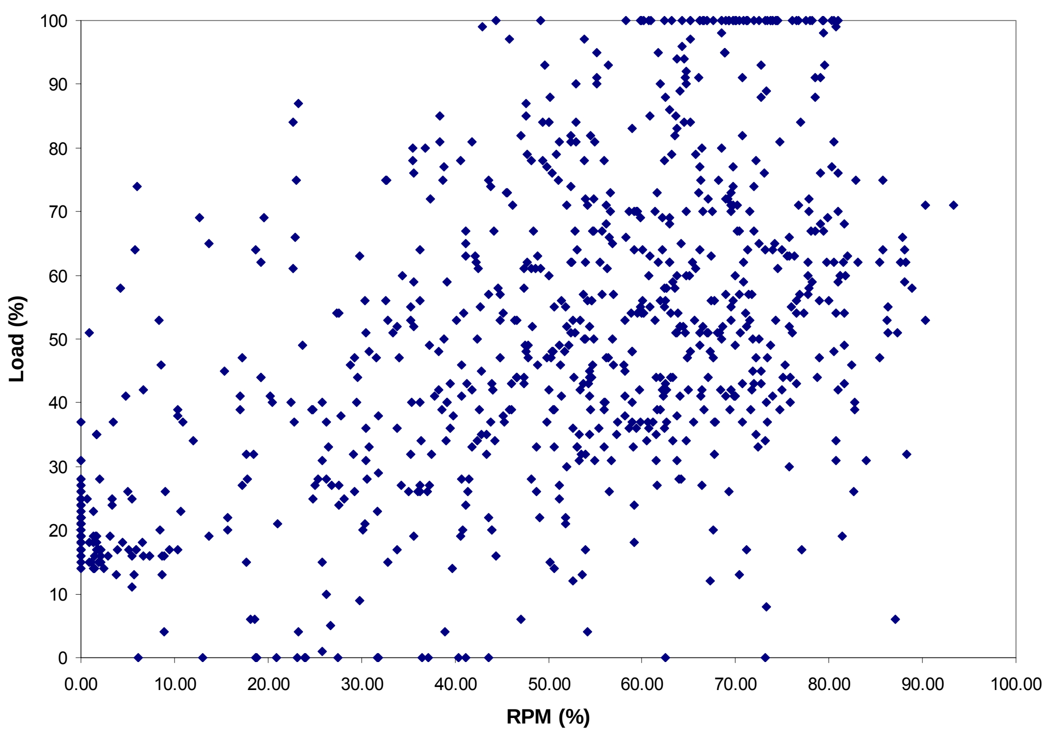
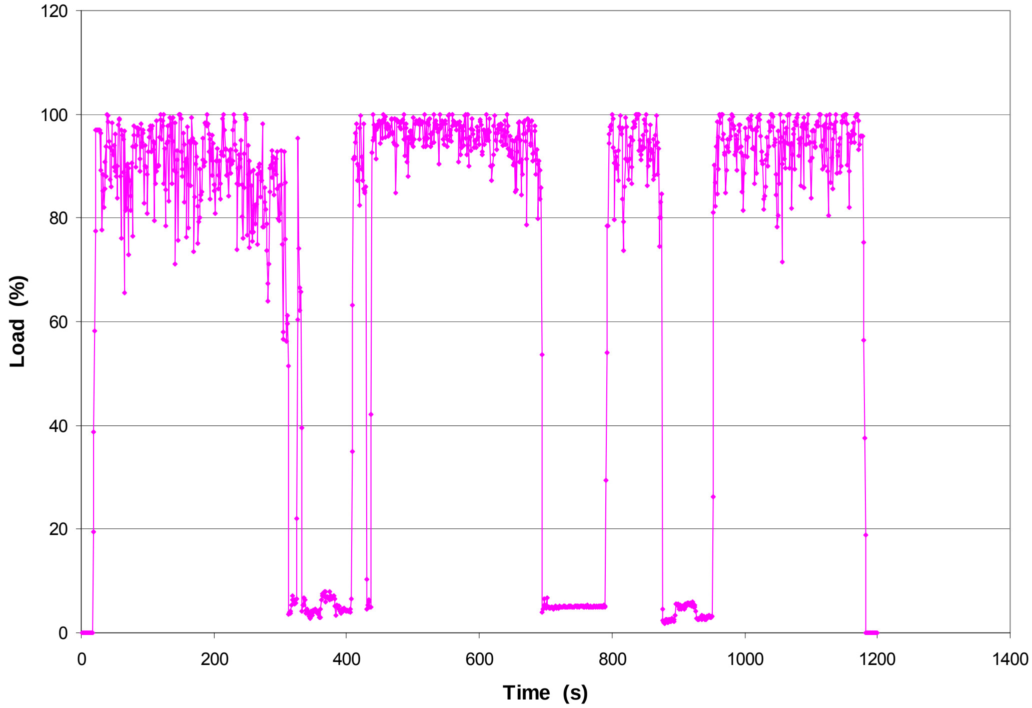


Figure A.2.5 AGC Loader Cycle Characteristics

In general, the structure of the AGC cycle is quite similar to that of the EPA cycles, but there are several differences that can be mentioned. Unlike the EPA cycles, the AGC cycle has periods of idle only at the beginning and end of the cycle. The AGC cycle is 919 seconds in duration, as compared with the 1,199-second-long EPA cycles. During the development of the loader cycle, we found that including additional microtrips did not significantly improve the representativeness of the cycle. The reason for this was that the job of the loader at Capital Aggregates was very repetitive. The loader repeatedly loaded dump trucks all day. The EPA cycles have larger percentages of high-RPM and high-load seconds (seen in the upper right corner of each figure) than the AGC cycle does. This may be an important difference, because high-load operation may be expected to produce high NOx emissions. Finally, the EPA cycles have instances of negative load indicating that the cycle development incorporated motoring, which could have been produced by downhill operation of the vehicles. The AGC cycle does not account for any motoring; the load remains non-negative.

Figure A.2.6 gives the RPM and engine load versus time for EPA's telescoping boom excavator cycle. As can be seen from the load versus RPM plot in Figure A.2.7, this cycle is very different from the cycle that we developed for TxDOT, which is shown in Figure A.1.10. However, there are several indications that the EPA data may be incorrect. We do not understand why the engine speed consistently rises above 100% or why the idle speed normalizes to approximately 45% rather than 0%. Possibly, EPA normalized the raw data with engine speeds that were not the maximum engine speed and curb idle speed. We contacted EPA for clarification, but we were unable to talk to the person who developed the cycle.



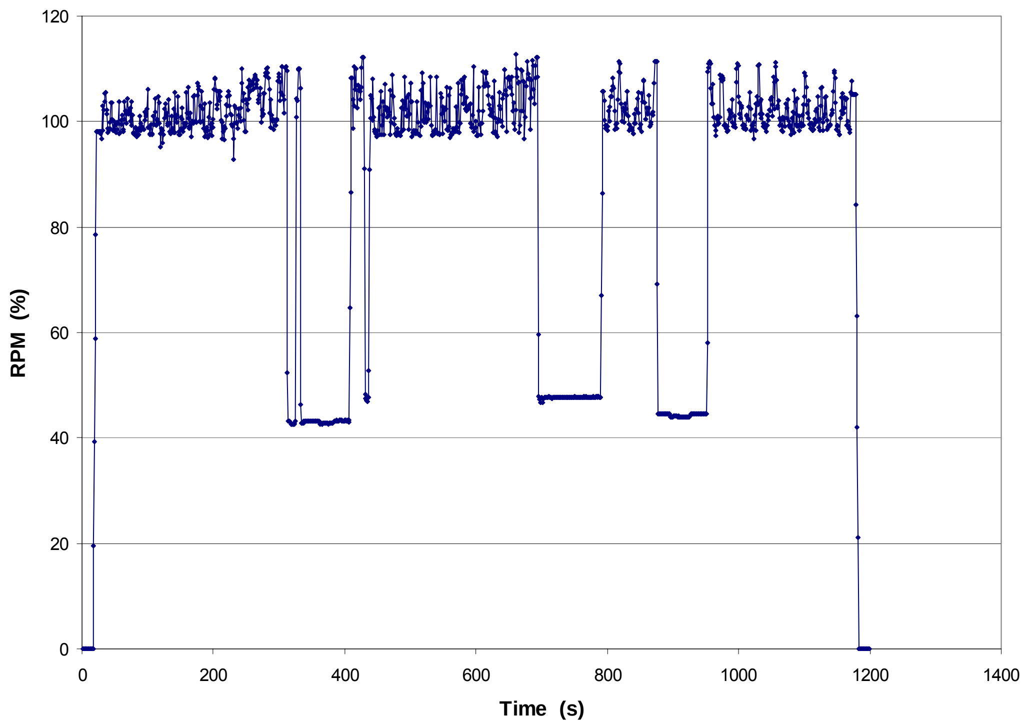


Figure A.2.6 EPA Telescoping Boom Excavator Cycle

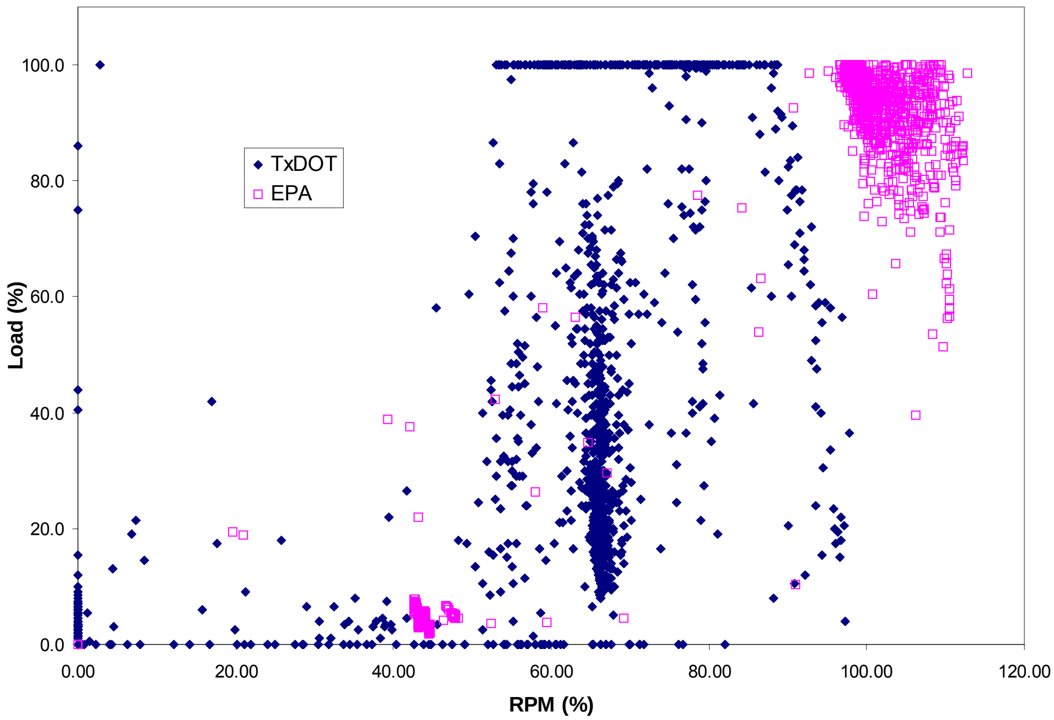


Figure A.2.7 Comparison of TxDOT and EPA Telescoping Boom Excavator Cycles

Appendix B. Emissions and Fuel Consumption

The emissions and fuel consumption for the engines evaluated in this project are discussed in this appendix. The results of tests over the Telescoping Boom Excavator Cycle are discussed in Section B.1, the Wheeled Loader Cycle tests are discussed in Section B.2, the Single-Axle Dump Truck Cycle tests are discussed in Section B.3, and the Tandem-Axle Dump Truck Cycle tests are discussed in Section B.4. These sections compare emissions and fuel consumption for PuriNOx relative to the baseline diesel fuel from which it was generated. Results for other fuels are compared in Section B.5. The results of tests of a small utility engine are discussed in Section B.6. Section B.7 presents the methodology used to account for emissions and fuel consumption penalties associated with the need to start the PuriNOx engines regularly when not otherwise needed.

In many of the figures presented in this appendix, comparisons are required between species that are emitted at significantly different rates. To allow all of these emissions (and, for some of the figures, the brake specific fuel consumption, BSFC) to be illustrated on the same scale, it was necessary to either multiply or divide one or more of the rates by some factor of 10. As an example of how to read these figures, in Figure B.1.1 for operation on 2D on-road diesel fuel, it is shown that PM*100 = 8.3 g/hp-hr. Thus, the PM emissions rate is 0.083 g/hp-hr (83 mg/hp-hr).

For the Telescoping Boom Excavator Cycle, SwRI performed measurements for one cold start cycle and two hot start cycles. For the two different dump truck cycles, SwRI performed measurements for one cold start cycle and four hot start cycles. The bar graphs presented for the regulated emissions are for the "composite" cycle:

Composite emissions = (1/7)*cold start emissions + (6/7)*hot start emissions (B.1)

where the weighting factors were taken from EPA's procedure for heavy-duty engines (diesel or gasoline). The average hot start emissions were used in Equation B.1 rather than the emissions from the first hot start to take advantage of the additional hot start tests. In general, only two hot start cycles were performed for the Wheeled Loader Cycle. The Wheeled Loader Cycle figures present the average for these two hot starts.

For one of the engines (the ISB 190 discussed in Sections B.1.A and B.2.A), the exhaust was speciated to acquire information about the composition of the hydrocarbon emissions. Specifically, the Clean Air Act Amendments of 1990 required EPA to perform a study to identify any "Hazardous Air Pollutants" (HAPs) that might be significant. The resulting EPA list of gas-phase "exhaust toxics" is composed of formaldehyde, acetaldehyde, 1,3-butadiene, and benzene. More recently, the California Air Resources Board generated a somewhat longer list of "Toxic Air Contaminants". These TACs are listed in Table 2.1. The TACs were measured for the ISB 190 operating over both the Telescoping Boom Excavator Cycle and the Wheeled Loader Cycle. SwRI estimates the typical repeatability of such measurements as +/- 40% but notes that the uncertainty approaches +/- 100% as the level approaches the limit of detection and/or the background concentration. The statistical significance of fuel-to-fuel differences in TAC emissions was evaluated for the present tests.

The composition of the particulate matter was also determined for these two cases, and is also discussed in this appendix. The PM is composed of agglomerates of carbon (from combustion of the fuel), a Soluble Organic Fraction (SOF, which is composed of unburned fuel vapor and lubricating oil that has condensed onto the solid PM), sulfates (from the sulfur in the fuel), and nitrates (from the nitrogen in the fuel). As noted in Section 1.B (Literature Review), all prior studies of emulsified diesel fuels have found PM benefits, with one exception (Henningsen, 1994). However, those studies that examined either the SOF or the Volatile Organic Fraction (which allows discrimination between the condensed oil and condensed fuel fractions) found increases in the condensed matter, especially lubricating oil. That is, although the total PM decreases with PuriNOx, it appears that this is dominated by a large decrease in carbonaceous material which more than offsets increases in condensed phases. The sulfates are of interest due to the potential for the water in the emulsified fuel to react with the fuel sulfur to form sulfuric acid, which should be captured on the particulate filter as a contributor to the sulfates. The prior studies that examined the sulfates had mixed results, with the sulfates decreasing by 40% when using PuriNOx (a macroemulsion) but increasing 100% for a 12% microemulsion. Although this difference in results may be due to the differences between macro- and microemulsions, it was of interest to examine sulfates in the present study. The PuriNOx additive package contains nitrates. It was of interest to determine the fate of these nitrates: whether or not they contribute to the nitrates in the PM.

One problem with conventional comparisons of PuriNOx and diesel fuel is that the torque loss resulting from the water in the emulsion affects the ability to stay on the prescribed cycle when using PuriNOx, as discussed in Appendix A.1. This affects emissions. For the dump trucks, which were tested on a chassis dynamometer, this problem was overcome via development of a new testing technique – the "route test" that is discussed in Section B.3. For now, it is sufficient to note that we ensured that the dump trucks went the same distance on both fuels. The off-road engines perform work without associated miles, so some means of comparison other than the route test technique was required. If, for example, an excavator is to be used to dig a hole of a prescribed size – such that it fills five dump trucks – it must perform this same amount of work using both fuels. Thus, for the tests over the TxDOT Telescoping Boom Excavator Cycle and the AGC Wheeled Loader Cycle, we attempted to ensure the same amount of work over the cycle, independent of the fuel.

B.1. Telescoping Boom Excavator Engines

Two engines were tested over the TxDOT Telescoping Boom Excavator Cycle at Southwest Research Institute. This cycle is described in Appendix A.1.C. The two engines were an electronically-controlled 2000 Cummins ISB-190 and a mechanically-controlled 1997 Cummins 6BTA5.9. The emissions and fuel consumption for each are discussed in the following two subsections.

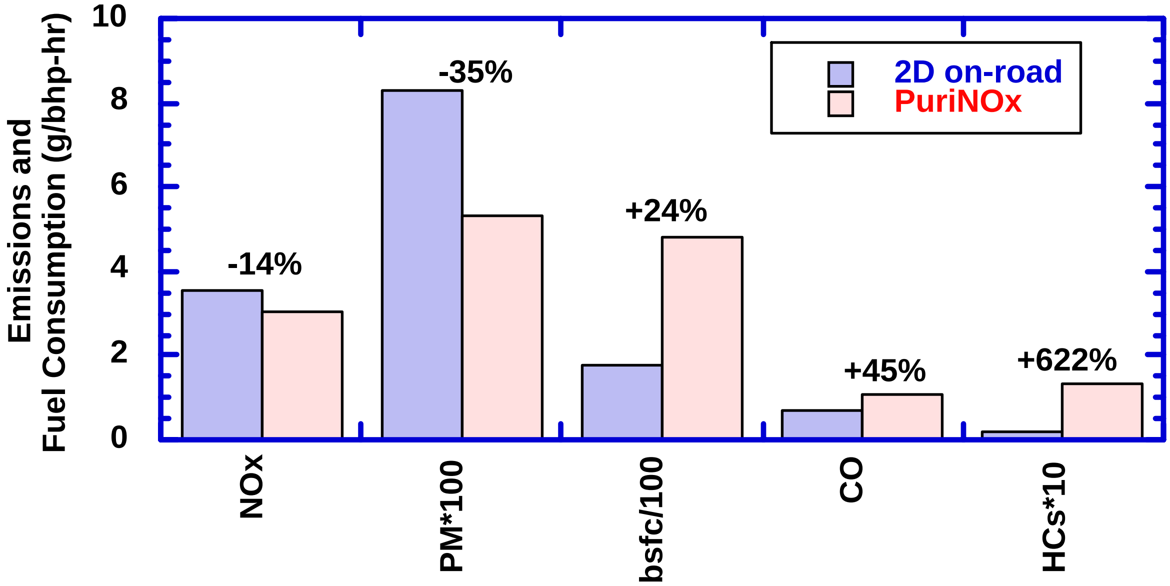


Figure B.1.1 Regulated emissions and fuel consumption for the Cummins ISB-190 operating over the TxDOT Telescoping Boom Excavator Cycle

B.1.A. Cummins ISB-190 – The BSFC and regulated emissions for the Cummins ISB-190 operating over the composite TxDOT Telescoping Boom Excavator Cycle are shown in Figure B.1.1. Detailed results are presented in Table B.1. As shown in Table B.1, the engine did 5.9% less work over the composite cycle when using PuriNOx. This is a conventional comparison, for which the PuriNOx-fueled engine was attempting to maintain the same engine speed (rpm) and torque as when operating on 2D on-road diesel fuel. The tests of this engine intended to assure the same work for both fuels were not successful: 7.7% more work was done with PuriNOx than for the diesel fuel tests that were intended to produce the same work. Because the original set of tests was closer to yielding the same work, only those results are discussed below.

To allow all of these emissions and the BSFC to be illustrated on the same scale, the BSFC is divided by 100, the PM is multiplied by 100, and the HC emissions are multiplied by 10. For this engine operating over this cycle, PuriNOx offers a 14% benefit in NOx and a 35% benefit in PM. However, there is also a 24% penalty in fuel consumption and penalties in the emissions of CO and HCs. Because the emissions of CO and HCs from diesels are inherently low, the penalties in the emissions of these species are not generally of significant concern.

As shown in Table B.1, the differences between the average hot starts for the two fuels are statistically significant at the 95% confidence level, except for the emissions of CO_2. It is believed that the differences in the composite results (except CO_2) are also statistically significant for three reasons:

- the percentage differences in emissions (and fuel consumption) for the two fuels are almost the same whether comparing the average hot starts or the composite results,
- the differences between the two fuels are relatively large, and
- the composite results are weighted 86% to hot starts.

Second-by-second results are available for the NOx and HC emissions, but not for the other species. Examination of such data can be useful to improving understanding of the effects of PuriNOx. These results are discussed below.

The second-by-second NOx emissions for the two hot start cycles are compared for each fuel in Figure B.1.2. For clarity, this figure shows only the first 500 seconds, which includes both highway driving (the time interval from ~40 to ~300 seconds) and excavating (starting at ~360 seconds). From the mass emissions perspective, PuriNOx offers the greatest advantage for highway driving (near 100% load), compared to excavating (peaking at ~80% load).

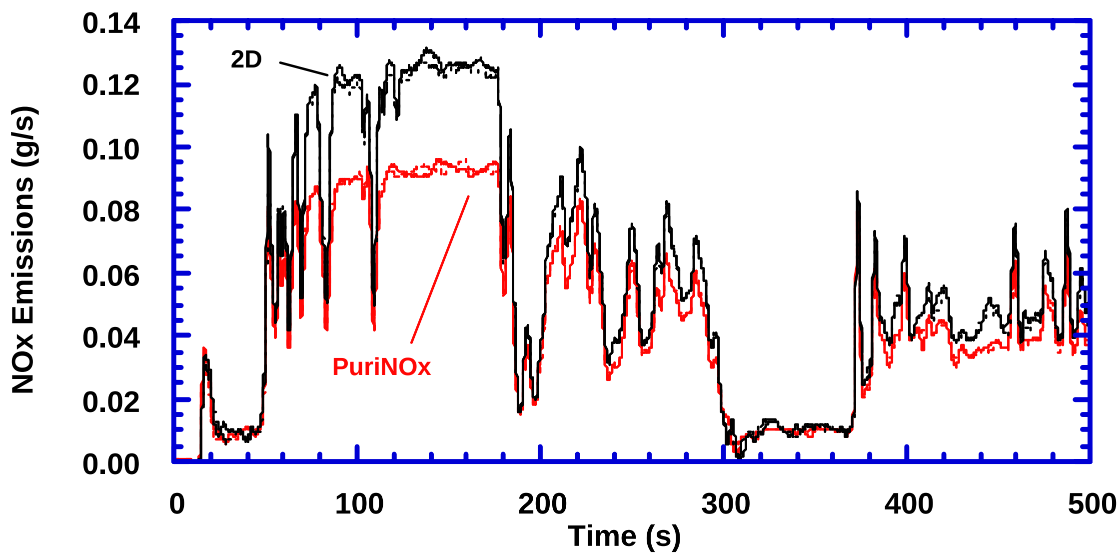


Figure B.1.2 NOx emissions rate comparisons for the Cummins ISB-190 operating over the first 500 seconds of the TxDOT Telescoping Boom Excavator Cycle

The second-by-second HC emissions for the two hot start cycles are compared for each fuel in Figure B.1.3. Again, only the first 500 seconds are shown. The HC penalty for PuriNOx is obvious for all operating conditions, but is most pronounced for the excavating activity. However, it should be pointed out that the HC emissions rate is very low for both fuels.

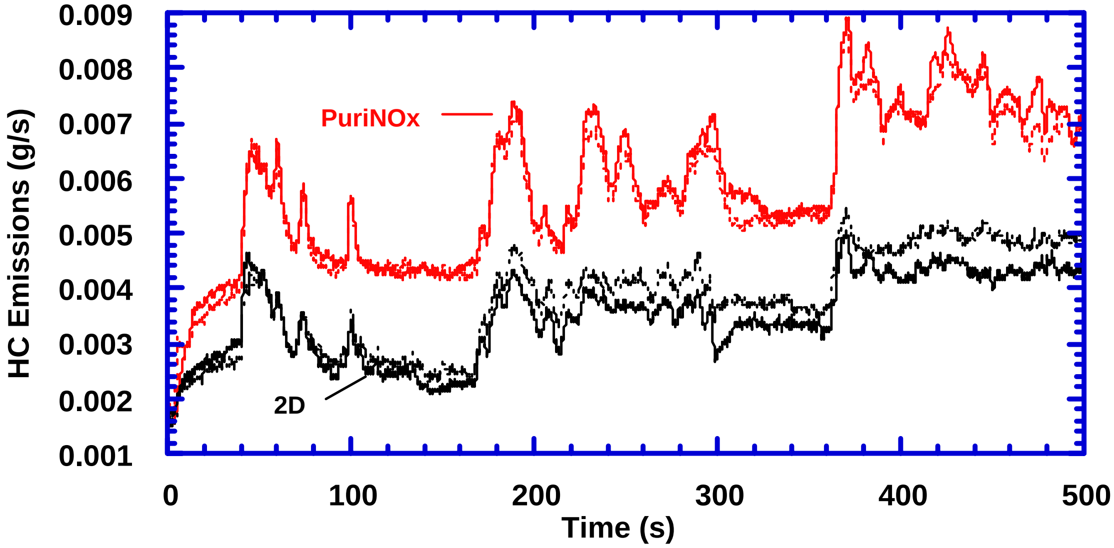


Figure B.1.3 HC emissions rate comparisons for the Cummins ISB-190 operating over the first 500 seconds of the TxDOT Telescoping Boom Excavator Cycle

Table B.1 Regulated Emissions from the ISB-190 for Each of the Cold and Hot Start TxDOT Telescoping Boom Excavator Cycles

Start	Fuel	Torque Map	HC (g/hp-hr)	PM (g/hp-hr)	NOx (g/hp-hr)	CO2 (g/hp-hr)	CO (g/hp-hr)	BSFC (g/hp-hr)	Ref. Work (hp-hr)	Actual Work (hp-hr)	Actual vs. Ref. (%)
Cold	2D on-road	2D on-road	0.065	0.083	3.72	557	0.84	175.5	23.81	22.83	-4.1
Hot	2D on-road	2D on-road	0.000	0.082	3.53	553	0.74	174.2	23.81	22.81	-4.2
Hot	2D on-road	2D on-road	0.029	0.084	3.52	554	0.69	174.6	23.81	22.86	-4.0
Average Hot Start			0.014	0.083	3.52	554	0.72	174.4	23.81	22.84	-4.1
Composite			**0.022**	**0.083**	**3.55**	**554**	**0.73**	**174.6**	23.81	22.83	-4.1
Hot Start Standard Deviation			0.020	0.002	0.002	0.707	0.031	0.321		0.035	0.148
Hot Start CoV (%)			141	1.9	0.1	0.1	4.4	0.2		0.2	-3.6
Cold	PuriNOx	2D on-road	0.192	0.056	3.22	577	1.35	225.9	23.81	21.28	-10.6
Hot	PuriNOx	2D on-road	0.125	0.053	3.03	555	1.02	216.8	23.81	21.53	-9.6
Hot	PuriNOx	2D on-road	0.174	0.054	3.05	549	1.00	214.6	23.81	21.49	-9.7
Average Hot Start			0.150	0.054	3.04	552	1.01	215.7	23.81	21.51	-9.7
Composite			**0.156**	**0.054**	**3.07**	**556**	**1.06**	**217.1**	23.81	21.48	-9.8
Hot Start Standard Deviation			0.035	0.001	0.012	4.243	0.010	1.604		0.028	0.119
Hot Start CoV (%)			23	1.6	0.4	0.8	1.0	0.7		0.1	-1.2
hot % change			941	-35.4	-13.7	-0.3	41.4	23.7		-5.8	
95% conf?			Y	Y	Y	N	Y	Y		Y	
comp. % change			622	-35.0	-13.6	0.3	44.6	24.4		-5.9	

Table B.2 Speciated Emissions from the ISB-190 for the TxDOT Telescoping Boom Excavator Cycle

Start	Fuel	Torque Map	formal dehyde (mg/hp-hr)	acetald ehyde	propion aldehyde	acrolein	MEK	1,3-butadiene	hexane	benzene	toluene	ethyl benzene	m&p xylene	o-xylene	sulfates	nitrates
Cold	2D on-road	2D on-road	9.5	3.5	1.7	1.3	0.1	ND	0.7	1.3	2.9	ND	0.7	0.5	3.0	0.79
Hot	2D on-road	2D on-road	9.6	3.5	1.7	1.3	0.1	ND	0.5	0.9	0.7	ND	0.6	0.0	3.0	0.44
Hot	2D on-road	2D on-road	9.0	3.4	1.3	1.2	0.1	ND	0.8	1.0	0.7	ND	0.5	0.0	3.0	0.54
Average Hot Start			9.3	3.4	1.5	1.2	0.1	ND	0.6	0.9	0.7	ND	0.5	0.0	3.0	0.49
Composite			**9.3**	**3.4**	**1.5**	**1.2**	**0.1**	**ND**	**0.6**	**1.0**	**1.0**	**ND**	**0.6**	0.1	3.0	0.53
Hot Start Standard Deviation			0.455	0.059	0.291	0.067	0.016		0.238	0.064	0.016		0.076	0.000	0.000	0.072
Hot Start CoV (%)			5	2	20	5	14		38	7	2		14		0	15
Cold	PuriNOx	2D on-road	23.2	8.3	2.7	3.6	0.5	ND	0.0	2.1	3.3	0.4	1.1	0.6	3.0	0.62
Hot	PuriNOx	2D on-road	17.2	6.2	2.1	2.6	0.3	ND	0.0	1.2	1.3	0.8	1.5	0.7	3.0	0.38
Hot	PuriNOx	2D on-road	17.0	6.1	1.9	2.5	0.3	ND	1.0	1.3	0.8	0.0	1.2	0.6	3.0	0.37
Average Hot Start			17.1	6.1	2.0	2.6	0.3	ND	0.5	1.3	1.1	0.4	1.3	0.6	3.0	0.37
Composite			**18.0**	**6.5**	**2.1**	**2.7**	**0.4**	**ND**	**0.4**	**1.4**	**1.4**	**0.4**	**1.3**	**0.6**	3.0	0.41
Hot Start Standard Deviation			0.140	0.086	0.124	0.069	0.003		0.717	0.086	0.353	0.554	0.210	0.026	0.000	0.005
Hot Start CoV (%)			1	1	6	3	1		141	7	34	141	16	4	0	1
% change: avg. hot start			84	80	38	107	197		-19	38	48	inf.	151	inf.	0	-24
95% confidence?			Y	Y	N	Y	Y	N	N	Y	N	N	Y	Y	N	Y
% change: composite			93	89	42	118	217		-32	43	34	inf.	134	777	0	-23

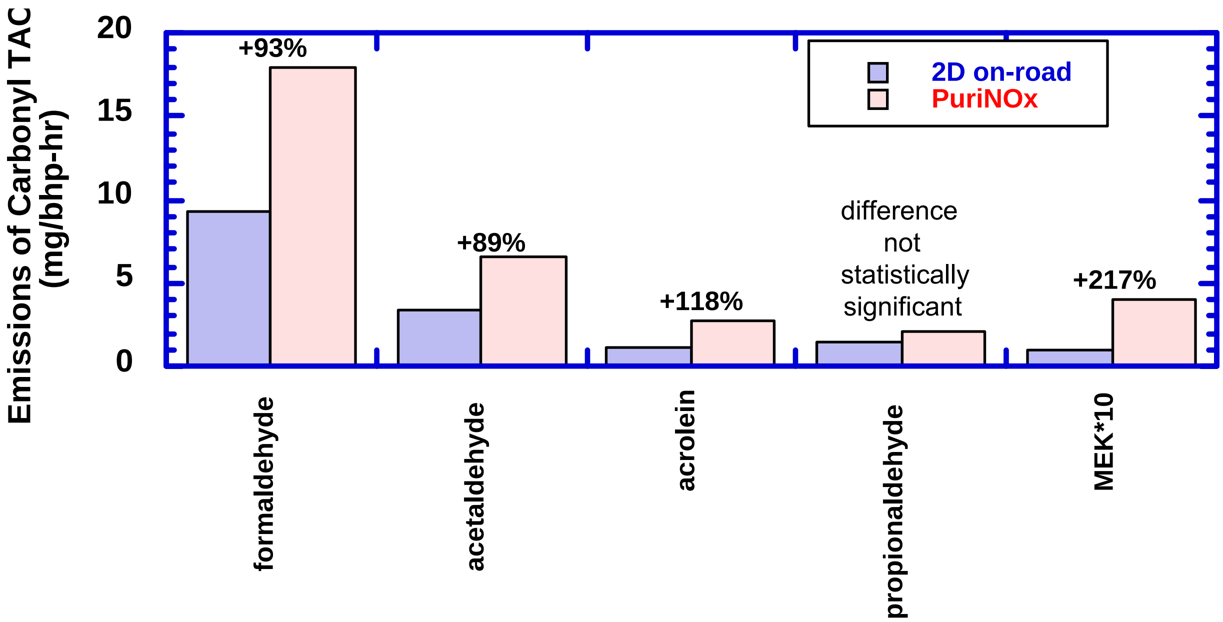


Figure B.1.4 Emissions of carbonyl TACs for the Cummins ISB-190 operating over the TxDOT Telescoping Boom Excavator Cycle

The speciated emissions from the ISB-190 operating over the TxDOT Telescoping Boom Excavator Cycle are presented in Table B.2 and Figures B.1.4-B.1.6. Emissions of these species are discussed below.

The emissions of the carbonyl TACs from the ISB-190 are illustrated in Figure B.1.4. The emissions of methyl ethyl ketone (MEK) are near the detectability limit (the MEK emissions rates are multiplied by 10 to show them on the same scale as the other carbonyls). Thus, what appears to be a rather large increase in MEK emissions for operation on PuriNOx is probably not important. The difference in the emissions of propionaldehyde is not statistically significant at the 95% confidence level, as shown in Table B.2. PuriNOx increases the emissions of the remaining aldehydes by 89-118%.

The emissions of the noncarbonyl TACs from the ISB-190 are illustrated in Figure B.1.5. The differences in the emissions of ethylbenzene, hexane, and toluene are not statistically significant at the 95% confidence level, as shown in Table B.2. The emissions of the remaining aromatics increased by 43-777% when using PuriNOx.

The breakdown of the PM emissions is shown in Figure B.1.6. There is no effect of the fuel on the sulfate emissions and a small, but statistically significant, effect on the nitrates (which are very small for both fuels). The SOF increases by 40%, in agreement with the increases in SOF noted in prior studies. As a percentage of the PM, the SOF increased from 40% for operation with the on-road diesel fuel to 86% for operation on PuriNOx.

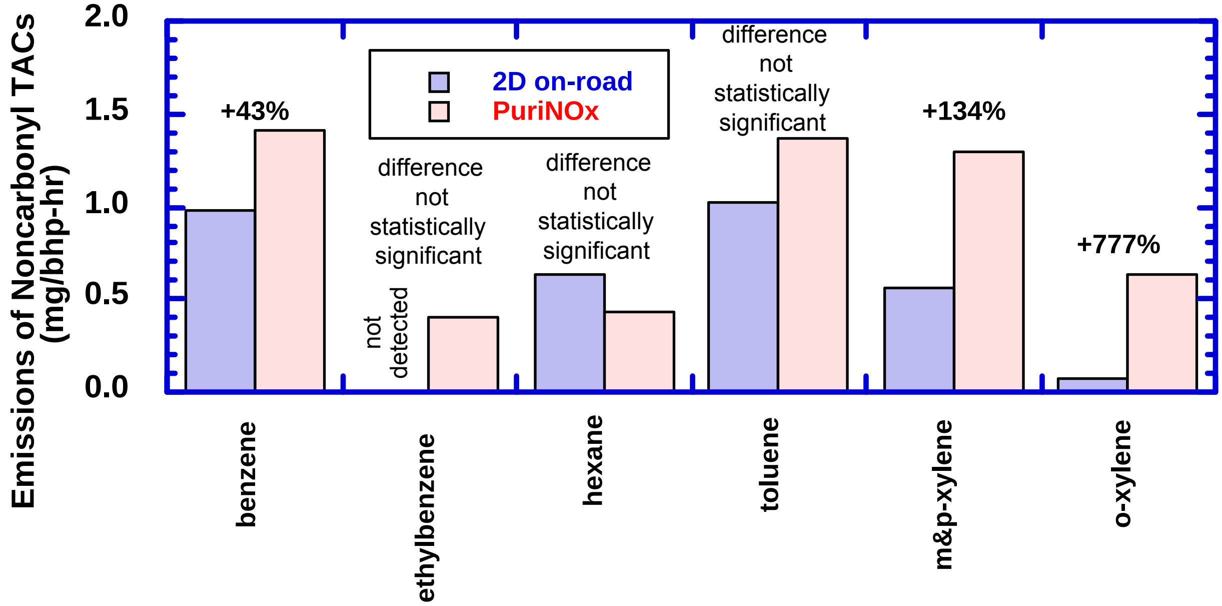


Figure B.1.5 Emissions of noncarbonyl TACs for the Cummins ISB-190 operating over the TxDOT Telescoping Boom Excavator Cycle

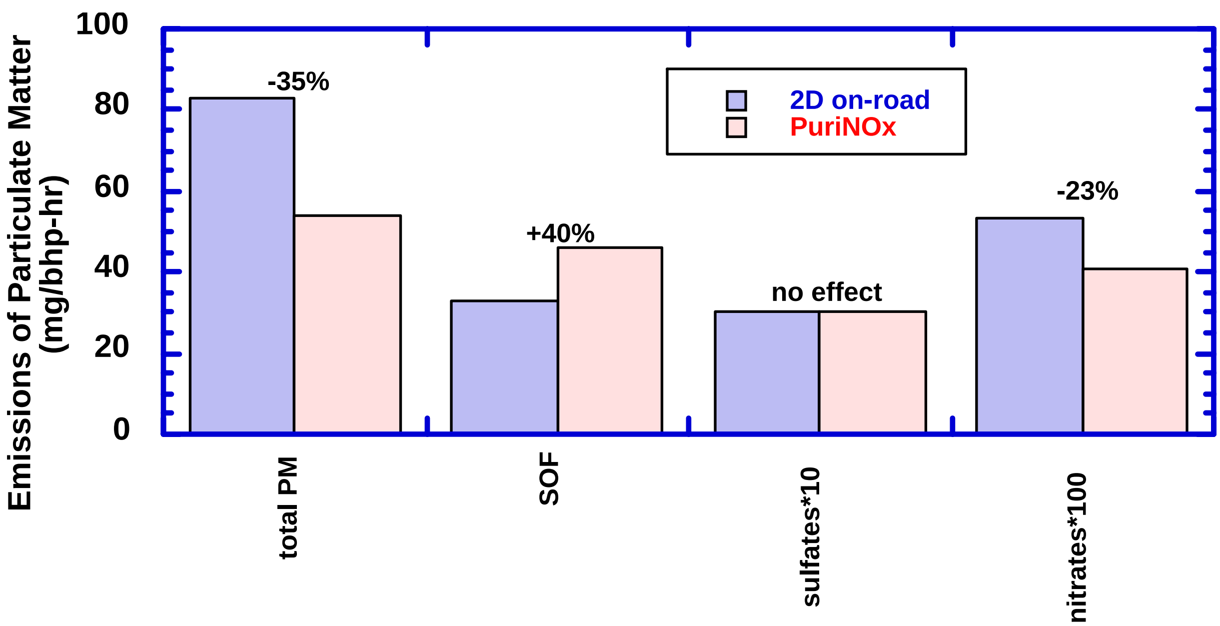


Figure B.1.6 Particulate matter breakdown for the Cummins ISB-190 operating over the TxDOT Telescoping Boom Excavator Cycle

B.1.B. Cummins 6BTA5.9 – The regulated emissions and BSFC for the Cummins 6BTA5.9 operating over the composite TxDOT Telescoping Boom Excavator Cycle are shown in Figure B.1.7. Detailed results are provided in Table B.3.

To explore the effects of the emulsion when the same work is done for both fuels, for the tests of the 6BTA5.9 the full load torque curve for PuriNOx was used for both fuels to convert the percent torque versus time specification for the cycle into absolute torque. Ideally, this should assure the same work over the cycle for both fuels. However, due to the complexity of this cycle, the engine did ~4% less work on PuriNOx, as shown in Table B.3.

As shown in Figure B.1.7, for this engine PuriNOx produced a 22% benefit in NOx and a 7% benefit in PM, with a 32% penalty in fuel consumption. The emissions of CO and HCs increased. As shown in Table B.3, all of these results are statistically different with 95% confidence.

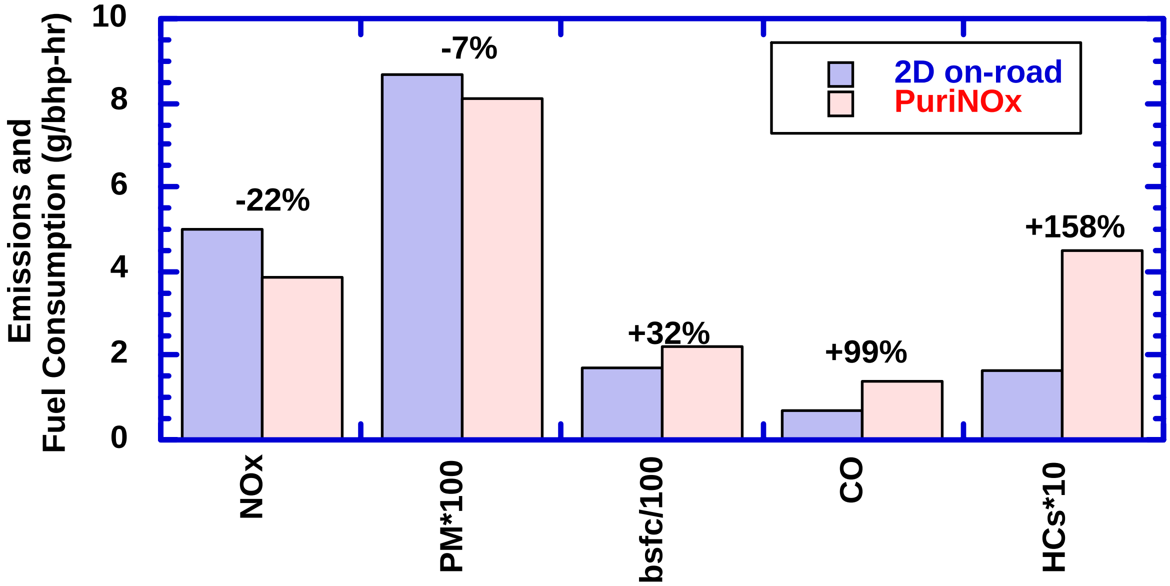


Figure B.1.7 Regulated emissions and fuel consumption for the Cummins 6BTA5.9 operating over the TxDOT Telescoping Boom Excavator Cycle

The history of the NOx emissions from the Cummins 6BTA5.9 operating over the TxDOT Telescoping Boom Excavator Cycle are shown in Figure B.1.8 and the HC emissions as a function of time are presented in Figure B.1.9. As noted for the ISB-190 operating over this cycle, discussed in the previous subsection, the NOx mass emissions advantage is most pronounced for the on-road portion of this cycle. The HC mass emissions rate from the 6BTA6.9 are much higher than for the ISB-190 during the first ~100 seconds of the cycle when operating on PuriNOx. However, for both engines, the HC emissions are higher at all times during the cycle for PuriNOx.

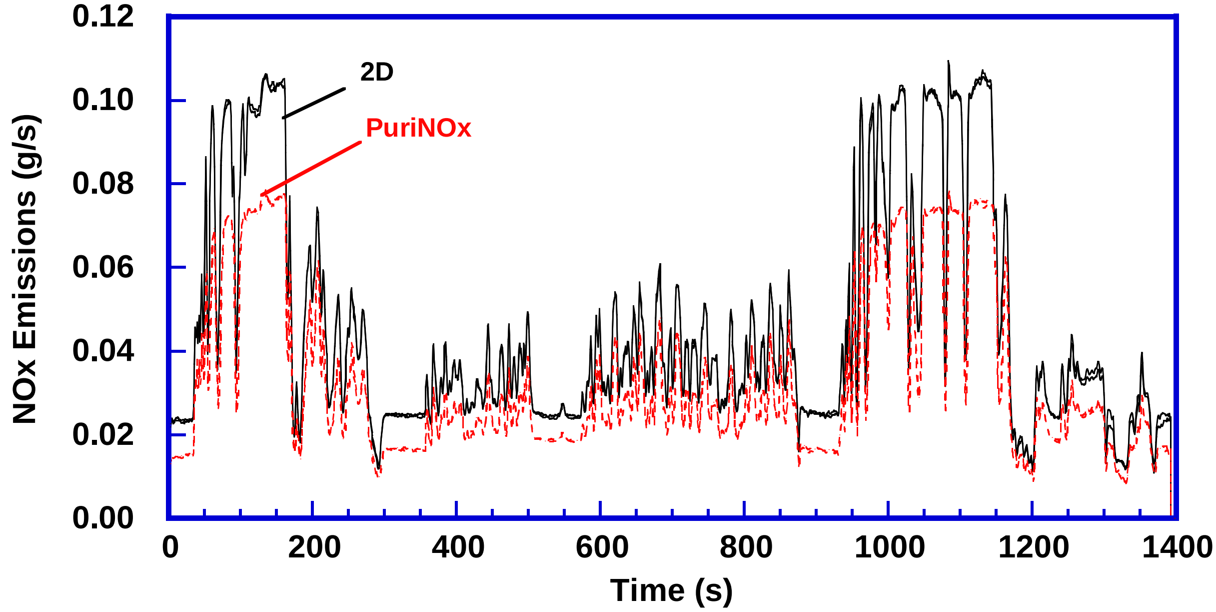


Figure B.1.8 NOx emissions comparison for the Cummins 6BTA5.9 operating over the TxDOT Telescoping Boom Excavator Cycle

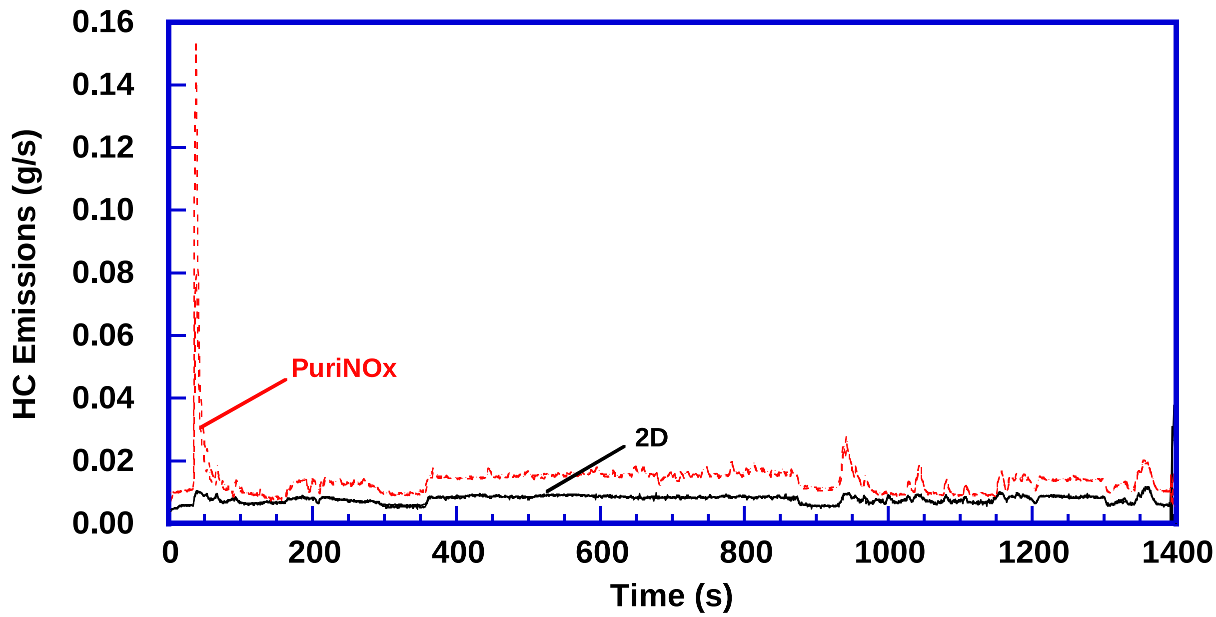


Figure B.1.9 HC emissions comparison for the Cummins 6BTA5.9 operating over the TxDOT Telescoping Boom Excavator Cycle

Table B.3 Regulated Emissions from the 6BTA5.9 for Each of the Cold and Hot Start TxDOT Telescoping Boom Excavator Cycles

Start	Fuel	Torque Map	HC (g/hp-hr)	PM (g/hp-hr)	NOx (g/hp-hr)	CO2 (g/hp-hr)	CO (g/hp-hr)	BSFC (g/hp-hr)	Ref. Work (hp-hr)	Actual Work (hp-hr)	Actual vs. Ref. (%)
Cold	2D on-road	PuriNOx	0.19	0.097	5.15	560	0.80	176.5	19.26	21.88	13.6
Hot	2D on-road	PuriNOx	0.18	0.087	5.00	534	0.70	168.3	19.26	21.97	14.1
Hot	2D on-road	PuriNOx	0.15	0.085	5.00	532	0.70	167.7	19.26	21.99	14.2
Average Hot Start			0.16	0.086	5.00	533	0.70	168.0	19.26	21.98	14.2
Composite			**0.17**	**0.087**	**5.02**	**537**	**0.72**	**169.2**	19.26	21.97	14.1
Hot Start Standard Deviation			0.017	0.001	0.000	1.50	0.000	0.489		0.014	0.071
Hot Start CoV (%)			10.5	1.5	0.0	0.3	0.0	0.3		0.1	0.5
Cold	PuriNOx	PuriNOx	0.65	0.113	4.00	583	1.74	228.7	19.26	20.78	7.9
Hot	PuriNOx	PuriNOx	0.43	0.077	3.89	568	1.37	222.6	19.26	21.10	9.6
Hot	PuriNOx	PuriNOx	0.40	0.074	3.82	564	1.29	220.9	19.26	21.22	10.2
Average Hot Start			0.41	0.076	3.85	566	1.33	221.8	19.26	21.16	9.9
Composite			**0.45**	**0.081**	**3.87**	**569**	**1.39**	**222.7**	19.26	21.11	9.6
Hot Start Standard Deviation			0.025	0.002	0.049	2.837	0.056	1.164		0.085	0.424
Hot Start CoV (%)			6.0	3.3	1.3	0.5	4.2	0.5		0.4	4.3
hot % change			152	-11.9	-22.9	6.2	89.4	32.0		-3.7	
95% conf?			Y	Y	Y	Y	Y	Y		Y	
comp. % change			158	-6.5	-22.2	6.0	98.5	31.8		-4.1	

B.2. Wheeled Loaders

The two engines that were tested over the TxDOT Telescoping Boom Excavator Cycle were also tested over the AGC Wheeled Loader Cycle at Southwest Research Institute. This cycle is described in Appendix A.1.C. The emissions and fuel consumption for PuriNOx compared to 2D on-road diesel are discussed in the following two subsections. Operation of these two engines on other fuels is discussed in Section B.5.

B.2.A. Cummins ISB-190 – The brake specific fuel consumption and regulated emissions for the Cummins ISB-190 operating over the composite AGC Wheeled Loader Cycle are shown in Figure B.2.1. Detailed results are presented in Table B.4. In this comparison, the percent torque and percent engine speed versus time specification for the cycle is converted to absolute torque and rpm versus time from the full load torque curve for this engine using 2D on-road diesel fuel for both PuriNOx and 2D on-road diesel. As shown in Table B.4, the engine does ~4% less work over the average cycle when using PuriNOx compared to 2D on-road diesel fuel. Given the complexity of this cycle, the authors believe that a 4% difference in work is acceptable for a valid comparison.

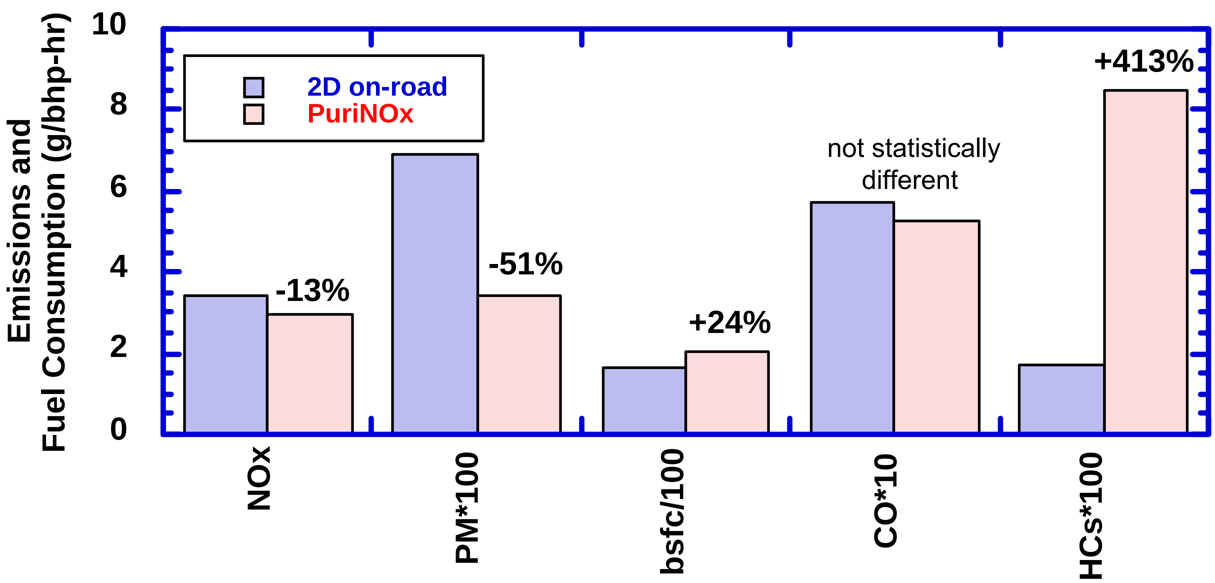


Figure B.2.1 Regulated emissions and fuel consumption for the Cummins ISB-190 operating over the AGC Wheeled Loader Cycle.

As shown in Figure B.2.1, PuriNOx offers a 13% benefit in NOx and a 51% benefit in PM with a 24% penalty in fuel consumption. Although the difference in CO emissions is not statistically significant with 95% confidence, PuriNOx does produce a large increase in HC emissions. As shown in Table B.4, the CO_2 difference between PuriNOx and 2D on-road diesel is not statistically significant.

The histories of the NOx and HC emissions are presented in Figures B.2.2 and B.2.3. PuriNOx produces NOx benefits but an HC penalty at virtually all times and for all operating conditions. The fact that the NOx benefit is almost the same at all times during the AGC Wheeled Loader Cycle contrasts with the results for this engine operating over the TxDOT Telescoping Boom Excavator Cycle, for which the NOx mass emissions benefit was much more pronounced for the on-road driving portions of the cycle. The difference is that this engine is near 100% load for on-road driving, but peaks at about 80% for both excavating and loading. Comparison of Figures B.2.2 and B.2.3 reveals that the test-to-test differences in the HC emissions are more pronounced than those for the NOx emissions.

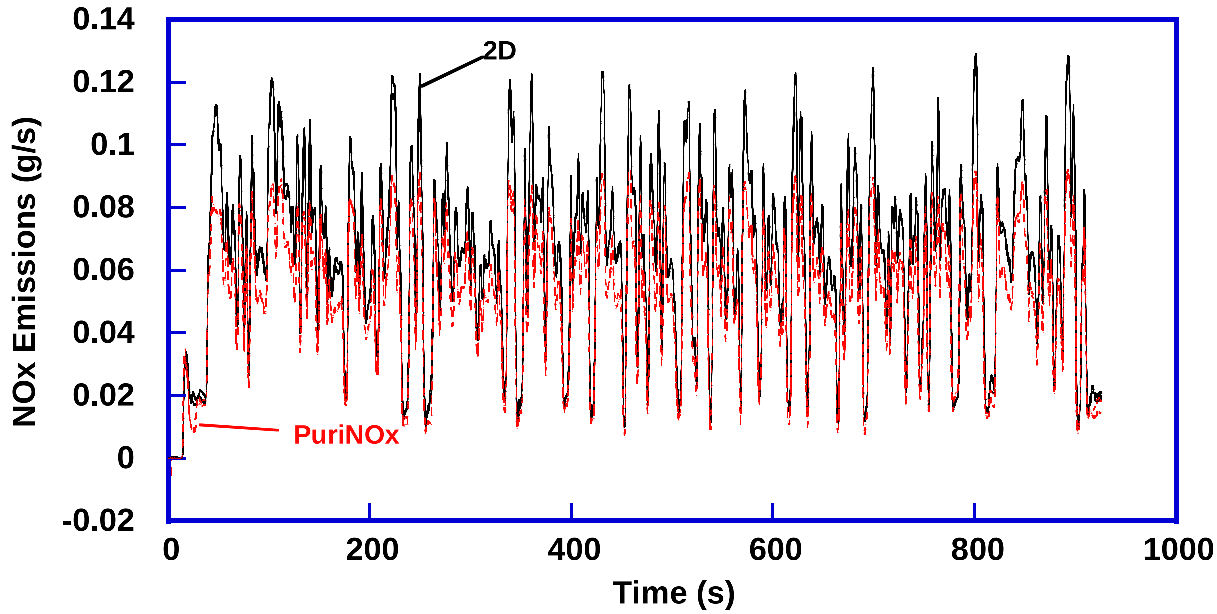


Figure B.2.2 Second-by-second NOx emissions for the ISB-190 operating over the AGC Wheeled Loader Cycle

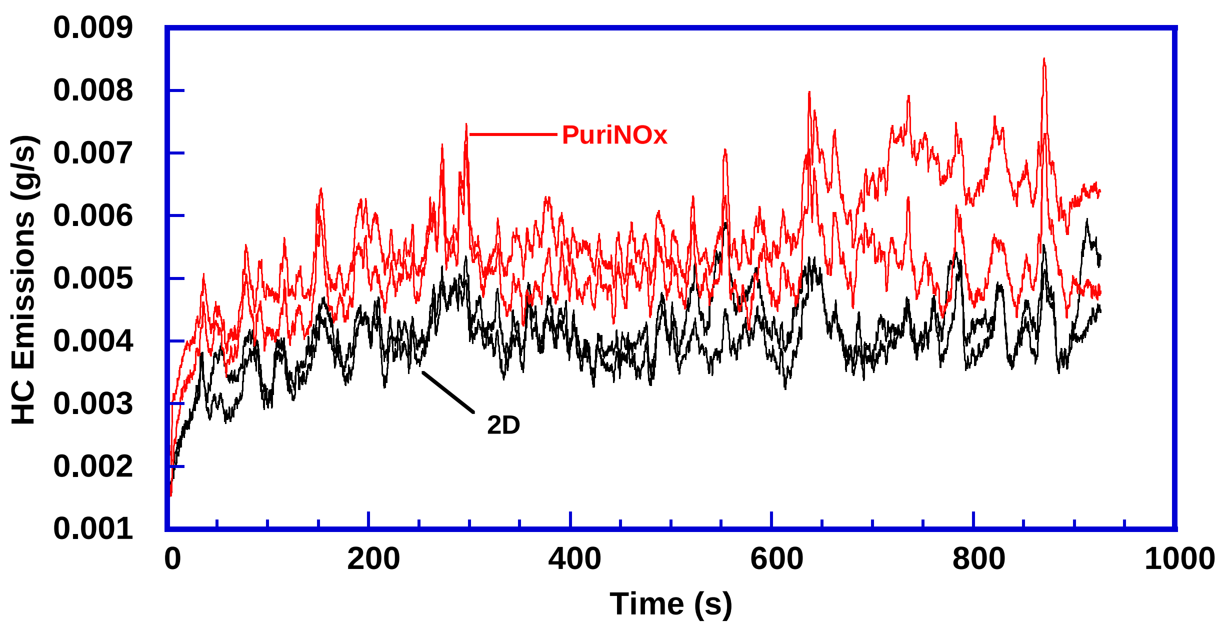


Figure B.2.3 Second-by-second HC emissions for the ISB-190 operating over the AGC Wheeled Loader Cycle

The speciated emissions from the ISB-190 operating over the AGC Wheeled Loader Cycle are presented in Table B.5 and Figures B.2.4-B.2.6. Emissions of these species are discussed below.

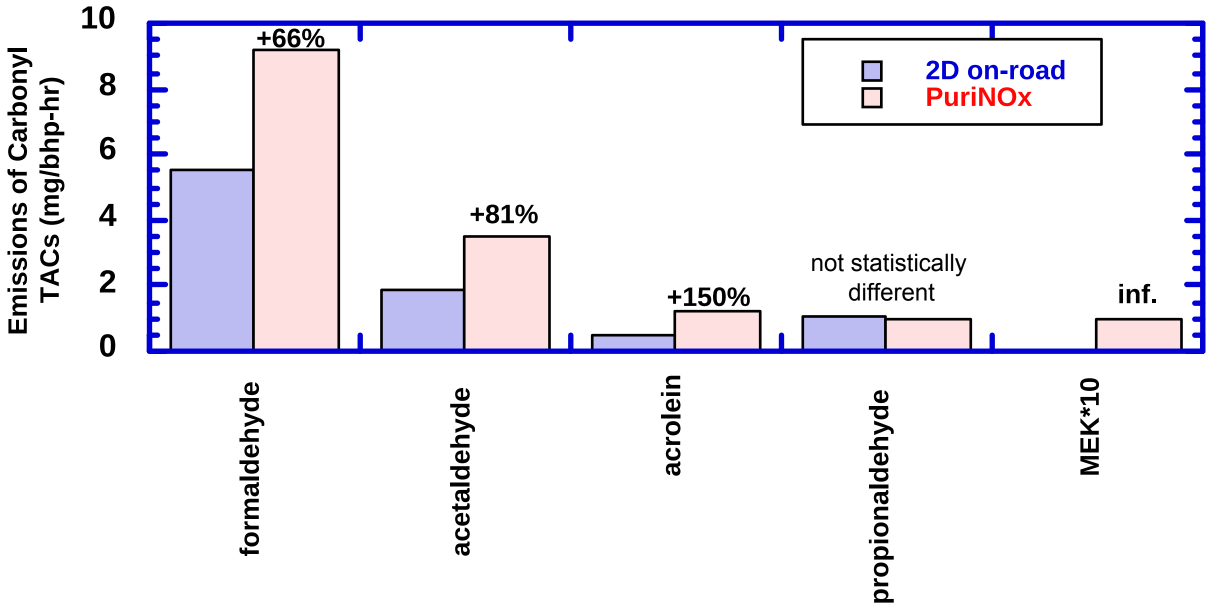


Figure B.2.4 Emissions of carbonyl TACs for the Cummins ISB-190 operating over the AGC Wheeled Loader Cycle

The emissions of the carbonyl TACs from the ISB-190 operating over the Wheeled Loader Cycle are illustrated in Figure B.2.4. The emissions of methyl ethyl ketone (MEK) were very low for operation on PuriNOx (the MEK emissions are multiplied by 10 to show them on the same scale as the other carbonyls) and below the detection limit for operation on the on-road diesel fuel. Thus, what appears to be a rather large increase in MEK emissions for operation on PuriNOx is probably not important. Compared to 2D on-road diesel fuel, PuriNOx increases the emissions of all of the carbonyls except propionaldehyde, for which the difference was not statistically significant.

The emissions of the noncarbonyl TACs from the ISB-190 operating over the Wheeled Loader Cycle are illustrated in Figure B.2.5. Hexane and ethyl benzene were below the detection limits for both fuels. The emissions of 1,3-butadiene were only detectable when using the on-road diesel fuel, but the repeatability in the measurements was such that the results for the on-road fuel were not statistically different from those for PuriNOx. Additionally, the test-to-test variability of the toluene measurements for the PuriNOx tests was such that what appears to be a very large increase in toluene emissions is, in fact, not statistically different from the diesel fuel tests. Therefore, the only differences in the noncarbonyl TAC emissions were that PuriNOx produced higher emissions of benzene and o-xylene, with 95% confidence.

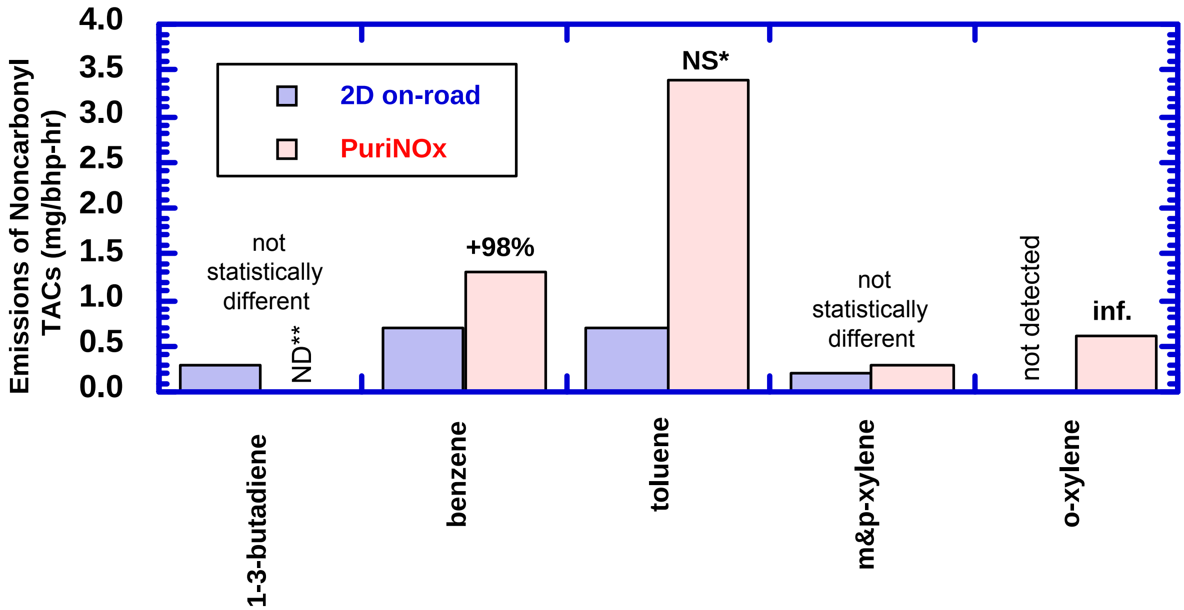
The breakdown of the PM emissions is shown in Figure B.2.6. Compared to the on-road diesel fuel, PuriNOx does not produce changes in the soluble organic fraction or the emissions of sulfates or nitrates that are statistically different at the 95% confidence level. As a percentage of the PM, the SOF increased from 37% for operation on the on-road diesel fuel to ~100% for PuriNOx.

Table B.4 Regulated Emissions from the ISB-190 for Each of the Hot Start AGC Wheeled Loader Cycles

Start	Fuel	Torque Map	HC (g/hp-hr)	PM (g/hp-hr)	NOx (g/hp-hr)	CO2 (g/hp-hr)	CO (g/hp-hr)	BSFC (g/hp-hr)	Ref. Work (hp-hr)	Actual Work (hp-hr)	Actual vs. Ref. (%)
Hot	2D on-road	2D on-road	0.03	0.069	3.42	524	0.59	164.8	17.63	16.98	-3.7
Hot	2D on-road	2D on-road	0.00	0.069	3.43	530	0.55	166.7	17.63	16.99	-3.6
Average Hot Start			**0.02**	**0.069**	**3.42**	**527**	**0.57**	**165.8**	**17.63**	**16.99**	**-3.7**
Hot Start Standard Deviation			0.023	0.000	0.011	4.243	0.031	1.379		0.007	0.040
Hot Start CoV (%)			141	0.1	0.3	0.8	5.5	0.8		0.0	-1.1
Hot	PuriNOx	2D on-road	0.08	0.035	2.99	529	0.57	206.4	17.63	16.25	-7.8
Hot	PuriNOx	2D on-road	0.09	0.033	2.96	523	0.49	204.1	17.63	16.26	-7.8
Average Hot Start			**0.08**	**0.034**	**2.98**	**526**	**0.53**	**205.3**	**17.63**	**16.26**	**-7.8**
Hot Start Standard Deviation			0.008	0.002	0.015	4.243	0.058	1.604		0.007	0.040
Hot Start CoV (%)			9	4.8	0.5	0.8	10.9	0.8		0.0	-0.5
% change: avg. hot start			413	-51.2	-13.1	-0.2	-6.3	23.8		-4.3	
95% confidence?			Y	Y	Y	N	N	Y		Y	

Table B.5 Speciated Emissions from the ISB-190 for the AGC Wheeled Loader Cycle

			mg/hp-hr													
Start	Fuel	Torque Map	formal dehyde	acetald ehyde	propion aldehyde	acrolein	MEK	1,3-butadiene	hexane	benzene	toluene	ethyl benzene	m&p xylene	o-xylene	sulfates	nitrates
Hot	2D on-rd.	on-rd.	5.6	2.0	1.1	0.5	ND	0.0	ND	0.7	0.8	ND	0.4	ND	1.9	0.452
Hot	2D on-rd.	on-rd.	5.4	1.9	1.0	0.5	ND	0.6	ND	0.6	0.7	ND	0.0	ND	2.1	0.531
Average Hot Start			**5.5**	**1.9**	**1.1**	**0.5**	ND	**0.3**	ND	**0.7**	**0.7**	ND	**0.2**	ND	**2.0**	**0.492**
Hot Start Standard Deviation			0.123	0.072	0.049	0.029		0.405		0.088	0.056		0.273		0.141	0.056
Hot Start CoV (%)			2	4	5	6		141		13	8		141		7	11
Hot	PuriNOx	on-rd.	9.4	3.5	1.1	1.3	0.1	ND	ND	1.2	0.1	ND	0.0	0.5	2.2	0.361
Hot	PuriNOx	on-rd.	8.9	3.5	1.0	1.1	0.1	ND	ND	1.4	6.7	ND	0.5	0.7	2.5	0.544
Average Hot Start			**9.2**	**3.5**	**1.0**	**1.2**	**0.1**	ND	ND	**1.3**	**3.4**	ND	**0.3**	**0.6**	**2.4**	**0.452**
Hot Start Standard Deviation			0.356	0.062	0.004	0.109	0.010			0.106	4.621		0.370	0.172	0.212	0.130
Hot Start CoV (%)			4	2	0	9	8			8	135		141	28	9	29
% change: avg. hot start			66	81	-1	150	inf.	-100		98	379		36	inf.	18	-8
95% confidence?			Y	Y	N	Y	Y	N	N	Y	N	N	N	Y	N	N



*** - emissions difference between the two fuels not statistically significant with 95% confidence**
**** - below detection limit**

Figure B.2.5 Emissions of noncarbonyl TACs for the Cummins ISB-190 operating over the AGC Wheeled Loader Cycle

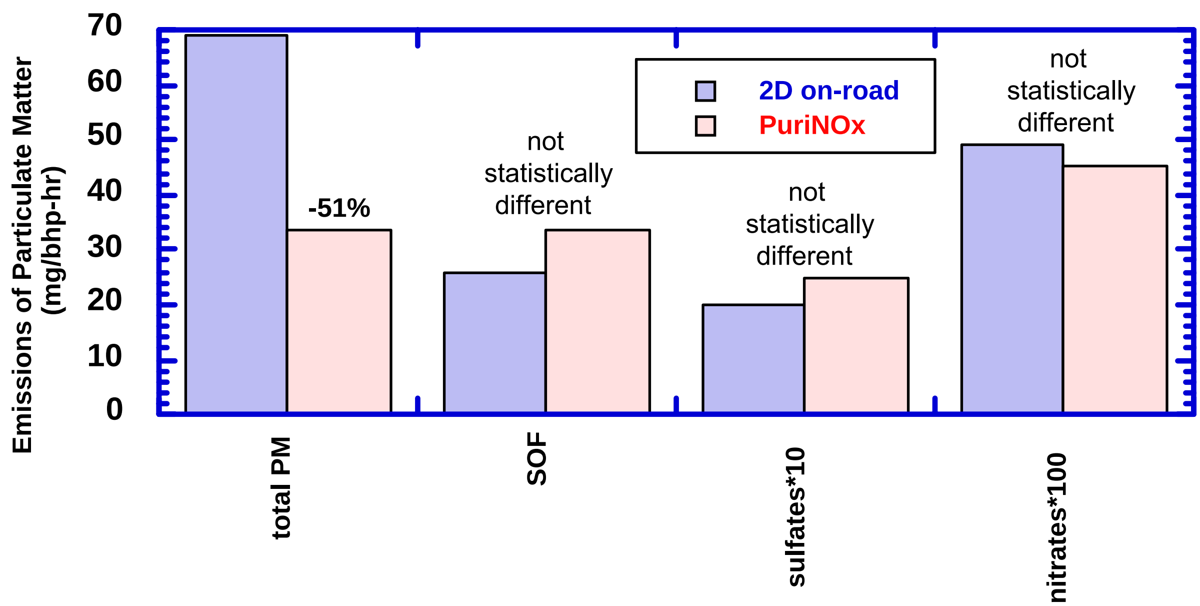


Figure B.2.6 Particulate matter breakdown for the Cummins ISB-190 operating over the AGC Wheeled Loader Cycle

B.2.B. Cummins 6BTA5.9 – The regulated emissions and brake specific fuel consumption for the Cummins 6BTA5.9 operating over the AGC Wheeled Loader Cycle are illustrated in Figure B.2.7 and detailed results are provided in Table B.6.

For the tests of the 6BTA5.9, the full load torque curve for PuriNOx was used for both fuels to convert the percent torque versus time specification for the cycle into absolute torque.

Ideally, this should assure the same work over the cycle for both fuels. However, the engine did 1.9% less work on PuriNOx, compared to 2D on-road diesel fuel, as shown in Table B.6. Given the complexity of this cycle and natural test-to-test variability, the authors believe that this difference is sufficiently small that the comparisons between the two fuels are valid.

For this engine, PuriNOx provides a 19% benefit in NOx, a 33% benefit in PM, a 29% penalty in fuel consumption, and penalties in CO and HC emissions.

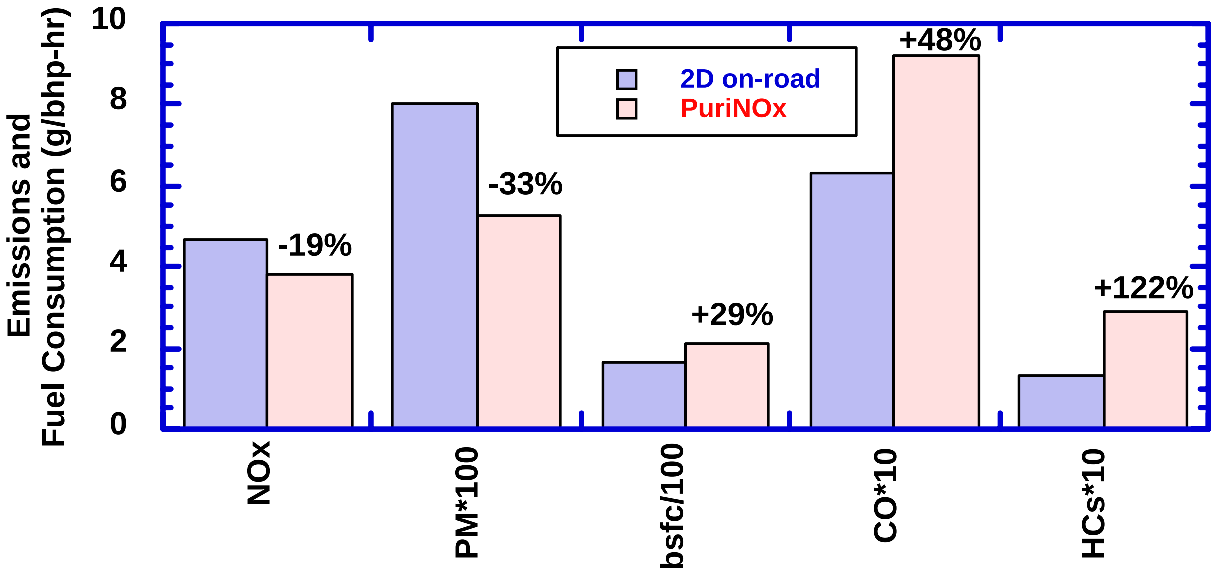


Figure B.2.7 Regulated emissions and fuel consumption for the Cummins 6BTA5.9 operating over the AGC Wheeled Loader Cycle

Figure B.2.8 shows the NOx histories for the Cummins 6BTA5.9 over the AGC Wheeled Loader Cycle and Figure B.2.9 shows the HC emission histories. PuriNOx provides a NOx benefit but an HC penalty at all times during the cycle.

Table B.6 Regulated Emissions from the 6BTA5.9 for Each of the AGC Wheeled Loader Cycles

Start	Fuel	Torque Map	HC (g/hp-hr)	PM (g/hp-hr)	NOx (g/hp-hr)	CO2 (g/hp-hr)	CO (g/hp-hr)	BSFC (g/hp-hr)	Ref. Work (hp-hr)	Actual Work (hp-hr)	Actual vs. Ref. (%)
Hot	2D on-road	PuriNOx	0.12	0.079	4.67	519	0.62	163.5	13.47	15.20	12.80
Hot	2D on-road	PuriNOx	0.14	0.081	4.73	519	0.63	163.4	13.47	15.31	13.70
Average Hot Start			**0.13**	**0.080**	**4.70**	**519**	**0.63**	**163.4**	13.47	15.26	13.25
Hot Start Standard Deviation			0.014	0.001	0.047	0.146	0.002	0.031		0.078	
Hot Start CoV (%)			10.7	1.6	1.0	0.0	0.3	0.0		0.5	
Hot	PuriNOx	PuriNOx	0.33	0.056	3.69	542	1.02	212.0	13.47	14.94	10.90
Hot	PuriNOx	PuriNOx	0.26	0.051	3.90	537	0.82	209.9	13.47	14.98	11.20
Average Hot Start			**0.29**	**0.053**	**3.79**	**540**	**0.92**	**211.0**	13.47	14.96	11.06
Hot Start Standard Deviation			0.047	0.004	0.148	3.590	0.141	1.532		0.028	
Hot Start CoV (%)			16.1	7.1	3.9	0.7	15.3	0.7		0.2	
% change: avg. hot start			122	-33.5	-19.3	4.0	47.8	29.1		-1.9	
95% confidence?			Y	Y	Y	Y	Y	Y		Y	

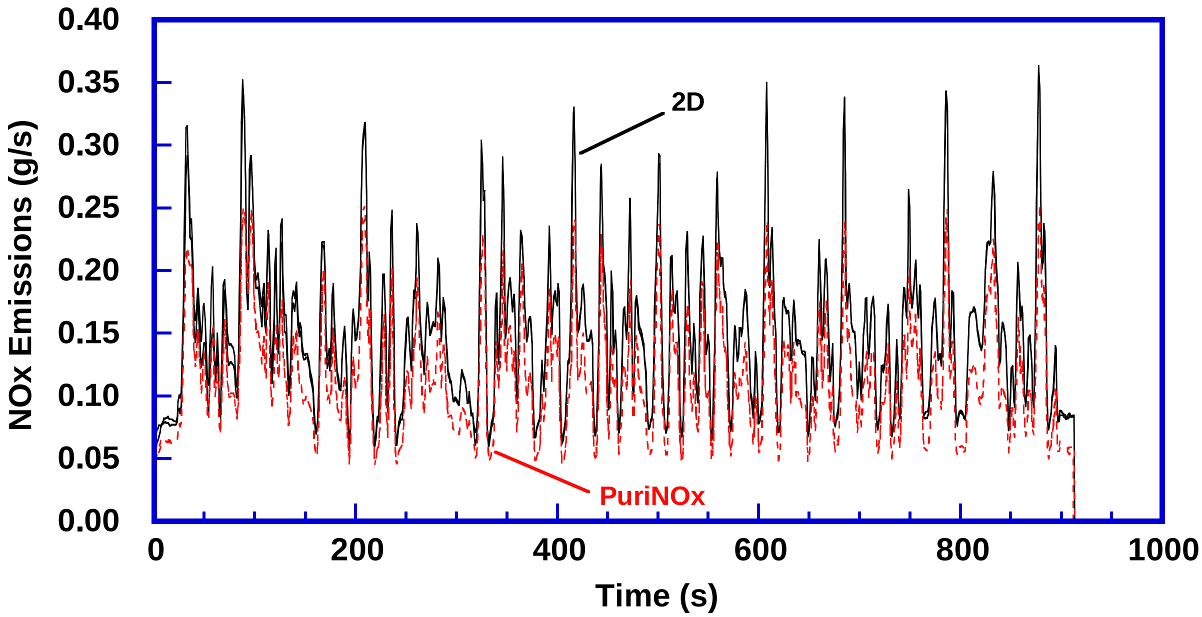


Figure B.2.8 NOx emissions comparison for the Cummins 6BTA5.9 operating over the AGC Wheeled Loader Cycle

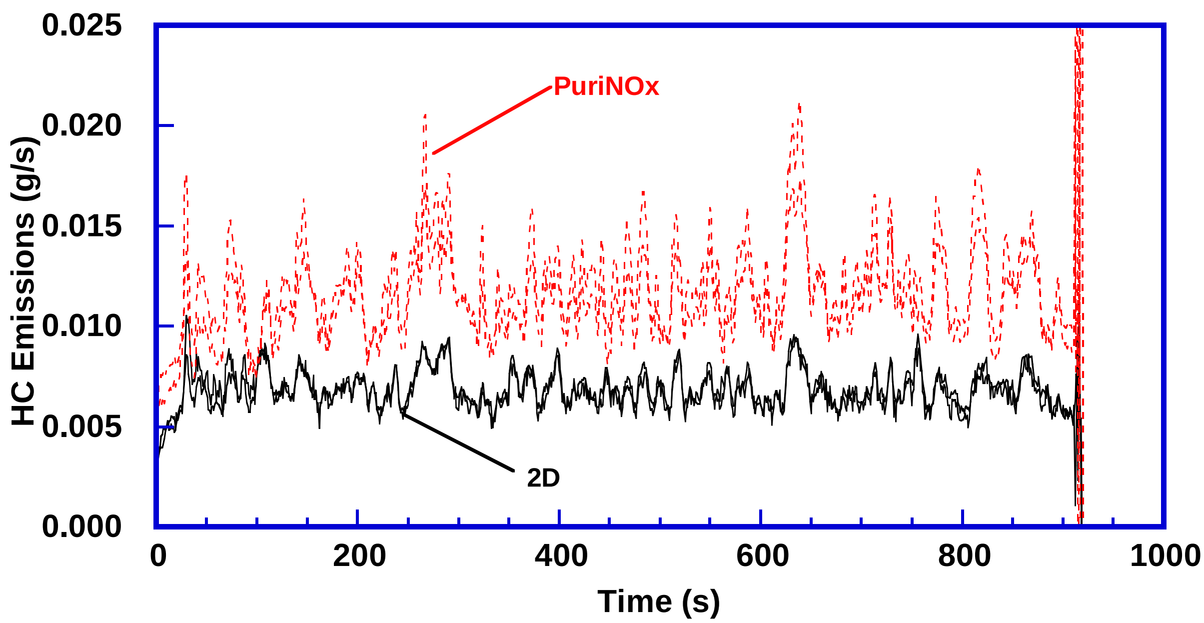


Figure B.2.9 HC emissions comparison for the Cummins 6BTA5.9 operating over the AGC Wheeled Loader Cycle

B.3. Single-Axle Dump Trucks

SwRI measured the emissions and fuel economy of four single-axle dump trucks operating over the TxDOT Single-Axle Dump Truck Cycle. This cycle is described in detail in Appendix A. The chassis dyno was set to simulate a loaded vehicle weight of 28,480 lb (these trucks have a GVW Rating of ~33,000 lb and weigh about 15,000 lb when empty, depending upon the specific truck). The four single-axle dump trucks were:

- 1999 GMC C7500 with an electronically-controlled Cat 3126B (6.6 L, 210 hp, 2600 rpm, serial no. FS6306A, engine family WCPXH0442HSK, TxDOT Eqpt. No. 15-4771-G; certification standards: 4.0 gNOx/hp-hr, 0.10 gPM/hp-hr; certification levels: 3.85 gNOx/hp-hr, 0.094 gPM/hp-hr)
- 1997 International with an electronically-controlled Navistar Power Stroke T444E-HT (7.27 L, 228 hp, 2500 rpm, engine family VN444C8DASW, TxDOT Eqpt. No. 5-3946-G; certification standards: 5.0 gNOx/hp-hr, 0.10 gPM/hp-hr)
- 1993 Navistar 4900 with a mechanically-controlled International 7.6TI-6 (7.6 L, 210 hp, 2400 rpm, engine family DTA466, TxDOT Eqpt. No. 15-5518-E; certification standards: 5.0 gNOx/hp-hr, 0.25 gPM/hp-hr)
- 1996 Ford F800 with a mechanically-controlled Cummins 1060 (5.9 L, 230 hp, 2300 rpm, serial no. 45564172, engine family TCE359D6DABW, TxDOT Eqpt. No. 15-3600-G; certification standards: 5.0 gNOx/hp-hr, 0.10 gPM/hp-hr)

One problem with conventional comparisons of PuriNOx and diesel fuel is that the torque loss associated with the water in PuriNOx affects the ability to stay on the prescribed cycle when using PuriNOx. This results in a different amount of work over the cycle, and thereby affects emissions. To overcome this problem, a new technique – the "route" test – was developed for this project. The route test is illustrated in Figure B.3.1, which represents a portion – including one microtrip - of the Single-Axle Dump Truck Cycle (seconds 400-600). The thin dashed line represents the dump truck negotiating this microtrip when using diesel fuel. The solid line represents the conventional method of comparison: trying as much as possible to stay on the prescribed trace, including starting the deceleration at the prescribed time. However, in this example the loss of torque means that the vehicle cannot accelerate as well at the higher speeds and is limited in peak speed. Here, it should be recalled that each microtrip has a physical interpretation; for example starting at a stop sign, accelerating to get onto the freeway, driving to the work site, and coming to a stop. In this example it is 6361 feet from the stop sign to the work site. However, with the conventional comparison, the dump truck stopped 540 feet short of the work site. The route technique (the bold dashed line in Figure B.3.1) dictates that the cruise must be continued to make up for the lower acceleration and cruising speed, such that the dump truck travels the full 6361 feet before coming to a stop at the end of the microtrip.

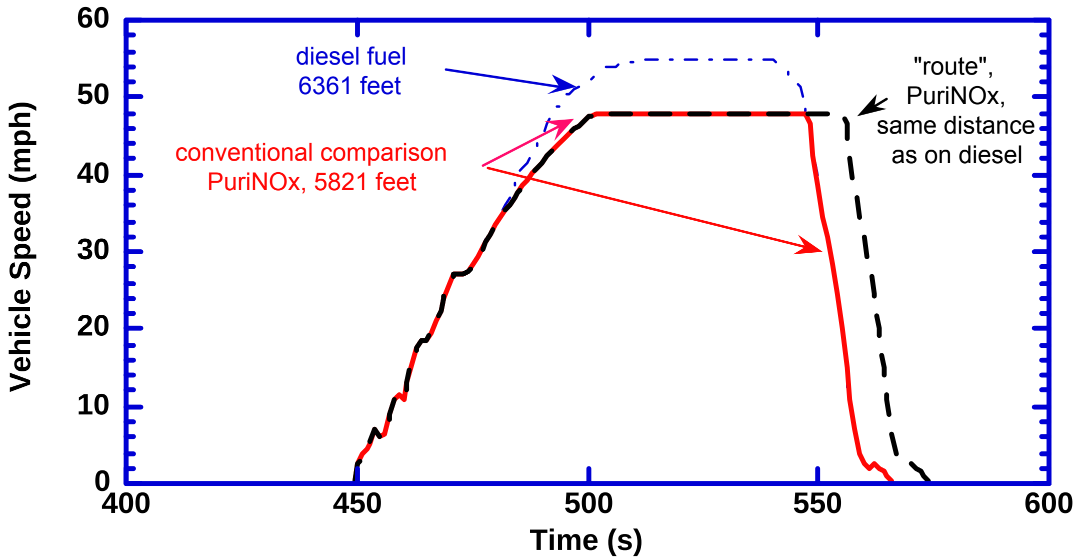


Figure B.3.1 Illustration of the "route" technique developed to compare fuels for this project

PuriNOx was compared only to 2D on-road diesel fuel in the dump truck tests that are discussed in this section. Comparisons for other fuels are discussed in Section B.5. The emissions and fuel economy for each of the four single-axle dump trucks are discussed in the following subsections.

<u>B.3.A. Cat 3126B</u> – The results for the GMC with the Caterpillar 3126B engine are illustrated in Figure B.3.2 for the composite TxDOT Single-Axle Dump Truck Cycle. Detailed results are provided in Table B.7. The distances traveled for each microtrip on each fuel are compared in Table B.8. As shown in Table B.7, the distance for the overall route is 0.2% shorter for the PuriNOx runs, and this difference is statistically significant with 95% confidence. However, the difference is less than 100 feet out of almost 9 miles. Also, as shown in Table B.8, for each of the 6 individual microtrips the difference in the distance per microtrip for the two fuels is not statistically different, with 95% confidence. Therefore, we believe that these tests are adequate for a valid comparison between the two fuels.

Figure B.3.2 shows that the NOx emissions benefit for PuriNOx is only 8% for this application. The difference in PM emissions between the two fuels was not statistically significant with 95% confidence. The fuel economy penalty is 15%. PuriNOx also provides a small benefit in CO emissions along with a large HC penalty.

The vehicle speed and NOx emissions are compared on a second-by-second basis in Figure B.3.3, and the HC emissions histories are shown in Figure B.3.4. This dump truck had more difficulty accelerating at the higher speeds on PuriNOx than when operating on diesel fuel (the average speed over the cycle was slower for PuriNOx, as shown in Table B.7). However, when the NOx emissions are compared at almost any specific distance during the route, PuriNOx provided a NOx benefit but a large penalty in HC emissions.

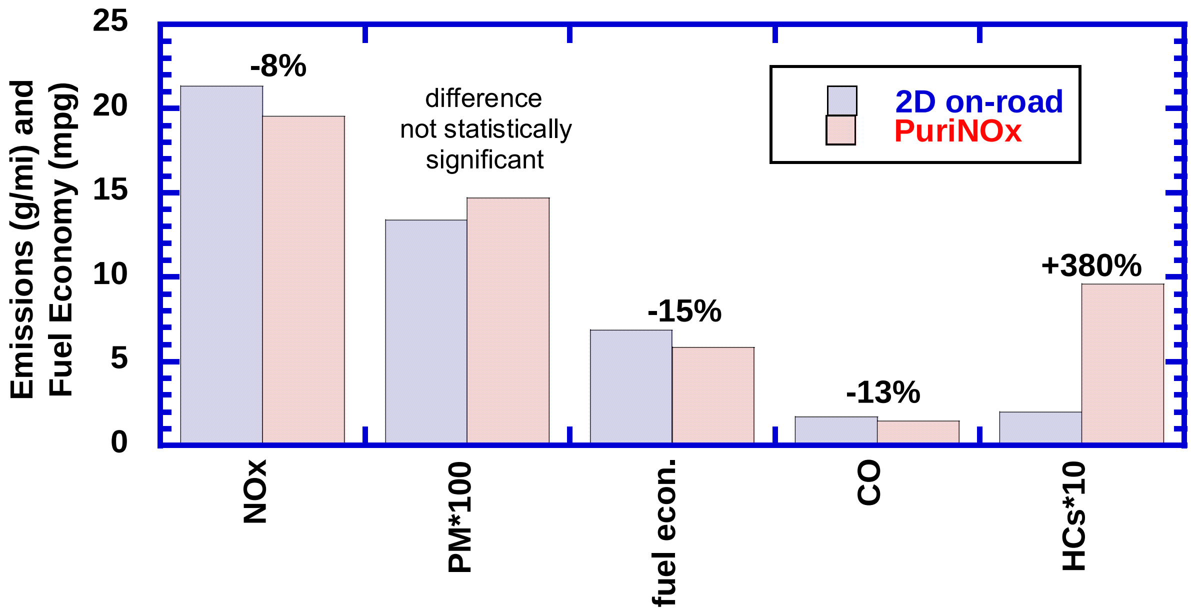


Figure B.3.2 Regulated emissions and fuel economy for the GMC single-axle dump truck with the Caterpillar 3126B engine

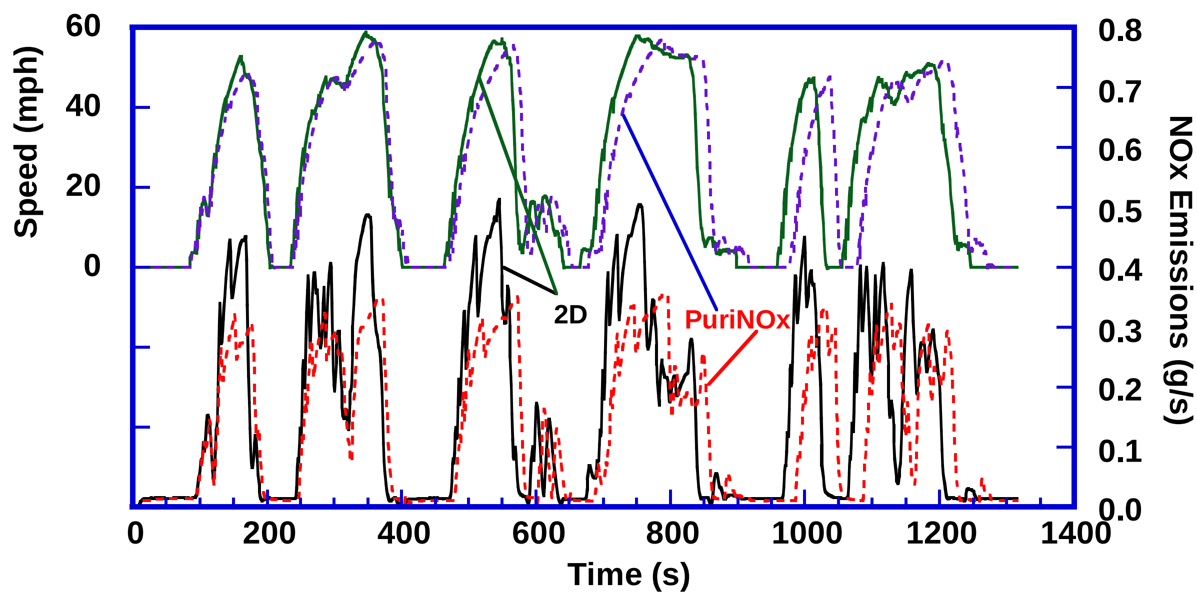


Figure B.3.3 Comparison of vehicle speeds and NOx emissions for the GMC single-axle dump truck with the Caterpillar 3126B engine

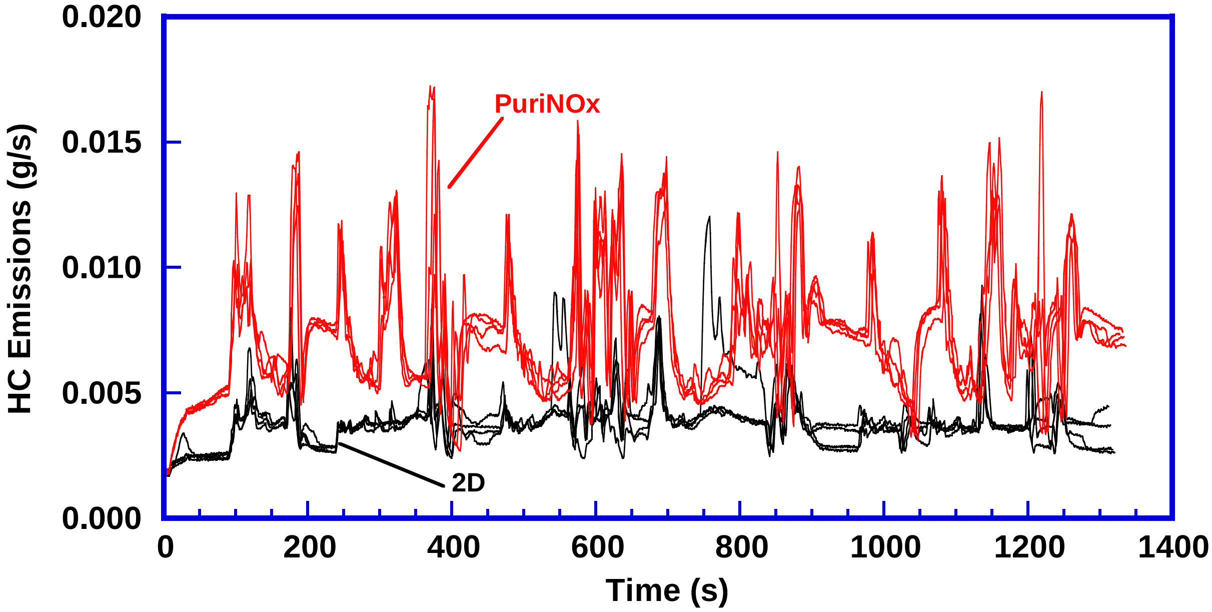


Figure B.3.4 Comparison of HC emissions for the GMC single-axle dump truck with the Caterpillar 3126B engine

Table B.7 Detailed Results for the Electronically-Controlled Caterpillar 3126B Engine in the 1999 GMC Single-Axle Dump Truck

Start	HC	PM	NOx	CO2	CO	Fuel Economy	Reference distance	Actual distance	Actual vs. Ref. (%)	Average speed
	g/mile					mpg	miles			mph
2D on-road diesel										
Cold	0.19	0.151	22.17	1552	2.22	6.31	8.78	8.80	0.23	24.06
Hot	0.20	0.134	21.23	1398	1.57	7.01	8.78	8.79	0.11	23.95
Hot	0.20	0.128	21.07	1423	1.61	6.88	8.78	8.80	0.23	24.00
Hot	0.21	0.135	21.28	1417	1.66	6.92	8.78	8.80	0.23	24.05
avg. hot	0.20	0.132	21.19	1413	1.61	6.94	8.78	8.80	0.19	24.00
composite	**0.20**	**0.135**	**21.33**	**1432**	**1.70**	**6.85**	8.78	**8.80**	**0.20**	**24.01**
hot std. dev.	0.004	0.004	0.110	13.347	0.043	0.067		0.006		0.052
hot CoV (%)	2.1	2.9	0.5	0.9	2.6	1.0		0.1		0.2
PuriNOx										
Cold	0.86	0.143	19.39	1512	1.78	5.45	8.78	8.79	0.11	23.67
Hot	0.93	0.134	19.69	1380	1.52	5.97	8.78	8.78	0.00	23.64
Hot	1.00	0.145	19.22	1373	1.43	6.00	8.78	8.78	0.00	23.68
Hot	1.01	0.149	20.45	1451	1.46	5.67	8.78	8.78	0.00	23.78
Hot	0.99	0.161	18.99	1372	1.27	6.00	8.78	8.79	0.11	23.73
avg. hot	0.98	0.147	19.59	1394	1.42	5.91	8.78	8.78	0.03	23.71
composite	**0.96**	**0.147**	**19.56**	**1411**	**1.47**	**5.84**	8.78	**8.78**	**0.04**	**23.70**
hot std. dev.	0.037	0.011	0.642	38.369	0.106	0.161		0.005		0.061
hot CoV (%)	3.8	7.6	3.3	2.8	7.5	2.7		0.1		0.3
hot % change	384	11.3	-7.6	-1.3	-11.9	-14.8		-0.2		-1.2
95% conf?	Y	N	Y	N	Y	Y		Y		Y
comp. % change	380	8.6	-8.3	-1.5	-13.4	-14.6		-0.2		-1.3

Table B.8 Comparison of Distances for each Microtrip for each Fuel for the Caterpillar 3126B Engine in the 1999 GMC Single-Axle Dump Truck

Fuel	Microtrip Number	Run No./Distance (m) 1	2	3	4	Avg.	Std. Dev.	Relative Difference	Lower limit	Upper limit	95% conf?
Diesel	1	1623.7	1625.4	1613.5	1610.4	1618.3	7.4		1611.0	1625.5	
	2	2855.5	2842.1	2858.1	2891.2	2861.7	20.9		2841.3	2882.2	
	3	2328.7	2255.7	2263.8	2249.1	2274.3	36.7		2238.3	2310.3	
	4	3467.6	3519.2	3521.6	3496.9	3501.3	25.1		3476.7	3525.9	
	5	945.7	978.9	965.5	968.4	964.6	13.9		951.0	978.2	
	6	2936.1	2938.2	2945.6	2948.6	2942.1	5.9		2936.3	2947.9	
PuriNOx	1	1608.3	1615.8	1602.2	1612.3	1609.7	5.8	-0.53%	1603.9	1615.4	N
	2	2881.8	2860.6	2866.9	2855.5	2866.2	11.4	0.16%	2855.0	2877.4	N
	3	2250.4	2262.0	2276.8	2269.5	2264.7	11.3	-0.42%	2253.6	2275.7	N
	4	3513.1	3514.5	3503.8	3512.3	3510.9	4.8	0.27%	3506.2	3515.7	N
	5	972.7	973.1	968.8	965.9	970.1	3.4	0.57%	966.8	973.5	N
	6	2922.2	2915.8	2933.9	2938.6	2927.6	10.5	-0.49%	2917.4	2937.9	N

B.3.B. Navistar T444E – The results for the 1997 International with the electronically-controlled T444E engine are illustrated in Figure B.3.5 for the composite TxDOT Single-Axle Dump Truck Cycle. Detailed results are provided in Table B.9. The distances traveled for each microtrip on each fuel are compared in Table B.10. Except for the final microtrip, the difference in the distance per microtrip for the two fuels is not statistically different, with 95% confidence. Although the last microtrip was ~26 meters shorter, on average, for the PuriNOx tests, and although this was statistically different, the difference was less than 0.9%. As shown in Table B.9, the difference in the distance for the overall cycle was not statistically significant at the 95% confidence level. Therefore, we believe that these tests are a valid basis for comparing the two fuels.

PuriNOx provides a 33% benefit in NOx emissions with a 7% penalty in fuel economy. Surprisingly, the PM emissions are 24% higher when using PuriNOx. The literature survey revealed only one previous test for which PuriNOx increased PM emissions (Henningsen, 1994). For the hot start cycles, the emissions and fuel economy differences are statistically significant. It is assumed that this is true for the composite results as well, justified primarily by the fact that the composite emissions are weighted 86% to the hot start. For the hot start tests, the differences in distance traveled over the cycle are not statistically different, but the average speeds are. The vehicle speed histories for this dump truck operating on 2D on-road diesel and PuriNOx are compared in Figure B.3.6.

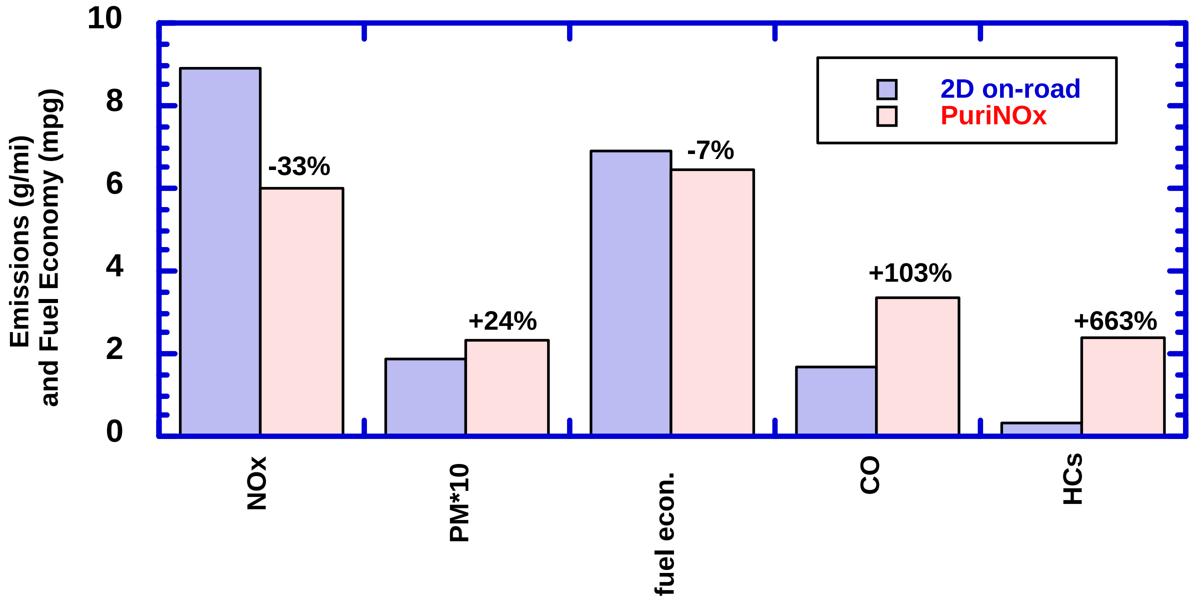


Figure B.3.5 Regulated emissions and fuel economy for the International single-axle dump truck with the Navistar T444E engine

Figure B.3.6 shows the vehicle speed and NOx emissions histories for this dump truck and both fuels. Figure B.3.7 compares the HC emissions on a second-by-second basis. This vehicle was more affected by the use of PuriNOx than any other dump truck, as illustrated in Figure B.3.6. It had much slower accelerations and lower cruising speeds when operating on PuriNOx compared to its behavior when using diesel fuel. This resulted in the time delay in NOx emissions in Figure B.3.6. However, the NOx emissions were much lower, and the HC emissions much higher, when using PuriNOx, when compared at the same distance during the route.

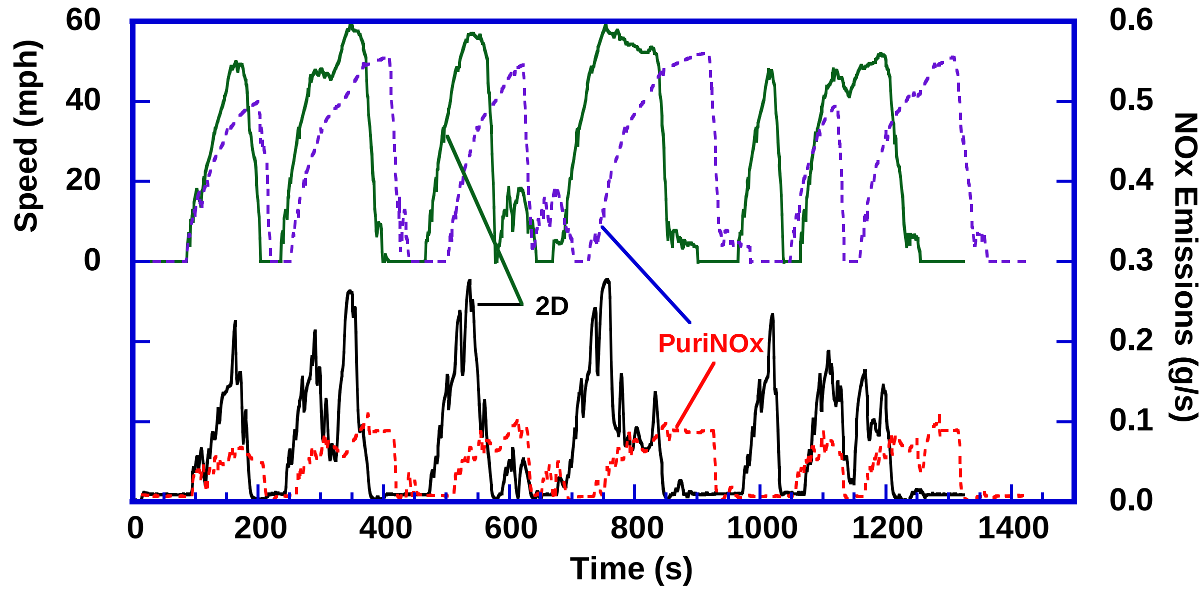


Figure B.3.6 Comparison of vehicle speeds and NOx emissions for the International single-axle dump truck with the Navistar T444E engine

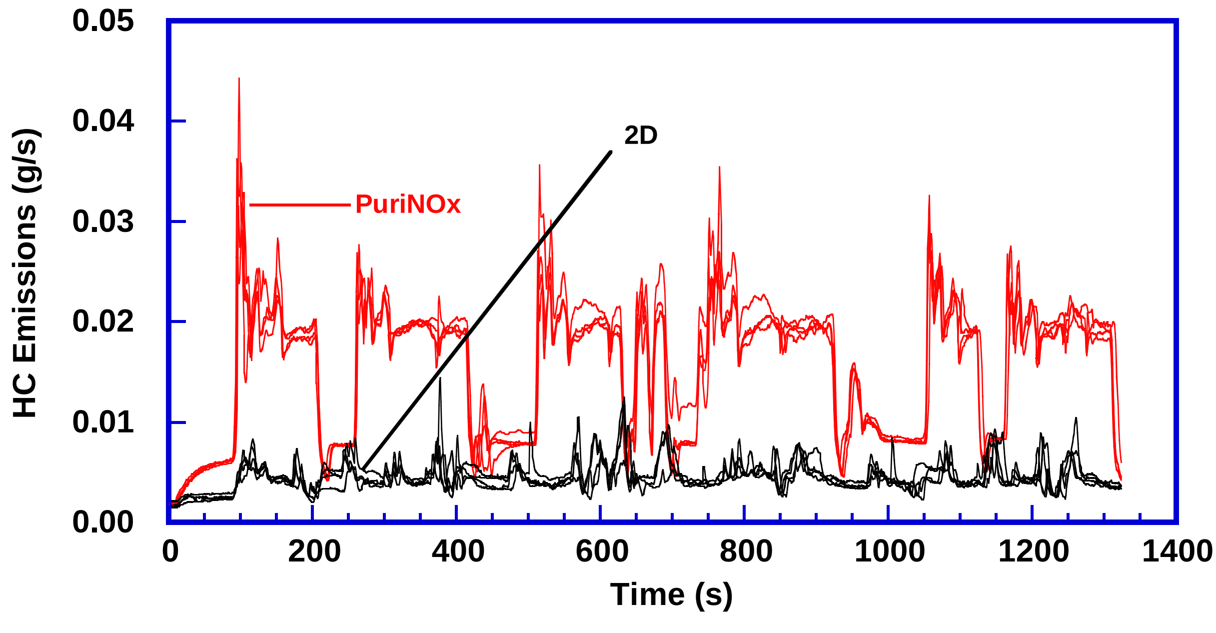


Figure B.3.7 Comparison of HC emissions for the International single-axle dump truck with the Navistar T444E engine

Table B.9 Detailed Results for the Electronically-Controlled Navistar T444E Engine in the 1997 International Single-Axle Dump Truck

Start	HC	PM	NOx	CO2	CO	Fuel Economy	Reference distance	Actual distance	Actual vs. Ref. (%)	Average speed
	g/mile					mpg	miles			mph
2D on-road diesel										
Cold	0.27	0.297	9.26	1528	2.31	6.41	8.78	8.78	0.0	23.8
Hot	0.31	0.179	9.05	1419	1.57	6.90	8.78	8.79	0.1	23.9
Hot	0.33	0.173	8.81	1394	1.63	7.03	8.78	8.81	0.3	23.9
Hot	0.34	0.167	8.75	1401	1.48	6.99	8.78	8.80	0.2	23.7
Hot	0.31	0.161	8.90	1385	1.58	7.07	8.78	8.80	0.2	23.8
avg. hot	0.32	0.170	8.88	1400	1.56	7.00	8.78	8.80	0.2	23.8
composite	**0.31**	**0.188**	**8.93**	**1418**	**1.67**	**6.91**	**8.78**	**8.80**	**0.2**	**23.8**
hot std. dev.	0.02	0.01	0.13	14.23	0.06	0.07		0.01		0.09
hot CoV (%)	5.3	4.6	1.5	1.0	4.0	1.0		0.1		0.4
PuriNOx										
Cold	1.87	0.221	6.70	1380	3.18	5.97	8.78	8.79	0.1	22.4
Hot	2.48	0.246	5.96	1267	3.18	6.49	8.78	8.78	0.0	22.1
Hot	2.47	0.228	5.86	1261	3.26	6.52	8.78	8.79	0.1	22.1
Hot	2.52	0.229	5.90	1255	3.62	6.55	8.78	8.77	-0.1	21.9
Hot	2.46	0.238	5.91	1259	3.63	6.53	8.78	8.79	0.1	22.1
avg. hot	2.48	0.235	5.90	1260	3.42	6.52	8.78	8.78	0.0	22.1
composite	**2.40**	**0.233**	**6.02**	**1277**	**3.39**	**6.44**	**8.78**	**8.78**	**0.0**	**22.1**
hot std. dev.	0.02	0.01	0.04	4.90	0.23	0.03		0.01		0.11
hot CoV (%)	1.0	3.6	0.7	0.4	6.9	0.4		0.1		0.5
hot % change	671	38.4	-33.5	-10.0	119	-6.8		-0.2		-7.5
95% conf?	Y	Y	Y	Y	Y	Y		N		Y
comp. % change	663	24.0	-32.7	-9.9	103	-6.8		-0.2		-7.3

Table B.10 Comparison of Distances for each Microtrip for each Fuel for the Navistar T444E Engine in the 1997 International Single-Axle Dump Truck

Fuel	Microtrip Number	Run No. 1	2	3	4	Avg.	Std. Dev.	Relative Difference	Lower limit	Upper limit	95% conf?
Diesel	1	1617.5	1606.4	1611.8	1603.2	1609.7	6.3		1603.6	1615.9	
	2	2838.3	2861.8	2842.3	2858.4	2850.2	11.6		2838.8	2861.6	
	3	2285.5	2282.3	2281.8	2301.7	2287.8	9.4		2278.6	2297.0	
	4	3527.5	3493.7	3528.6	3500.5	3512.6	18.1		3494.8	3530.3	
	5	938.1	990.1	965.1	956.4	962.4	21.6		941.2	983.6	
	6	2950.9	2950.2	2939.2	2952.4	2948.2	6.1		2942.2	2954.1	
PuriNOx	1	1605.3	1614.9	1606.4	1606.2	1608.2	4.5	-0.09%	1603.8	1612.6	N
	2	2844.3	2826.4	2847.1	2862.4	2845.1	14.8	-0.18%	2830.6	2859.5	N
	3	2276.5	2300.1	2293.4	2272.9	2285.7	13.1	-0.09%	2272.9	2298.6	N
	4	3518.3	3523.0	3511.4	3525.3	3519.5	6.1	0.20%	3513.5	3525.5	N
	5	982.3	955.8	961.5	966.3	966.5	11.4	0.42%	955.3	977.6	N
	6	2919.5	2933.1	2910.8	2926.4	2922.5	9.5	-0.87%	2913.1	2931.8	Y

B.3.C. International 7.6TI-6 – The results for the 1993 Navistar with the mechanically-controlled International 7.6TI-6 engine are illustrated in Figure B.3.8 for the composite TxDOT Single-Axle Dump Truck Cycle. Detailed results are provided in Table B.11. The distances traveled for each microtrip on each fuel are compared in Table B.12. As shown in this table, the difference in the distance per microtrip for the two fuels is not statistically different, with 95% confidence, for any of the 6 individual microtrips. Obviously, the difference in the distance for the overall cycle was not statistically significant either, as shown in Table B.11. Therefore, these tests are a valid basis for comparison of the two fuels.

PuriNOx produces the expected benefits in NOx (25%) and PM (55%) with a fuel economy penalty of 11%. The differences in the CO_2 and CO emissions are not statistically significant at the 95% confidence level. PuriNOx does produce a statistically significant increase in HC emissions.

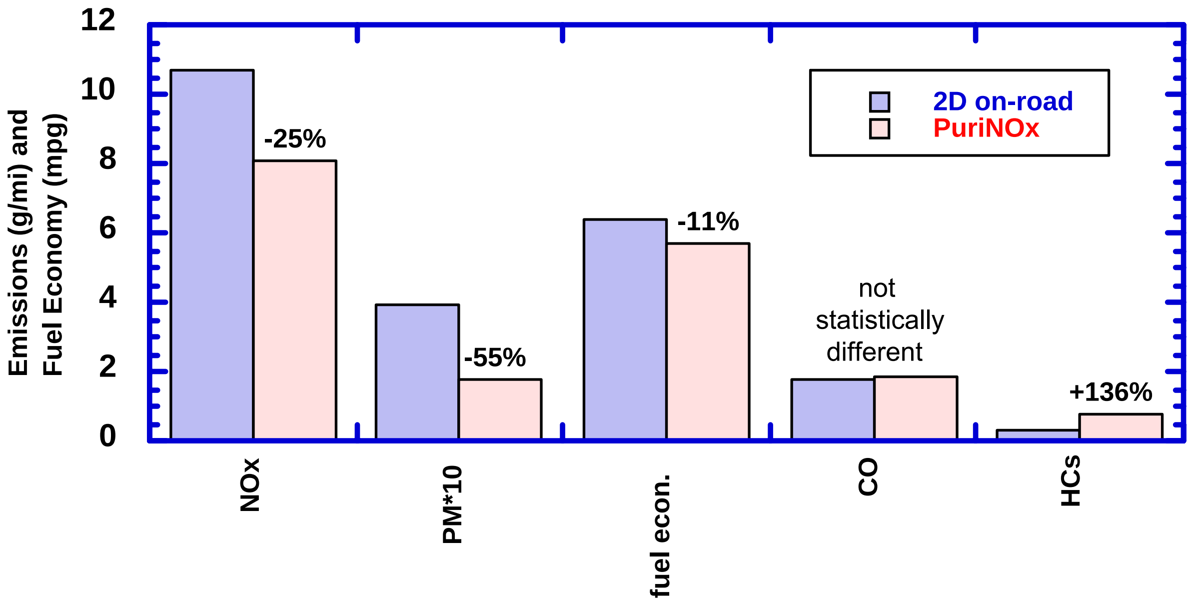


Figure B.3.8 Regulated emissions and fuel economy for the Navistar single-axle dump truck with the International 7.6TI-6 engine

Although the average distances per microtrip are not statistically different, as shown in Table B.12, the average vehicle speeds are, as shown in Table B.11. The vehicle speed histories for this dump truck operating on 2D on-road diesel and PuriNOx are compared in Figure B.3.9. This figure also compares the NOx emissions, and the HC emissions are compared in Figure B.3.10. This dump truck also had some difficulty in accelerating when using PuriNOx, although not as pronounced as the dump truck with the T444E engine that was discussed in Subsection B.3.B. At any specific distance during the cycle, the NOx emissions were lower and the HC emissions were higher for operation on PuriNOx compared to diesel fuel.

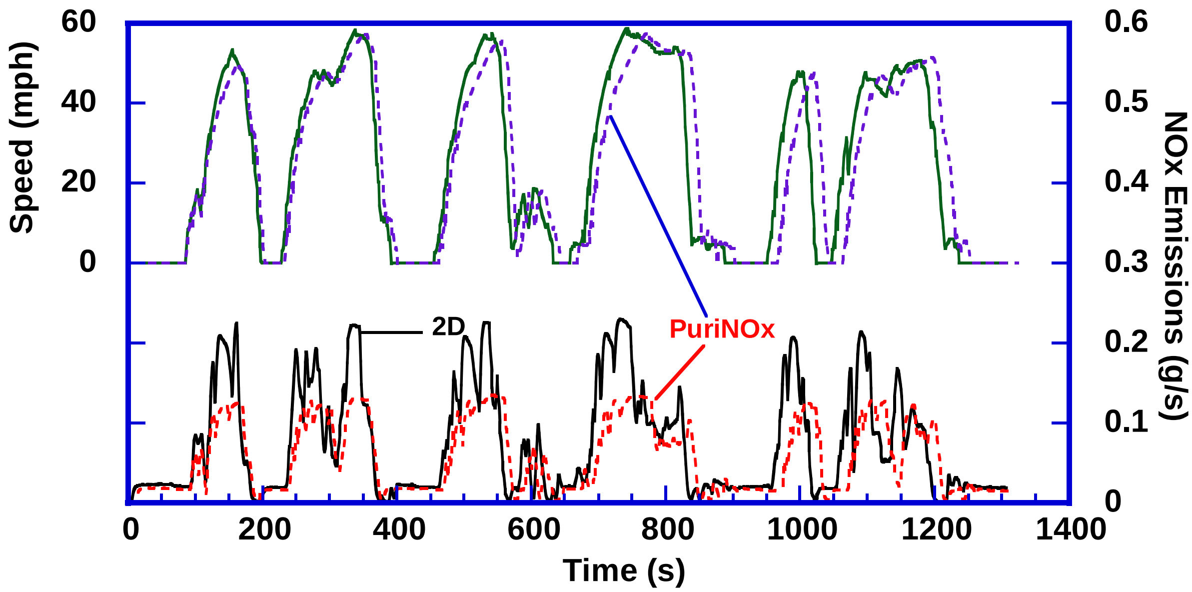


Figure B.3.9 Comparison of vehicle speeds and NOx emissions for the Navistar single-axle dump truck with the International 7.6TI-6 engine

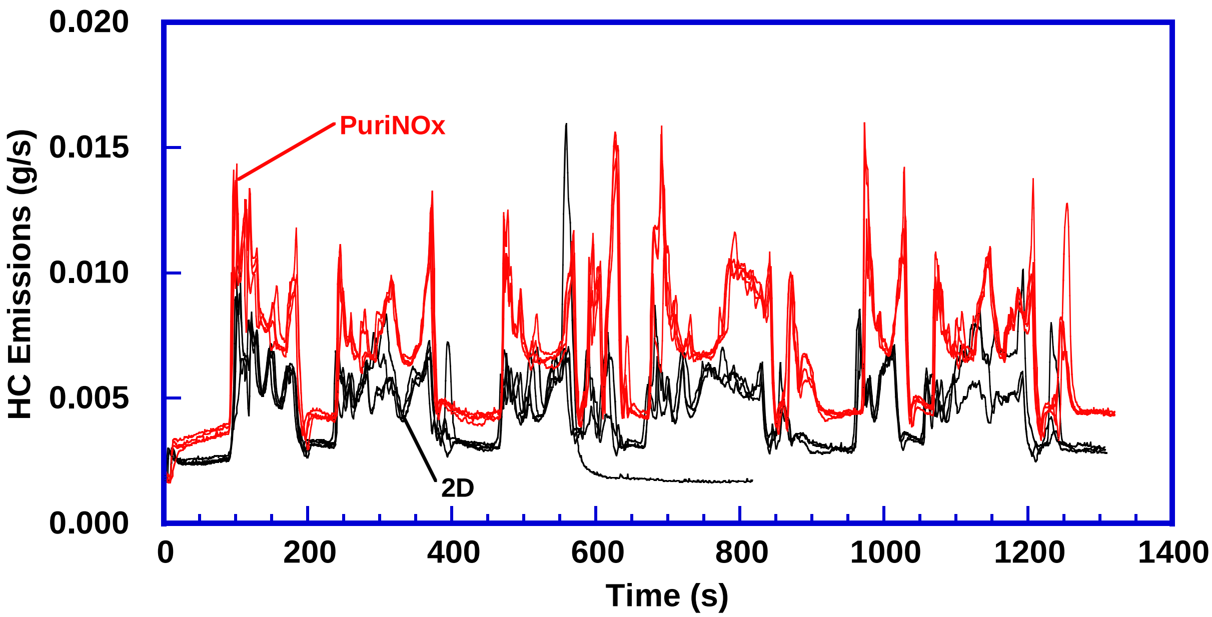


Figure B.3.10 Comparison of HC emissions for the Navistar single-axle dump truck with the International 7.6TI-6 engine

Table B.11 Detailed Results for the Mechanically-Controlled International 7.6TI-6 Engine in the 1993 Navistar Single-Axle Dump Truck

Start	HC	PM	NOx	CO2	CO	Fuel Economy	Reference distance	Actual distance	Actual vs. Ref. (%)	Average speed
	g/mile					mpg	miles			mph
2D on-road diesel										
Cold	0.34	0.480	11.15	1633	2.07	6.00	8.78	8.80	0.2	24.1
Hot	0.35	0.388	10.56	1584	1.73	6.18	8.78	8.79	0.1	24.2
Hot	0.33	0.363	10.50	1524	1.67	6.43	8.78	8.80	0.2	24.2
Hot	0.31	0.350	10.75	1448	1.52	6.77	8.78	8.82	0.5	24.3
Hot	0.36	0.408	10.84	1553	1.84	6.31	8.78	8.82	0.5	24.3
avg. hot	0.34	0.377	10.66	1527	1.69	6.42	8.78	8.81	0.3	24.2
composite	**0.34**	**0.392**	**10.73**	**1542**	**1.74**	**6.36**	**8.78**	**8.81**	**0.3**	**24.2**
hot std. dev.	0.02	0.03	0.16	58.43	0.13	0.25		0.01		0.06
hot CoV (%)	7.0	6.9	1.5	3.8	7.7	3.9		0.2		0.2
PuriNOx										
Cold	0.79	0.206	8.21	1536	2.23	5.38	8.78	8.81	0.3	23.9
Hot	0.85	0.177	7.94	1488	1.87	5.56	8.78	8.80	0.2	24.0
Hot	0.78	0.168	7.84	1458	1.69	5.68	8.78	8.80	0.2	23.9
Hot	0.82	0.168	8.09	1428	1.80	5.79	8.78	8.78	0.0	23.9
Hot	0.77	0.170	8.27	1407	1.72	5.88	8.78	8.79	0.1	23.9
avg. hot	0.80	0.171	8.04	1445	1.77	5.73	8.78	8.79	0.1	23.9
composite	**0.80**	**0.176**	**8.06**	**1458**	**1.83**	**5.68**	**8.78**	**8.80**	**0.2**	**23.9**
hot std. dev.	0.04	0.00	0.19	35.33	0.08	0.14		0.01		0.04
hot CoV (%)	4.5	2.5	2.3	2.4	4.5	2.4		0.1		0.2
hot % change	137	-54.7	-24.6	-5.4	5	-10.8		-0.2		-1.3
95% conf?	Y	Y	Y	N	N	Y		N		Y
comp. % change	136	-55.1	-24.9	-5.5	5	-10.8		-0.1		-1.2

Table B.12 Comparison of Distances for each Microtrip for each Fuel for the International 7.6TI-6 Engine in the 1993 Navistar Single-Axle Dump Truck

Fuel	Microtrip Number	Run No./Distance (m)				Avg.	Std. Dev.	Relative Difference	Lower limit	Upper limit	95% conf?
		1	2	3	4						
Diesel	1	1633.0	1646.1	1617.6	1620.2	1629.2	13.1		1616.4	1642.1	
	2	2847.6	2871.7	2863.0	2847.7	2857.5	11.9		2845.8	2869.2	
	3	2275.0	2246.3	2281.5		2267.6	18.7		2246.4	2288.8	
	4	3496.8	3484.7	3521.7		3501.1	18.9		3479.7	3522.4	
	5	992.7	980.4	958.8		977.3	17.2		957.9	996.7	
	6	2913.7	2940.2	2967.0		2940.3	26.7		2910.1	2970.5	
PuriNOx	1	1619.7	1623.9	1634.6	1617.8	1624.0	7.5	-0.32%	1616.6	1631.4	N
	2	2843.7	2827.8	2829.4	2852.0	2838.2	11.6	-0.67%	2826.8	2849.6	N
	3	2277.5	2294.6	2276.7	2267.4	2279.1	11.3	0.50%	2267.9	2290.2	N
	4	3510.2	3507.8	3517.1	3511.3	3511.6	3.9	0.30%	3507.7	3515.5	N
	5	968.0	983.0	975.0	976.6	975.7	6.2	-0.17%	969.6	981.7	N
	6	2953.4	2937.0	2914.4	2932.2	2934.3	16.0	-0.21%	2918.5	2950.0	N

B.3.D. Cummins 1060 – The results for the 1996 Ford F800 with the mechanically-controlled Cummins 1060 engine are illustrated in Figure B.3.11 for the composite TxDOT Single-Axle Dump Truck Cycle. Detailed results are provided in Table B.13. The distances traveled for each microtrip on each fuel are compared in Table B.14. As shown in this table, the differences between the two fuels in the distance per microtrip for the 6 individual microtrips are not statistically significant, with 95% confidence. This is also true for the distance for the overall cycle, as shown in Table B.13. Therefore, these tests are a valid basis for comparing the two fuels.

PuriNOx produces the expected benefits in NOx (24%) and PM (21%) with a fuel economy penalty of 16% and penalties in CO and HC emissions. All differences for the hot starts, except CO_2 and distance traveled (Table B.13) are statistically significant at the 95% confidence level. It is assumed that this is true for the composite results as well. The vehicle speed histories for this dump truck operating on 2D on-road diesel and PuriNOx are compared in Figure B.3.12.

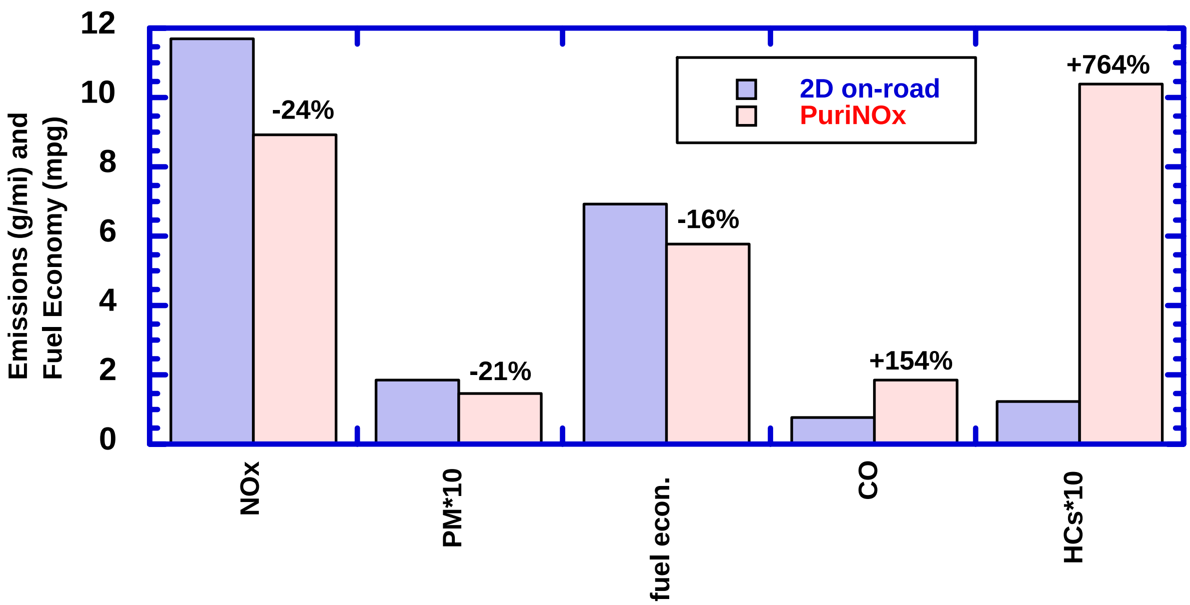


Figure B.3.11 Regulated emissions and fuel economy for the 1996 Ford with the Cummins 1060 engine operating over the TxDOT Single-Axle Dump Truck Cycle

Although the average distances per microtrip are not statistically different, there is a small but statistically significant difference in the average vehicle speeds, as shown in Table B.13. The vehicle speed histories for this dump truck operating on 2D on-road diesel and PuriNOx are compared in Figure B.3.12. This figure also compares the NOx emissions, and the HC emissions are compared in Figure B.3.13. This vehicle did not have much trouble staying on the cycle when using PuriNOx, but the average speed over the cycle was slightly lower when operating on PuriNOx. The NOx emissions were lower at all times when using PuriNOx but the HC emissions were higher, especially during the accels.

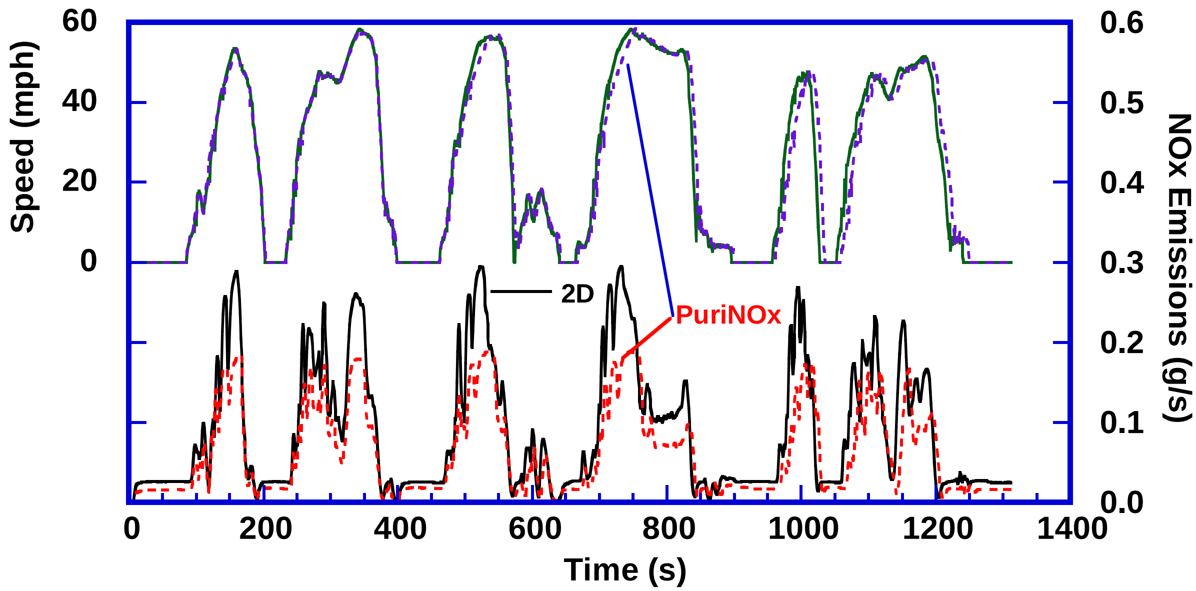


Figure B.3.12 Comparison of vehicle speeds and NOx emissions for the Ford single-axle dump truck with the Cummins 1060 engine

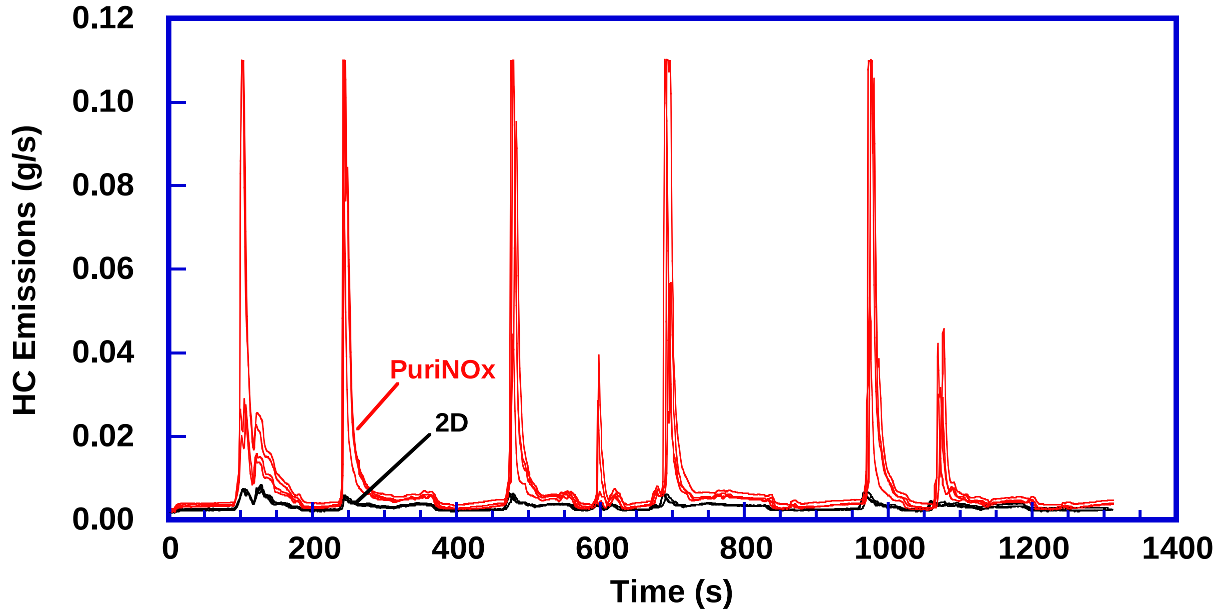


Figure B.3.13 Comparison of HC emissions for the Ford single-axle dump truck with the Cummins 1060 engine

Table B.13 Regulated Emissions from the Cummins 1060 for Each of the Cold and Hot Start TxDOT Single-Axle Dump Truck Cycles

Start	HC	PM	NOx	CO2	CO	Fuel Economy	Reference distance	Actual distance	Actual vs. Ref. (%)	Average speed
	g/mile					mpg	miles			mph
2D on-road diesel										
Cold	0.17	0.196	12.14	1503	1.02	6.52	8.78	8.80	0.23	24.16
Hot	0.15	0.176	11.78	1420	0.74	6.91	8.78	8.80	0.23	24.12
Hot	0.10	0.186	11.68	1412	0.70	6.94	8.78	8.79	0.11	24.21
Hot	0.11	0.190	11.56	1407	0.69	6.97	8.78	8.80	0.23	24.25
Hot	0.09	0.190	11.58	1400	0.67	7.01	8.78	8.79	0.11	24.16
avg. hot	0.11	0.186	11.65	1410	0.70	6.96	8.78	8.80	0.17	24.19
composite	**0.12**	**0.187**	**11.72**	**1423**	**0.75**	**6.90**	**8.78**	**8.80**	**0.18**	**24.18**
hot std. dev.	0.03	0.01	0.10	8.67	0.03	0.04		0.01		0.05
hot CoV (%)	22.5	3.6	0.9	0.6	4.3	0.6		0.1		0.2
PuriNOx										
Cold	1.51	0.226	8.97	1498	2.93	5.48	8.78	8.81	0.34	24.03
Hot	0.80	0.135	8.77	1428	1.53	5.78	8.78	8.79	0.11	24.07
Hot	0.95	0.136	8.94	1406	1.75	5.87	8.78	8.79	0.11	24.00
Hot	0.94	0.127	9.22	1404	1.76	5.87	8.78	8.80	0.23	23.99
Hot	1.15	0.144	8.80	1401	1.85	5.89	8.78	8.79	0.11	23.95
avg. hot	0.96	0.136	8.93	1410	1.72	5.85	8.78	8.79	0.14	24.00
composite	**1.04**	**0.148**	**8.94**	**1422**	**1.89**	**5.80**	**8.78**	**8.80**	**0.17**	**24.01**
hot std. dev.	0.14	0.01	0.20	12.25	0.14	0.05		0.00		0.05
hot CoV (%)	14.9	5.1	2.3	0.9	8.1	0.8		0.1		0.2
hot % change	760	-27.0	-23.3	0.0	146	-15.9		0.0		-0.8
95% conf?	Y	Y	Y	N	Y	Y		N		Y
comp. % change	764	-20.6	-23.7	-0.1	154	-15.9		0.0		-0.7

Table B.14 Comparison of Distances for each Microtrip for each Fuel for the Cummins 1060 Engine in the 1996 Ford F800 Single-Axle Dump Truck

Fuel	Microtrip Number	Run No./Distance (m) 1	2	3	4	Avg.	Std. Dev.	Relative Difference	Lower limit	Upper limit	95% conf?
Diesel	1	1619.4	1610.5	1627.6	1626.4	1621.0	7.9		1613.3	1628.7	
	2	2845.0	2864.8	2890.7	2854.9	2863.9	19.6		2844.6	2883.1	
	3	2273.1	2261.7	2273.1	2267.9	2269.0	5.4		2263.6	2274.3	
	4	3538.2	3541.9	3531.2	3520.7	3533.0	9.3		3523.9	3542.1	
	5	955.9	958.3	920.5	955.7	947.6	18.1		929.9	965.3	
	6	2938.7	2927.0	2937.1	2938.2	2935.3	5.5		2929.8	2940.7	
PuriNOx	1	1607.2	1619.1	1616.9	1626.9	1617.5	8.1	-0.21%	1609.6	1625.5	N
	2	2865.8	2852.2	2846.5	2840.4	2851.2	10.8	-0.44%	2840.6	2861.9	N
	3	2271.8	2268.7	2299.2	2278.0	2279.4	13.7	0.46%	2266.0	2292.9	N
	4	3515.4	3526.1	3503.9	3524.7	3517.5	10.2	-0.44%	3507.5	3527.6	N
	5	971.1	958.3	985.9	959.5	968.7	12.8	2.23%	956.1	981.3	N
	6	2929.0	2933.1	2927.7	2933.1	2930.7	2.8	-0.15%	2928.0	2933.5	N

B.4. Tandem-Axle Dump Trucks

SwRI measured the emissions and fuel economy of four tandem-axle dump trucks operating over the TxDOT Tandem-Axle Dump Truck Cycle. This cycle is described in detail in Appendix A. The chassis dyno was set to simulate a loaded vehicle weight of 47,000 lb (these trucks have a GVW Rating of ~54,000 lb and weigh about 24,000 lb when empty, depending upon the specific truck). The four tandem-axle dump trucks were:

- 1990 Volvo WG64F with a mechanically-controlled Cummins L10-300 (10.0 L, 300 hp, 1900 rpm, engine serial no. 34613220, Engine Family 343G, TxDOT Eqpt no. 15-4144-E; certification standards: 5.0 gNOx/hp-hr, 0.10 gPM/hp-hr)
- 2000 International 2574 with an electronically-controlled Caterpillar C10 (10.3 L, 305 hp, 1700 rpm, engine serial no. 3CS0382, Engine Family XCPXH0629ERK, TxDOT Eqpt no. 15-5186-G; certification standards: 4.0 gNOx/hp-hr, 0.10 gPM/hp-hr)
- 1989 GMC-White with a mechanically-controlled Cummins L10-300 (10 L, 295 hp, 1800 rpm, engine serial no. 34591612 CPL1223, Engine Family 343C, TxDOT Eqpt no. 23-5675-D; certification standards: 6.0 gNOx/hp-hr, 0.6 gPM/hp-hr)
- 1996 Ford LT9000 with an electronically-controlled Caterpillar 3176 (10.3 L, 300 hp,1700 rpm, engine serial no. CA9CK24776, TxDOT Eqpt no. 17-5573-F; certification standards: 5.0 gNOx/hp-hr, 0.10 gPM/hp-hr)

As discussed in Section B.3 for the single-axle dump trucks, “route” tests were performed for the tandem-axle dump trucks as well. Again, only two fuels are compared in this subsection: PuriNOx and 2D on-road diesel fuel (results for other fuels are discussed in Section B.5). The emissions and fuel economy for each of the four tandem-axle dump trucks are discussed in the following subsections.

B.4.A. 1990 Cummins L10-300 – The test plan called for a 2000 Volvo with an electronically-controlled Cummins ISM305V engine. However, a 1990 Volvo with a mechanically-controlled Cummins L10-300 was inadvertently delivered and tested. This may have been fortunate due to the unusual response of the 1989 L10-300 to PuriNOx. The results for the 1989 L10-300 are discussed in Subsection B.4.C. Both L10-300s responded similarly to PuriNOx.

The results for the 1990 Volvo with the Cummins L10-300 engine are illustrated in Figure B.4.1 for the composite TxDOT Tandem-Axle Dump Truck Cycle. Detailed results are provided in Table B.15. The distances traveled for each microtrip on each fuel are compared in Table B.16. As shown in this table, the difference in the distance per microtrip for the two fuels is not statistically significant, with 95% confidence, for any of the 5 individual microtrips. This is also true for the overall cycle distance, as shown in Table B.15. Therefore, these tests are a valid basis for comparing the two fuels.

PuriNOx produces only a 7% NOx benefit and PM emissions that are not statistically different at the 95% confidence level. The fuel economy penalty is 14%. PuriNOx produced the usual increase in HC emissions but a decrease in CO for this application.

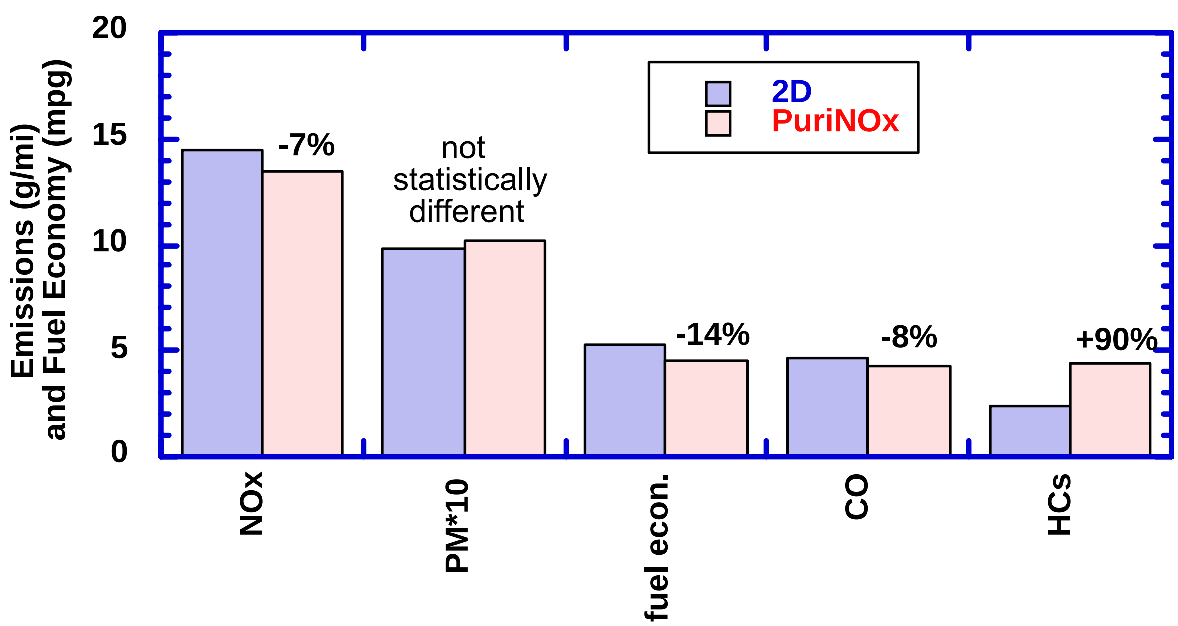


Figure B.4.1 Regulated emissions and fuel economy for the 1990 Volvo with the Cummins L10-300 operating over the TxDOT Tandem-Axle Dump Truck Cycle

The second-by-second histories for this dump truck are provided in Figure B.4.2, for speed and NOx emissions, and Figure B.4.3 for HC emissions. As shown in Figure B.4.2, this vehicle had no difficulty running the same speed versus time trace on PuriNOx as when using diesel fuel. This is also indicated in Table B.15: the difference in the average speed over the cycle for PuriNOx compared to diesel fuel is not statistically significant with 95% confidence. As shown in Figure B.4.2, the difference in the NOx emissions is very small for most times during the cycle, and there are a few occasions when the NOx emissions are higher when using PuriNOx. These observations from Figure B.4.2 support the small (7%) NOx benefit for the overall cycle. The HC emissions are higher at most times during the cycle.

Table B.15 Regulated Emissions from the 1990 Cummins L10-300 for Each of the Cold and Hot Start TxDOT Tandem-Axle Dump Truck Cycles

Start	HC	PM	NOx	CO2	CO	Fuel Economy	Reference distance	Actual distance	Actual vs. Ref. (%)	Average speed
	g/mile					mpg	miles			mph
2D on-road diesel										
Cold	2.75	1.12	14.72	1829	5.02	5.32	10.58	10.61	0.28	24.91
Hot	2.35	0.99	14.61	1851	4.70	5.26	10.58	10.64	0.57	25.06
Hot	2.27	0.99	14.52	1853	4.56	5.26	10.58	10.62	0.38	25.04
Hot	2.32	0.92	14.42	1840	4.56	5.30	10.58	10.61	0.28	25.05
Hot	2.23	0.94	14.29	1837	4.44	5.30	10.58	10.62	0.38	25.04
avg. hot	2.29	0.96	14.46	1845	4.56	5.28	10.58	10.62	0.40	25.05
composite	**2.36**	**0.983**	**14.50**	**1843**	**4.63**	**5.29**	**10.58**	**10.62**	**0.38**	**25.03**
hot std. dev.	0.053	0.037	0.139	7.958	0.103	0.023		0.013		0.011
hot CoV (%)	2.3	3.9	1.0	0.4	2.3	0.4		0.1		0.0
PuriNOx										
Cold	5.36	1.175	13.61	1896	5.04	4.33	10.58	10.63	0.47	24.95
Hot	4.29	0.995	13.60	1815	4.14	4.53	10.58	10.64	0.57	25.00
Hot	4.08	0.942	13.42	1810	4.02	4.54	10.58	10.61	0.28	24.94
Hot	4.03	0.909	13.61	1817	3.92	4.53	10.58	10.61	0.28	24.93
Hot	4.89	1.116	12.97	1765	4.32	4.65	10.58	10.62	0.38	25.01
avg. hot	4.32	0.991	13.40	1802	4.10	4.56	10.58	10.62	0.38	24.97
composite	**4.47**	**1.017**	**13.43**	**1815**	**4.24**	**4.53**	**10.58**	**10.62**	**0.39**	**24.97**
hot std. dev.	0.397	0.091	0.302	24.574	0.172	0.059		0.014		0.041
hot CoV (%)	9.2	9.2	2.3	1.4	4.2	1.3		0.1		0.2
hot % change	89	3.1	-7.3	-2.3	-10	-13.6		0.0		-0.3
95% conf?	Y	N	Y	Y	Y	Y		N		N
comp. % change	90	3.4	-7.4	-1.5	-8	-14.3		0.0		-0.3

Table B.16 Comparison of Distances for each Microtrip for each Fuel for the Cummins L10-300 Engine in the 1990 Volvo Tandem-Axle Dump Truck

Fuel	Microtrip Number	Run No./Distance (m) 1	2	3	4	Avg.	Std. Dev.	Relative Difference	Lower limit	Upper limit	95% conf?
Diesel	1	5489.4	5508.0	5509.1	5502.3	5502.2	9.0		5493.3	5511.1	
	2	2629.1	2608.8	2610.2	2614.0	2615.5	9.3		2606.4	2624.7	
	3	2158.2	2165.9	2167.1	2178.4	2167.4	8.3		2159.2	2175.6	
	4	1646.8	1640.5	1633.2	1623.4	1636.0	10.1		1626.1	1645.8	
	5	4863.0	4837.8	4841.3	4840.9	4845.8	11.6		4834.4	4857.1	
PuriNOx	1	5491.7	5485.3	5491.4	5471.4	5485.0	9.5	-0.31%	5475.6	5494.3	N
	2	2626.2	2620.6	2622.1	2614.0	2620.7	5.1	0.20%	2615.8	2625.7	N
	3	2167.3	2163.5	2151.1	2154.2	2159.0	7.6	-0.39%	2151.5	2166.5	N
	4	1631.0	1642.5	1654.4	1650.8	1644.7	10.4	0.53%	1634.5	1654.9	N
	5	4857.9	4838.7	4828.5	4830.4	4838.9	13.4	-0.14%	4825.7	4852.0	N

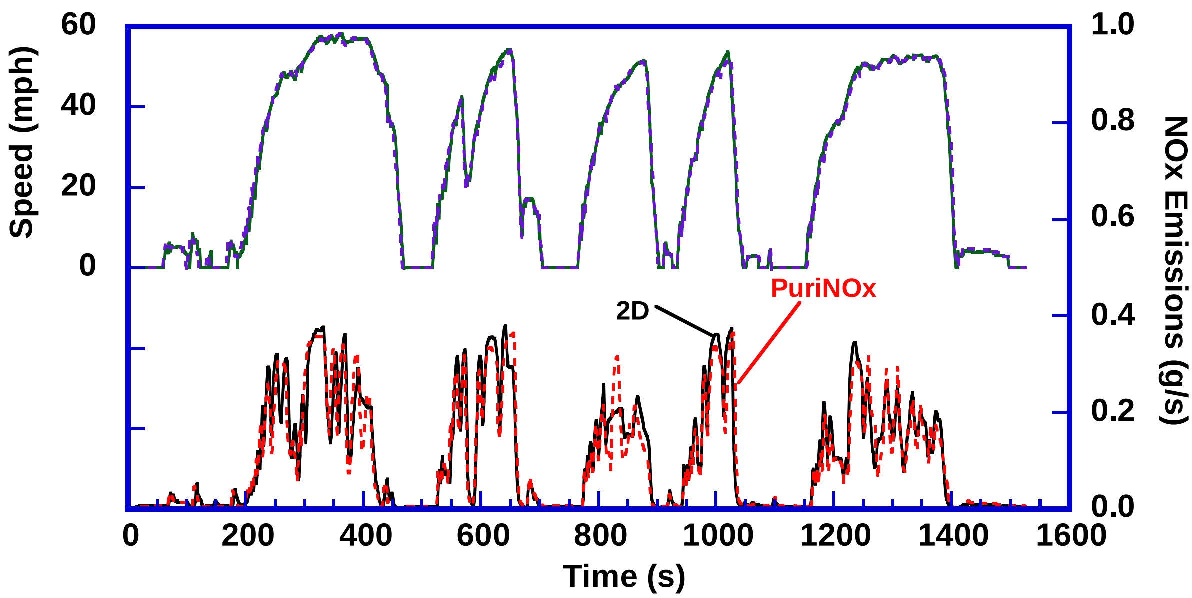


Figure B.4.2 Vehicle speed and NOx emissions comparisons for the 1990 Volvo with the Cummins L10-300 operating over the TxDOT Tandem-Axle Dump Truck Cycle

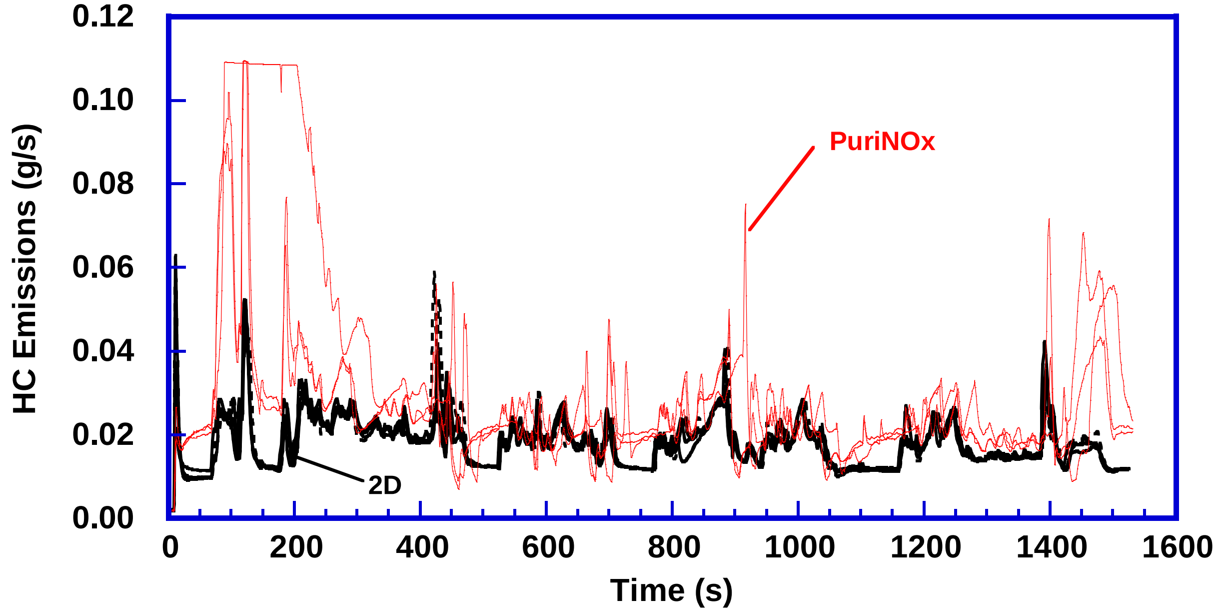


Figure B.4.3 Comparison of HC emissions for the 1990 Volvo with the Cummins L10-300 operating over the TxDOT Tandem-Axle Dump Truck Cycle

B.4.B. Caterpillar C10 – The results for the 2000 International with the Cat C10 engine are illustrated in Figure B.4.4 for the composite TxDOT Tandem-Axle Dump Truck Cycle. Detailed results are provided in Table B.17. The distances traveled for each microtrip on each fuel are compared in Table B.18. For 3 of the 5 microtrips, the distance per microtrip was not statistically different for the two fuels, with 95% confidence. The second and fifth microtrips were longer - by ~40 and ~18 meters, respectively, on average – for the PuriNOx tests. However, these differences were only 1.61% and 0.36% of the respective microtrip lengths. As shown in Table B.17, the difference in the distance traveled for the overall cycle was not statistically significant. Therefore, we believe that these tests are acceptable for valid comparisons of the two fuels.

PuriNOx produces the expected benefits in NOx (13%) and PM (34%) with a fuel economy penalty of 13%. All differences for the hot starts, except overall distance and average speed (Table B.18), are statistically significant with 95% confidence. It is assumed that this is true for the composite results as well.

The vehicle speed, NOx, and HC histories for this dump truck operating on 2D on-road diesel and PuriNOx are compared in Figures B.4.5 and B.4.6. This dump truck had no difficulty keeping up with the cycle when using PuriNOx. The NOx emissions were lower but the HC emissions were much higher at all times during the cycle.

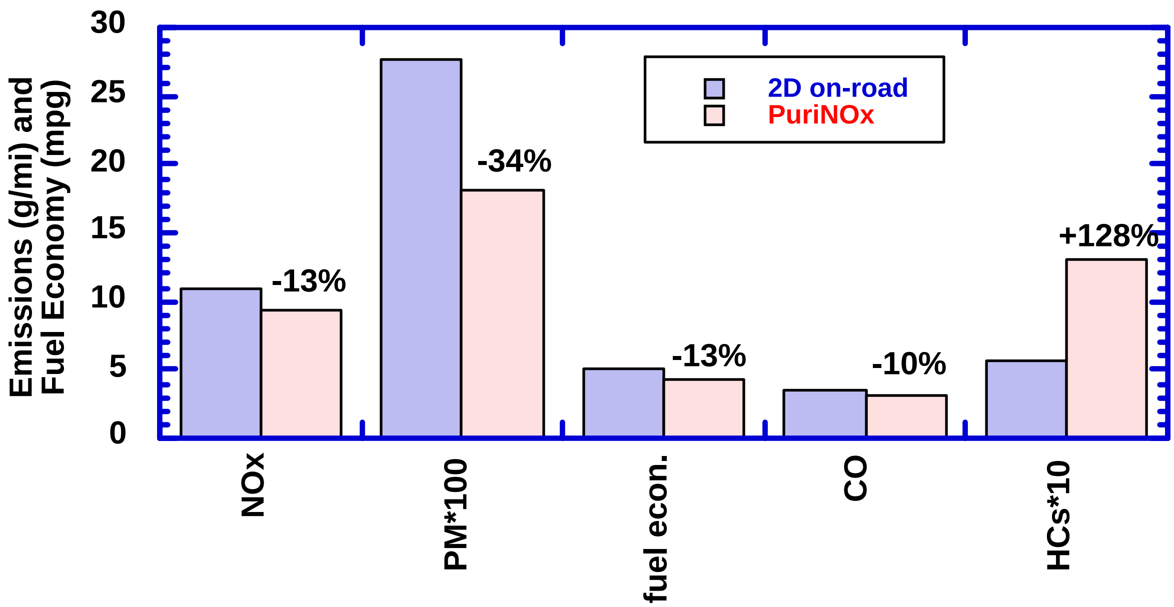


Figure B.4.4 Regulated emissions and fuel economy for the 2000 International 2574 with the Cat C10 operating over the TxDOT Tandem-Axle Dump Truck Cycle

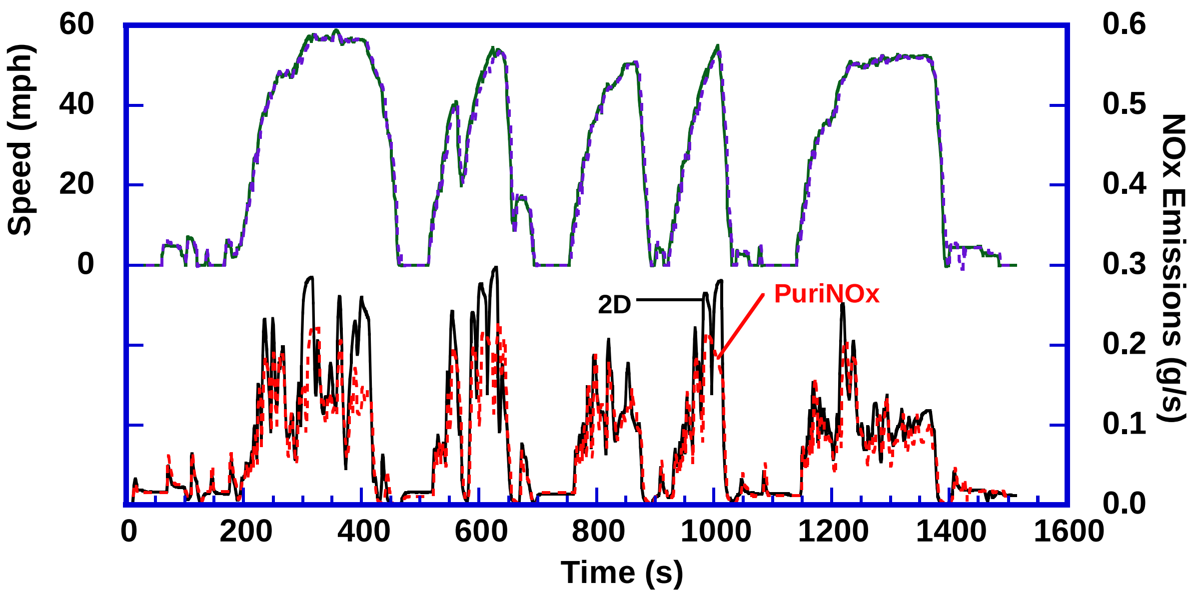


Figure B.4.5 Vehicle speed and NOx emissions comparisons for the 2000 International 2574 with the Cat C10 operating over the TxDOT Tandem-Axle Dump Truck Cycle

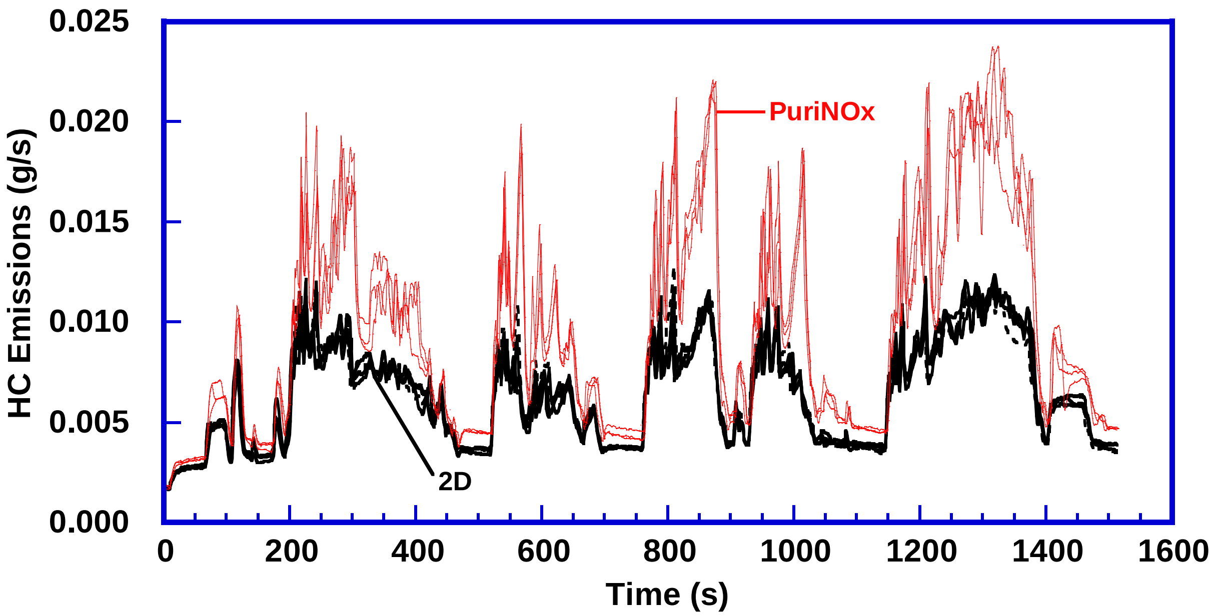


Figure B.4.6 Comparison of HC emissions for the 2000 International 2574 with the Cat C10 operating over the TxDOT Tandem-Axle Dump Truck Cycle

Table B.17 Regulated Emissions from the Caterpillar C10 for Each of the Cold and Hot Start TxDOT Tandem-Axle Dump Truck Cycles

Start	HC	PM	NOx	CO2	CO	Fuel Economy	Reference distance	Actual distance	Actual vs. Ref. (%)	Average speed
	g/mile					mpg	miles			mph
2D on-road diesel										
Cold	0.51	0.289	11.52	2028	3.79	4.82	10.58	10.38	-1.9	24.70
Hot	0.60	0.270	10.53	1948	3.63	5.02	10.58	10.41	-1.6	24.77
Hot	0.57	0.277	10.70	1950	3.56	5.02	10.58	10.44	-1.3	24.84
Hot	0.58	0.271	10.65	1956	3.53	5.00	10.58	10.45	-1.2	24.86
Hot	0.56	0.276	10.95	1932	3.50	5.06	10.58	10.47	-1.0	24.91
avg. hot	0.58	0.274	10.71	1946	3.55	5.03	10.58	10.44	-1.3	24.85
composite	**0.57**	**0.276**	**10.82**	**1958**	**3.59**	**5.00**	**10.58**	**10.43**	**-1.4**	**24.83**
hot std. dev.	0.02	0.00	0.17	10.32	0.05	0.03		0.02		0.06
hot CoV (%)	3.3	1.3	1.6	0.5	1.5	0.5		0.2		0.2
PuriNOx										
Cold	1.37	0.219	9.07	1973	4.05	4.19	10.43	10.48	0.4	24.85
Hot	1.24	0.180	9.78	1881	3.13	4.39	10.43	10.47	0.3	24.86
Hot	1.27	0.169	9.48	1885	3.06	4.38	10.43	10.49	0.5	24.90
Hot	1.28	0.165	9.19	1883	3.05	4.39	10.43	10.51	0.7	24.95
Hot	1.35	0.185	9.59	1881	3.07	4.39	10.43	10.47	0.3	24.90
avg. hot	1.28	0.175	9.51	1882	3.07	4.39	10.43	10.49	0.5	24.90
composite	**1.30**	**0.181**	**9.45**	**1895**	**3.21**	**4.36**	**10.43**	**10.48**	**0.5**	**24.89**
hot std. dev.	0.05	0.01	0.25	2.19	0.03	0.00		0.02		0.04
hot CoV (%)	3.6	5.3	2.6	0.1	1.1	0.1		0.2		0.1
hot % change	122	-36.1	-11.2	-3.3	-13.5	-12.7		0.4		0.2
95% conf?	Y	Y	Y	Y	Y	Y		N		N
comp. % change	128	-34.3	-12.7	-3.2	-10.4	-12.7		0.5		0.3

Table B.18 Comparison of Distances for each Microtrip for each Fuel for the Caterpillar C10 Engine in the 2000 International 2574 Tandem-Axle Dump Truck

Fuel	Microtrip Number	Run No./Distance (m) 1	2	3	4	Avg.	Std. Dev.	Relative Difference	Lower limit	Upper limit	95% conf?
Diesel	1	5449.8	5456.5	5482.3	5471.2	5465.0	14.6		5450.6	5479.3	
	2	2497.4	2520.8	2492.5	2516.5	2506.8	13.9		2493.1	2520.5	
	3	2135.2	2134.5	2141.8	2149.5	2140.3	7.0		2133.4	2147.1	
	4	1575.6	1561.4	1581.0	1577.0	1573.8	8.5		1565.4	1582.1	
	5	4788.2	4809.4	4814.9	4817.9	4807.6	13.4		4794.5	4820.7	
PuriNOx	1	5469.9	5479.8	5478.7	5466.2	5473.7	6.7	0.16%	5467.1	5480.2	N
	2	2543.2	2545.5	2555.5	2544.0	2547.1	5.7	1.61%	2541.5	2552.6	Y
	3	2150.5	2140.5	2149.0	2148.6	2147.2	4.5	0.32%	2142.7	2151.6	N
	4	1577.6	1580.7	1578.7	1585.1	1580.5	3.3	0.43%	1577.3	1583.8	N
	5	4820.5	4823.0	4827.3	4829.7	4825.1	4.1	0.36%	4821.1	4829.2	Y

B.4.C. 1989 Cummins L10-300 – The results for the 1989 GMC-White with the Cummins L10-300 engine are illustrated in Figure B.4.7 for the composite TxDOT Tandem-Axle Dump Truck Cycle. Detailed results are provided in Table B.19. The distances traveled for each microtrip on each fuel are compared in Table B.20. As shown in this table, for the last 3 of the 5 microtrips, the difference in the distance per microtrip for the two fuels is not statistically different, with 95% confidence. However, the first microtrip was 29 meters longer and the second was 24 meters shorter, on average, for the diesel fuels runs compared to PuriNOx. Since each represents less than a 1% difference, and because the difference in distance for the overall cycle was not statistically significant, we believe that these tests are a valid means for comparison between the two fuels.

As shown in Figure B.4.7 and Table B.19, PuriNOx produced only a 4.5% NOx benefit. However, since the average 3.8% NOx benefit for the hot starts was not statistically distinguishable – with 95% confidence - for the two fuels, it is assumed that the difference in the composite NOx emissions are not statistically significant either. However, the emissions reduction calculations in Section 5 are based upon the Emissions Index (grams of NOx per kilogram of fuel consumed) rather than on the emissions rate (g/mi). The Emissions Index is the product of the emissions rate and the fuel economy, divided by the density of the fuel. For the hot starts, the Emissions Index for NOx is 15.4% lower for the PuriNOx tests, and this difference is statistically significant with 95% confidence. As also shown in Figure B.4.7, PuriNOx produced a 30% PM benefit with an 11% penalty in fuel economy, along with a CO benefit and a penalty in HC emissions.

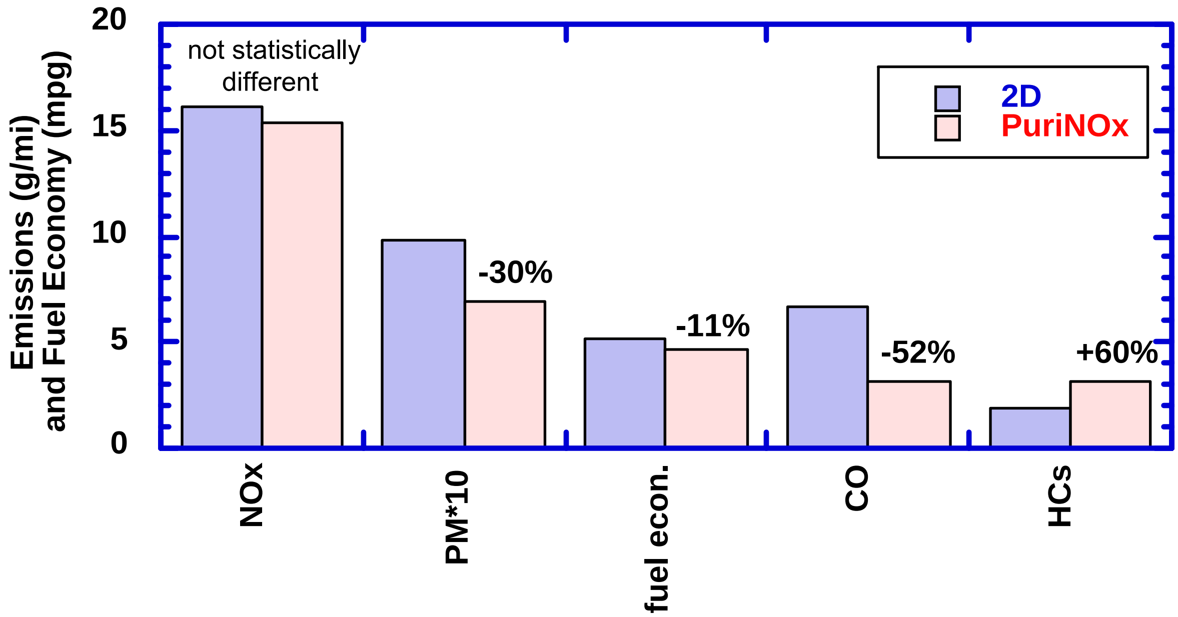


Figure B.4.7 Regulated emissions and fuel economy for the 1989 GMC-White with the Cummins L10-300 operating over the TxDOT Tandem-Axle Dump Truck Cycle

The vehicle speed and NOx emissions histories for the two fuels are presented in Figure B.4.8 and the HC histories are shown in Figure B.4.9. This dump truck had little problem staying on the cycle when using PuriNOx, but the average speed was slightly slower due to some difficulties with the more demanding accels. At any given time, or distance, during the cycle, there is little difference in the NOx mass emissions rates, with some occasions when the NOx emissions for PuriNOx were higher. These observations from Figure B.4.8 support the finding of a very small NOx benefit for the overall cycle. As shown in Figure B.4.9, the HC emissions are higher at almost all times when using PuriNOx.

Table B.19 Regulated Emissions from the 1989 Cummins L10-300 for Each of the Cold and Hot Start TxDOT Tandem-Axle Dump Truck Cycles

Start	HC	PM	NOx	CO2	CO	Fuel Economy	Reference distance	Actual distance	Actual vs. Ref. (%)	Average speed
	g/mile					mpg	miles			mph
2D on-road diesel										
Cold	2.07	1.139	16.89	1962	7.55	4.96	10.58	10.65	0.66	25.22
Hot	1.90	0.956	15.76	1839	6.64	5.29	10.58	10.64	0.57	25.25
Hot	1.95	0.973	15.28	1840	6.24	5.29	10.58	10.64	0.57	25.20
Hot	1.91	0.953	15.96	1866	6.74	5.21	10.58	10.65	0.66	25.24
Hot	1.90	0.942	16.66	1890	6.44	5.15	10.58	10.63	0.47	25.18
avg. hot	1.91	0.956	15.92	1859	6.52	5.24	10.58	10.64	0.57	25.22
composite	**1.94**	**0.982**	**16.05**	**1873**	**6.66**	**5.20**	**10.58**	**10.64**	**0.58**	**25.22**
hot std. dev.	0.02	0.01	0.57	24.67	0.22	0.07		0.01		0.03
hot CoV (%)	1.3	1.3	3.6	1.3	3.4	1.3		0.1		0.1
PuriNOx										
Cold	3.47	0.799	15.48	1897	3.87	4.34	10.58	10.62	0.38	24.98
Hot	2.99	0.650	15.76	1795	3.00	4.59	10.58	10.63	0.47	25.08
Hot	3.01	0.660	15.03	1760	3.11	4.68	10.58	10.63	0.47	25.11
Hot	3.08	0.720	15.03	1734	2.97	4.75	10.58	10.64	0.57	25.12
Hot	3.04	0.656	15.44	1757	3.27	4.69	10.58	10.64	0.57	25.10
avg. hot	3.03	0.672	15.31	1761	3.09	4.68	10.58	10.64	0.52	25.10
composite	**3.09**	**0.690**	**15.34**	**1781**	**3.20**	**4.63**	**10.58**	**10.63**	**0.50**	**25.09**
hot std. dev.	0.04	0.03	0.35	25.49	0.14	0.07		0.01		0.02
hot CoV (%)	1.3	4.9	2.3	1.4	4.4	1.4		0.1		0.1
hot % change	58	-29.8	-3.8	-5.2	-53	-10.6		0.0		-0.5
95% conf?	Y	Y	N	Y	Y	Y		N		Y
comp. % change	60	-29.8	-4.5	-4.9	-52	-10.9		-0.1		-0.5

Table B.20 Comparison of Distances for each Microtrip for each Fuel for the Cummins L10-300 Engine in the 1989 GMC-White Tandem-Axle Dump Truck

Fuel	Microtrip Number	Run No./Distance (m)				Avg.	Std. Dev.	Relative Difference	Lower limit	Upper limit	95% conf?
		1	2	3	4						
Diesel	1	5535.3	5511.4	5502.6	5514.2	5515.9	13.9		5502.3	5529.5	
	2	2586.9	2604.7	2614.2	2605.6	2602.9	11.5		2591.6	2614.1	
	3	2184.2	2165.0	2168.1	2157.6	2168.7	11.2		2157.7	2179.7	
	4	1623.9	1653.7	1658.5	1644.2	1645.1	15.3		1630.1	1660.1	
	5	4851.2	4845.6	4854.0	4867.4	4854.6	9.3		4845.5	4863.6	
PuriNOx	1	5494.5	5486.5	5491.0	5475.3	5486.8	8.4	-0.53%	5478.6	5495.0	Y
	2	2624.5	2631.1	2620.7	2629.3	2626.4	4.7	0.90%	2621.8	2631.0	Y
	3	2159.2	2170.2	2158.5	2166.4	2163.6	5.7	-0.24%	2158.0	2169.1	N
	4	1648.5	1625.9	1643.2	1646.3	1641.0	10.3	-0.25%	1630.9	1651.1	N
	5	4840.7	4844.0	4842.1	4847.5	4843.6	2.9	-0.23%	4840.7	4846.5	N

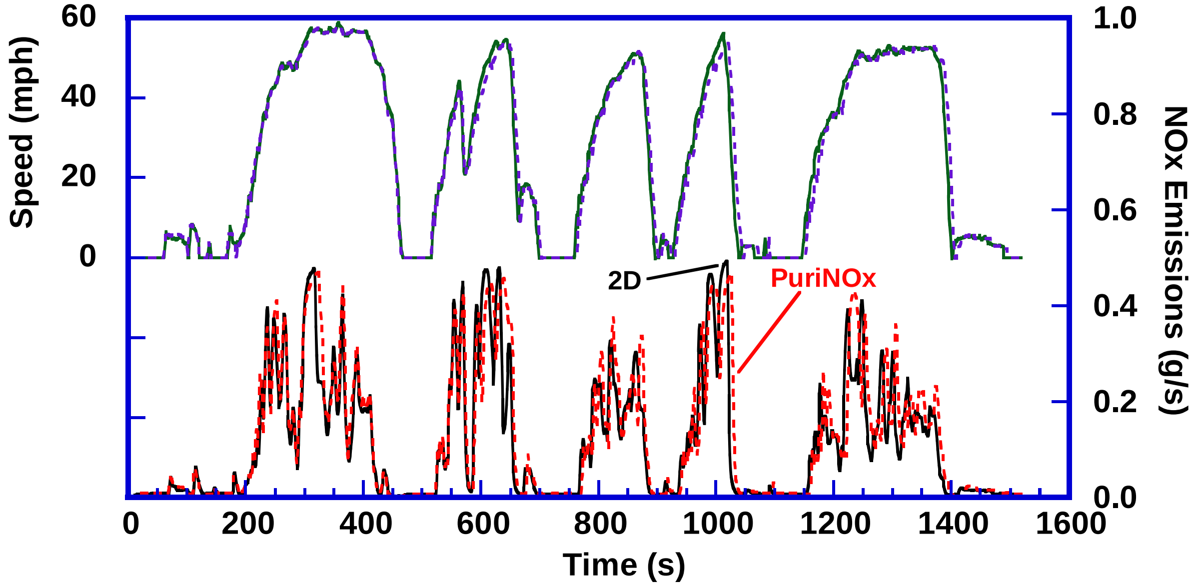


Figure B.4.8 Vehicle speed and NOx emissions comparisons for the 1989 GMC-White with the Cummins L10-300 operating over the TxDOT Tandem-Axle Dump Truck Cycle

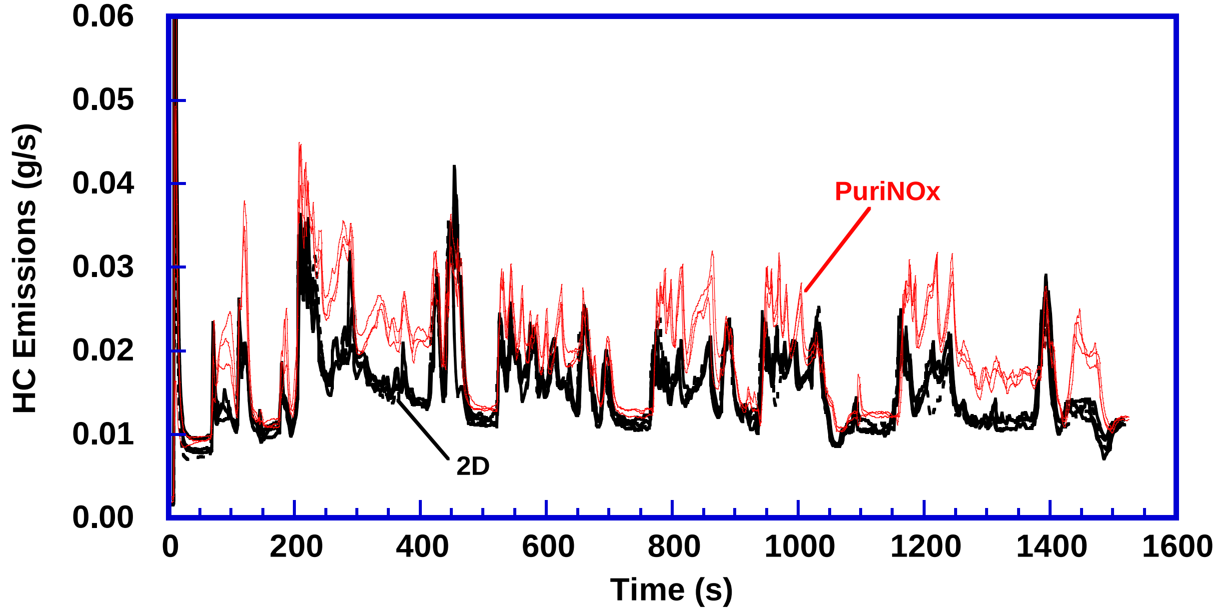


Figure B.4.9 Comparison of HC emissions for the 1989 GMC-White with the Cummins L10-300 operating over the TxDOT Tandem-Axle Dump Truck Cycle

B.4.D. Cat 3176 – The results for the 1996 Ford tandem with the Cat 3176 engine are illustrated in Figure B.4.10 for the composite TxDOT Tandem-Axle Dump Truck Cycle. Detailed results are provided in Table B.21. The distances traveled for each microtrip on each fuel are compared in Table B.22. As shown in this table, the difference in the distance per microtrip for the two fuels is not statistically significant, with 95% confidence, for any of the 5 microtrips. This is also true for the overall cycle distance, as shown in Table B.21. Therefore, the present results are a valid basis for comparing the two fuels.

PuriNOx produces the expected benefits in NOx (13%) and PM (14%) with a fuel economy penalty of 7%. As shown in Figure B.4.10, CO decreased while HCs increased. All differences for the hot starts, except overall distance (Table B.21), are statistically significant with 95% confidence. It is assumed that this is true for the composite results as well.

The vehicle speed, NOx, and HC histories for this dump truck operating on 2D on-road diesel and PuriNOx are compared in Figures B.4.11 and B.4.12. This dump truck had little problem staying on the cycle when using PuriNOx, but the average speed was slightly slower for PuriNOx. As shown in Figure B.4.11, the NOx mass emissions rate was lower at most times, but there were occasions when the NOx emissions were higher when using PuriNOx. As shown in Figure B.4.12, the HC emissions were generally higher when using PuriNOx, but there were some occasions when diesel fuel produced higher HC emissions rates. This observation helps explain the fact that the HC penalty for use of PuriNOx in this application was not as high as for most of the engines tested.

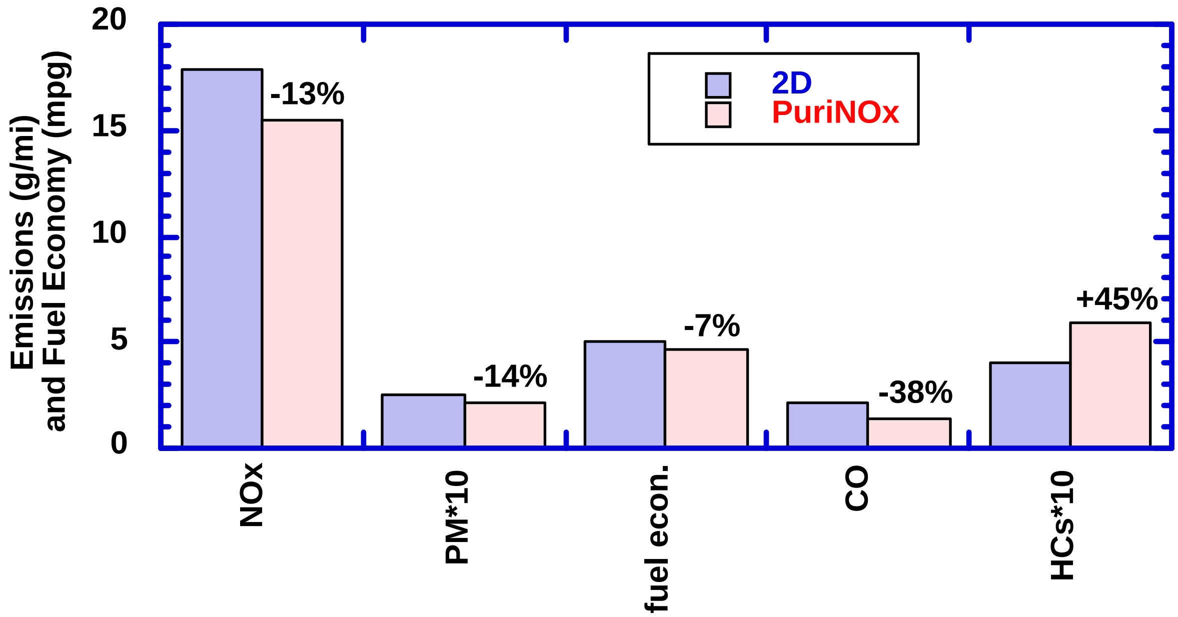


Figure B.4.10 Regulated emissions and fuel economy for the 1996 Ford with the Cat 3176 operating over the TxDOT Tandem-Axle Dump Truck Cycle

Table B.21 Regulated Emissions from the Caterpillar 3176 for Each of the Cold and Hot Start TxDOT Tandem-Axle Dump Truck Cycles

Start	HC	PM	NOx	CO2	CO	Fuel Economy	Reference distance	Actual distance	Actual vs. Ref. (%)	Average speed
	g/mile					mpg	miles			mph
2D on-road diesel										
Cold	0.45	0.293	19.64	2029	2.37	4.83	10.58	10.61	0.28	25.15
Hot	0.43	0.232	17.91	1956	2.06	5.01	10.58	10.62	0.38	25.13
Hot	0.41	0.260	17.76	1904	2.11	5.14	10.58	10.63	0.47	25.18
Hot	0.38	0.235	17.44	1941	2.18	5.05	10.58	10.61	0.28	25.14
Hot	0.37	0.237	17.15	1927	2.20	5.08	10.58	10.61	0.28	25.12
avg. hot	0.40	0.241	17.56	1932	2.14	5.07	10.58	10.62	0.35	25.15
composite	**0.40**	**0.248**	**17.86**	**1946**	**2.17**	**5.04**	**10.58**	**10.62**	**0.34**	**25.15**
hot std. dev.	0.03	0.01	0.34	21.84	0.07	0.05		0.01		0.03
hot CoV (%)	7.1	5.3	1.9	1.1	3.1	1.1		0.1		0.1
PuriNOx										
Cold	0.61	0.215	16.51	1926	1.67	4.30	10.58	10.61	0.28	25.09
Hot	0.60	0.201	15.52	1778	1.28	4.66	10.58	10.61	0.28	25.07
Hot	0.50	0.205	15.22	1760	1.33	4.71	10.58	10.60	0.19	25.06
Hot	0.57	0.216	15.15	1776	1.33	4.66	10.58	10.60	0.19	25.05
Hot	0.66	0.227	15.25	1700	1.24	4.87	10.58	10.60	0.19	25.04
avg. hot	0.58	0.212	15.29	1754	1.29	4.73	10.58	10.60	0.21	25.05
composite	**0.59**	**0.213**	**15.46**	**1778**	**1.35**	**4.66**	**10.58**	**10.60**	**0.22**	**25.06**
hot std. dev.	0.07	0.01	0.16	36.91	0.04	0.10		0.00		0.01
hot CoV (%)	11.9	5.5	1.1	2.1	3.4	2.1		0.0		0.1
hot % change	47	-11.9	-13.0	-9.2	-40	-6.8		-0.1		-0.4
95% conf?	Y	Y	Y	Y	Y	Y		N		Y
comp. % change	45	-14.4	-13.4	-8.6	-38	-7.4		-0.1		-0.3

Table B.22 Comparison of Distances for each Microtrip for each Fuel for the Caterpillar 3176 Engine in the 1996 Ford Tandem-Axle Dump Truck

Fuel	Microtrip Number	Run No./Distance (m) 1	2	3	4	Avg.	Std. Dev.	Relative Difference	Lower limit	Upper limit	95% conf?
Diesel	1	5501.5	5489.0	5485.1	5496.4	5493.0	7.4		5485.8	5500.2	
	2	2615.9	2636.8	2626.9	2623.8	2625.9	8.6		2617.4	2634.3	
	3	2148.4	2156.0	2170.8	2141.1	2154.1	12.7		2141.6	2166.5	
	4	1662.2	1657.5	1634.0	1673.0	1656.7	16.5		1640.6	1672.8	
	5	4842.0	4840.0	4828.1	4839.4	4837.4	6.3		4831.2	4843.5	
PuriNOx	1	5499.5	5493.3	5496.4	NA	5496.4	3.1	0.06%	5492.9	5499.9	N
	2	2620.8	2630.3	2623.8	NA	2625.0	4.9	-0.03%	2619.5	2630.5	N
	3	2154.1	2150.4	2141.1	NA	2148.5	6.7	-0.26%	2141.0	2156.1	N
	4	1655.1	1661.7	1673.0	NA	1663.3	9.1	0.40%	1653.0	1673.5	N
	5	4827.2	4836.5	4839.4	NA	4834.4	6.4	-0.06%	4827.2	4841.6	N

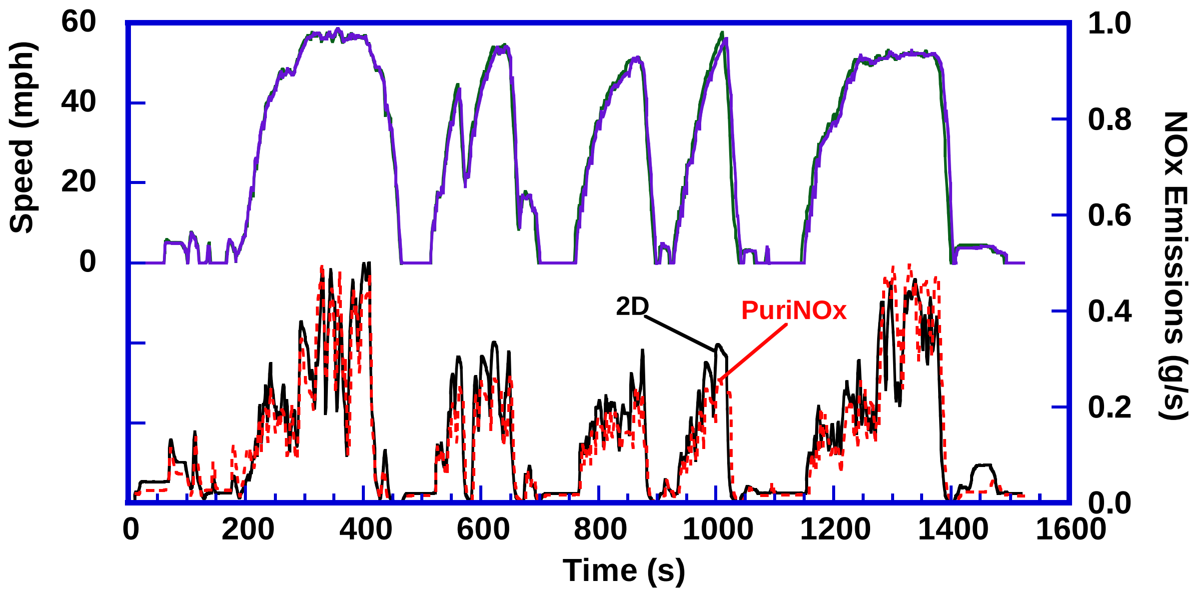


Figure B.4.11 Vehicle speed and NOx emissions comparisons for the 1996 Ford with the Cat 3176 operating over the TxDOT Tandem-Axle Dump Truck Cycle

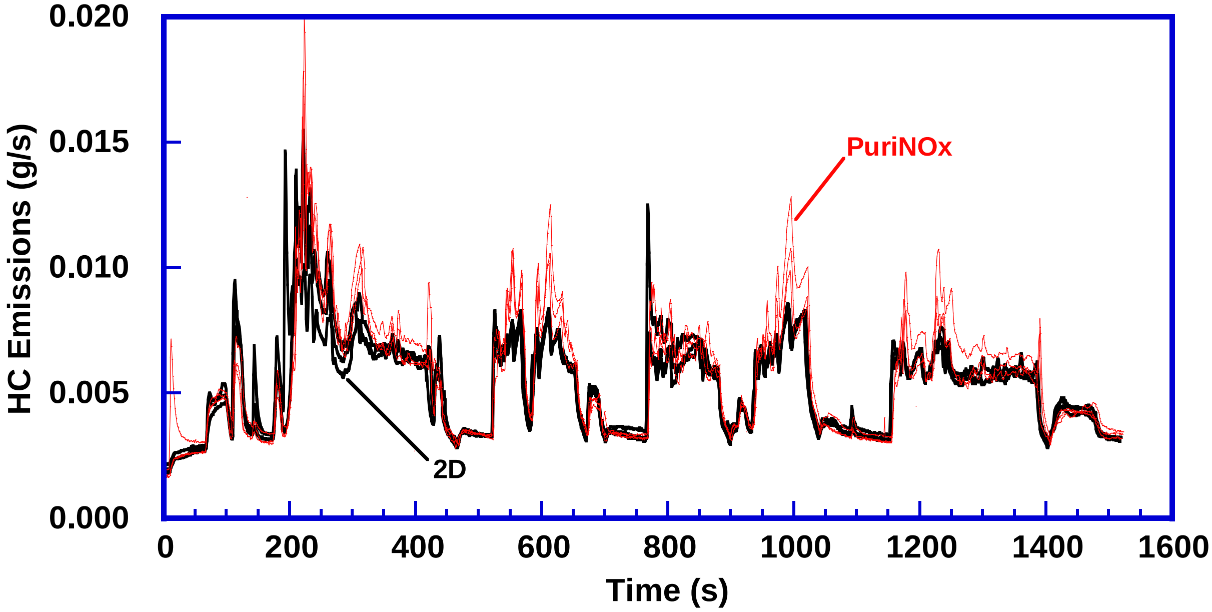


Figure B.4.12 Comparison of HC emissions for the 1996 Ford with the Cat 3176 operating over the TxDOT Tandem-Axle Dump Truck Cycle

B.5. Comparisons with Other Fuels

TxDOT uses 2D on-road diesel fuel even in their off-road equipment. However, some members of the AGC use off-road 2D diesel fuel in their off-road equipment. In some areas of Texas, this fuel has high sulfur (~2500 ppm by mass). Both high sulfur and low sulfur (~500 ppm) off-road 2D diesel is available in Houston. The high sulfur off-road fuel typically costs 2-3 cents per gallon less than the low sulfur off-road fuel. Some of the AGC contractors in the Houston District take advantage of the lower cost of the high sulfur fuel while others do not. Therefore, additional tests were made using these fuels for comparison to PuriNOx.

Additionally, the baseline diesel fuel provided to SwRI for the tests discussed in the previous sections had a higher Cetane Number than typical. As shown in Appendix F, the Cetane Number of the baseline diesel fuel provided to SwRI was 51.5. In comparison, a diesel survey found that the range of Cetane Numbers for commercially available 2D on-road fuels was 40.0 – 47.7. Also, a sample of 2D on-road diesel provided by the Houston District of TxDOT was found to have a Cetane Number of 47.3. As also shown in Appendix F, the PuriNOx provided to SwRI had a Cetane Number of 44.7 while a sample of the PuriNOx that is sold to TxDOT for its operations had a Cetane Number of 47.9. The differences in the composition of the fuels that result in these differences in Cetane Number may also affect emissions and fuel consumption. Therefore, it was of interest to make comparisons between the two diesel fuels and the two versions of PuriNOx.

The emissions and fuel consumption for the various fuels discussed above are discussed in the following subsections.

B.5.A. High Sulfur Diesel – Two tests were performed that compared the summer-grade PuriNOx that was provided to SwRI by Lubrizol, the baseline diesel fuel that was provided to SwRI by Lubrizol, and a high sulfur off-road 2D diesel that SwRI provided. The results of these tests are discussed in this subsection.

The Cummins ISB-190 operating over the AGC Wheeled Loader Cycle was tested using these three fuels. Comparisons between the two fuels that were provided by Lubrizol were discussed in Section B.2. The results for all three fuels are discussed in this section.

The BSFC and regulated emissions for the Cummins ISB-190 operating over the composite AGC Wheeled Loader Cycle are shown in Figure B.5.1. Detailed results are presented in Table B.22.

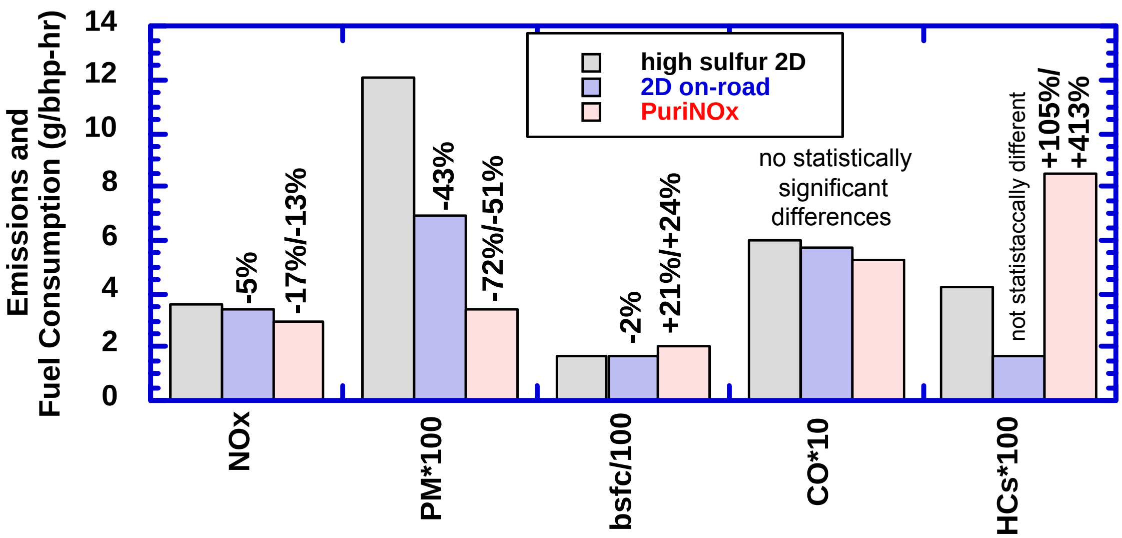
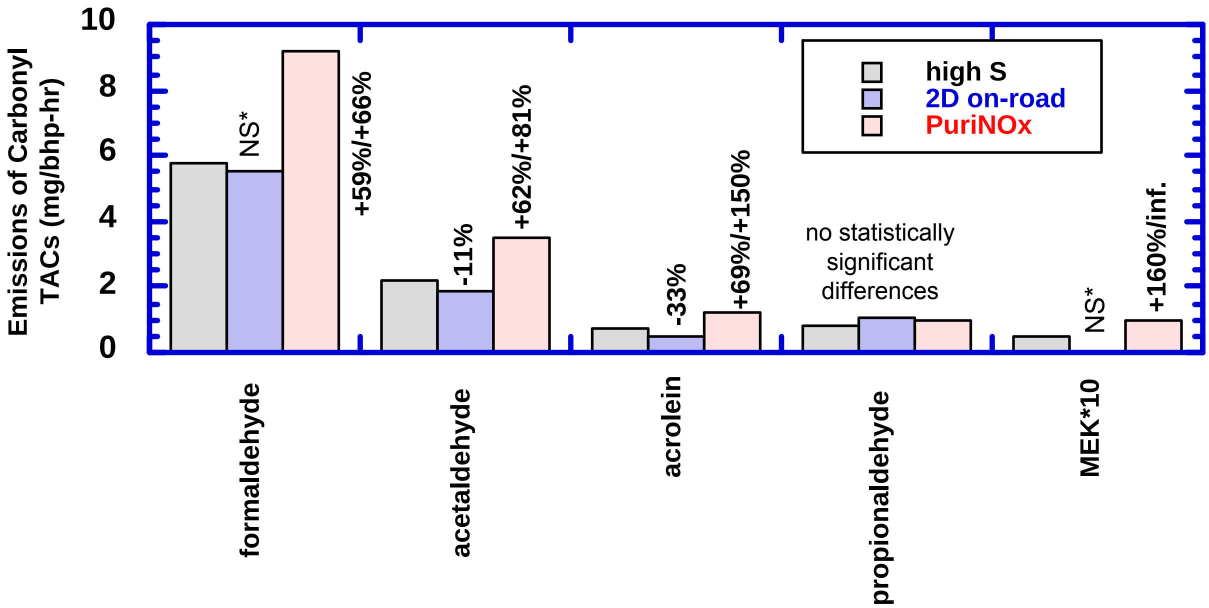


Figure B.5.1 Regulated emissions and fuel consumption for the Cummins ISB-190 operating over the AGC Wheeled Loader Cycle using three different fuels

In this comparison, the percent torque and percent engine speed versus time specification for the cycle is converted to absolute torque and rpm versus time from the full load torque curve for this engine using 2D on-road diesel fuel for both PuriNOx and 2D on-road diesel, but using the full load torque curve for the high sulfur fuel to generate the absolute values for its cycle. As shown in Table B.22, the engine does ~4% less work over the average cycle when using PuriNOx compared to 2D on-road diesel fuel. However, ~7% more work is done over this cycle for the high sulfur fuel compared to 2D on-road diesel fuel, and ~10% more work for the high sulfur fuel compared to PuriNOx. As for the tests of this engine using the Telescoping Boom Excavator Cycle, the tests that were performed to ensure the same work for all three fuels were not successful.

As shown in Figure B.5.1, 2D on-road diesel provides a 5% NOx benefit compared to the high sulfur diesel. PuriNOx offers a 17% benefit in NOx compared to the high sulfur diesel (and, as discussed in Section B.2, a 13% benefit compared to 2D on-road diesel). Compared to the high sulfur diesel, 2D on-road diesel fuel produces a 43% benefit in PM and a 2% benefit in fuel consumption. PuriNOx produces a 72% benefit in PM compared to high sulfur diesel (and a 51% benefit compared to 2D on-road diesel). However, there is also a 21% penalty in fuel consumption compared to high sulfur diesel. PuriNOx produces an HC penalty compared to both diesel fuels. The fuel-to-fuel differences in CO between these three fuels are not statistically significant with 95% confidence. The CO_2 difference between PuriNOx and 2D on-road diesel is not statistically significant, and the difference in HC emissions between high sulfur diesel and 2D on-road diesel is not statistically significant. All other differences in emissions and fuel consumption between the three fuels are statistically significant with 95% confidence.

The speciated emissions from the ISB-190 operating over the AGC Wheeled Loader Cycle using all three fuels are presented in Table B.23 and Figures B.5.2-B.5.4. Emissions of these species are discussed below.



*** - emissions difference between on-road and high sulfur diesel not statistically significant with 95% confidence**

Figure B.5.2 Emissions of carbonyl TACs for the Cummins ISB-190 operating over the AGC Wheeled Loader Cycle using three different fuels

The emissions of the carbonyl TACs from the ISB-190 operating over the Wheeled Loader Cycle are illustrated in Figure B.5.2. The emissions of MEK were very low for operation on PuriNOx and the high sulfur diesel fuel (the MEK emissions rates are multiplied by 10 to show them on the same scale as the other carbonyls) and below the detection limit for operation on the on-road diesel fuel. Thus, what appears to be a rather large increase in MEK emissions for operation on PuriNOx is probably not important. The differences in the emissions of only two of the carbonyls were statistically different with 95% confidence for the on-road diesel fuel compared to the high sulfur diesel fuel: an 11% decrease in acetaldehyde and a 33% decrease in acrolein for the on-road fuel. Compared to the high sulfur diesel fuel, PuriNOx increases the emissions of all of the carbonyls except propionaldehyde, for which the difference was not statistically significant.

The emissions of the noncarbonyl TACs from the ISB-190 operating over the Wheeled Loader Cycle are illustrated in Figure B.5.3. Hexane was below the detection limit for all three fuels. The emissions of ethyl benzene were not detectable when operating on the on-road diesel fuel and PuriNOx, and were very low for the high sulfur diesel fuel. The emissions of 1,3-butadiene were only detectable when using the on-road diesel fuel, but the repeatability in the measurements was such that the results for the on-road fuel were not statistically different from those for the other two fuels. Compared to the high sulfur diesel fuel, the on-road diesel produced lower emissions of toluene, ethyl benzene, and the xylenes with 95% confidence. Compared to the high sulfur diesel fuel, the only statistically significant effects were that PuriNOx produced lower emissions of ethyl benzene and higher emissions of the sum of m-xylene and p-xylene, with 95% confidence.

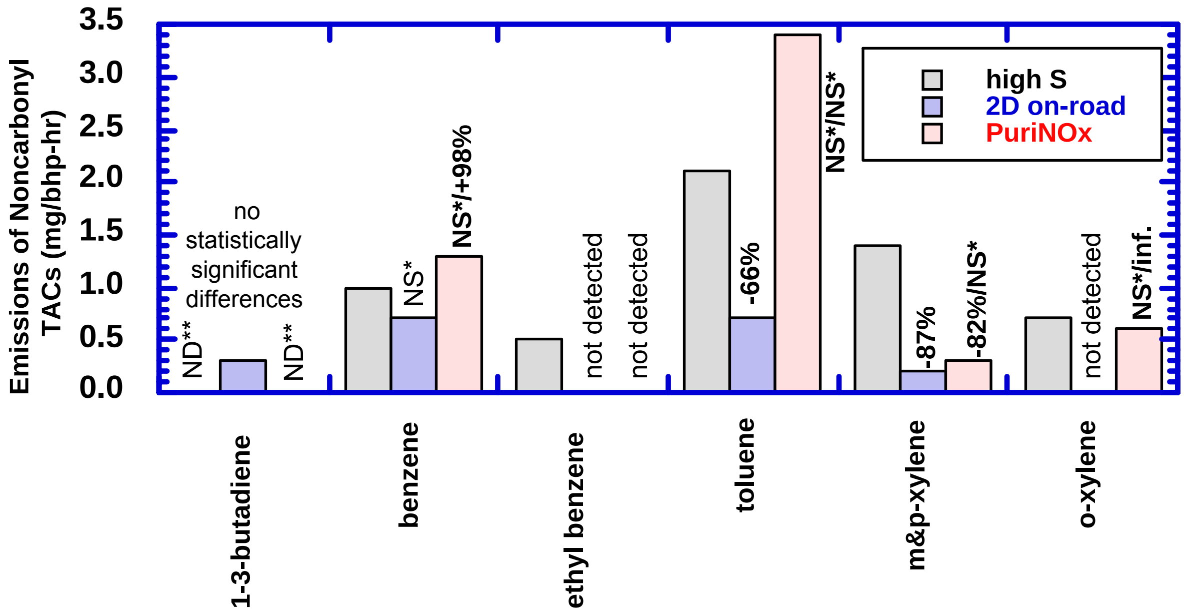
The breakdown of the PM emissions is shown in Figure B.5.4. Compared to the high sulfur diesel fuel, the on-road diesel fuel produced lower total PM, lower SOF, and lower sulfates (due to the decreased sulfur impurity in the fuel) but higher nitrates. Compared to the high sulfur diesel fuel, PuriNOx produced 72% lower PM, 57% lower SOF, 92% lower sulfates, and ~300% higher nitrates. However, the nitrate emissions are quite low for all three fuels (multiplied by 100 in Figure B.5.4 so that they can be seen on the same scale as the other species). As a percentage of the PM, the SOF increased from 37% for operation on the on-road diesel fuel, to 66% for the high sulfur fuel, to ~100% for PuriNOx.

Table B.23 Regulated Emissions from the ISB-190 for Each of the Hot Start AGC Wheeled Loader Cycles when Operating on Three Different Fuels

Start	Fuel	Torque Map	HC (g/hp-hr)	PM (g/hp-hr)	NOx (g/hp-hr)	CO2 (g/hp-hr)	CO (g/hp-hr)	BSFC (g/hp-hr)	Ref. Work (hp-hr)	Actual Work (hp-hr)	Actual vs. Ref. (%)
Hot	2D on-road	2D on-road	0.03	0.069	3.42	524	0.59	164.8	17.63	16.98	-3.7
Hot	2D on-road	2D on-road	0.00	0.069	3.43	530	0.55	166.7	17.63	16.99	-3.6
Average Hot Start			**0.02**	**0.069**	**3.42**	**527**	**0.57**	**165.8**	17.63	16.99	-3.7
Hot Start Standard Deviation			0.023	0.000	0.011	4.243	0.031	1.379		0.007	0.040
Hot Start CoV (%)			141	0.1	0.3	0.8	5.5	0.8		0.0	-1.1
Hot	PuriNOx	2D on-road	0.08	0.035	2.99	529	0.57	206.4	17.63	16.25	-7.8
Hot	PuriNOx	2D on-road	0.09	0.033	2.96	523	0.49	204.1	17.63	16.26	-7.8
Average Hot Start			**0.08**	**0.034**	**2.98**	**526**	**0.53**	**205.3**	17.63	16.255	-7.8
Hot Start Standard Deviation			0.008	0.002	0.015	4.243	0.058	1.604		0.007	0.040
Hot Start CoV (%)			9	4.8	0.5	0.8	10.9	0.8		0.0	-0.5
Hot	high sulfur	high sulfur	0.05	0.119	3.61	538	0.62	169.5	18.76	18.13	-3.4
Hot	high sulfur	high sulfur	0.03	0.122	3.59	540	0.58	170.1	18.76	18.16	-3.2
Average Hot Start			**0.04**	**0.121**	**3.60**	**539**	**0.60**	**169.8**	18.76	18.145	-3.3
Hot Start Standard Deviation			0.012	0.002	0.019	1.414	0.025	0.417		0.021	0.113
Hot Start CoV (%)			30	1.8	0.5	0.3	4.2	0.2		0.1	-3.4
PuriNOx compared to 2D on-road diesel											
% change: avg. hot start			413	-51.2	-13.1	-0.2	-6.3	23.8		-4.3	
95% confidence?			Y	Y	Y	N	N	Y		Y	
PuriNOx compared to high sulfur 2D off-road diesel											
% change: avg. hot start			105	-72.0	-17.3	-2.4	-11.1	20.9		-10.4	
95% confidence?			Y	Y	Y	Y	N	Y		Y	
On-road compared to high sulfur off-road 2D diesel											
% change: avg. hot start			-60	-42.7	-4.8	-2.2	-5.2	-2.4		-6.4	
95% confidence?			N	Y	Y	Y	N	Y		Y	

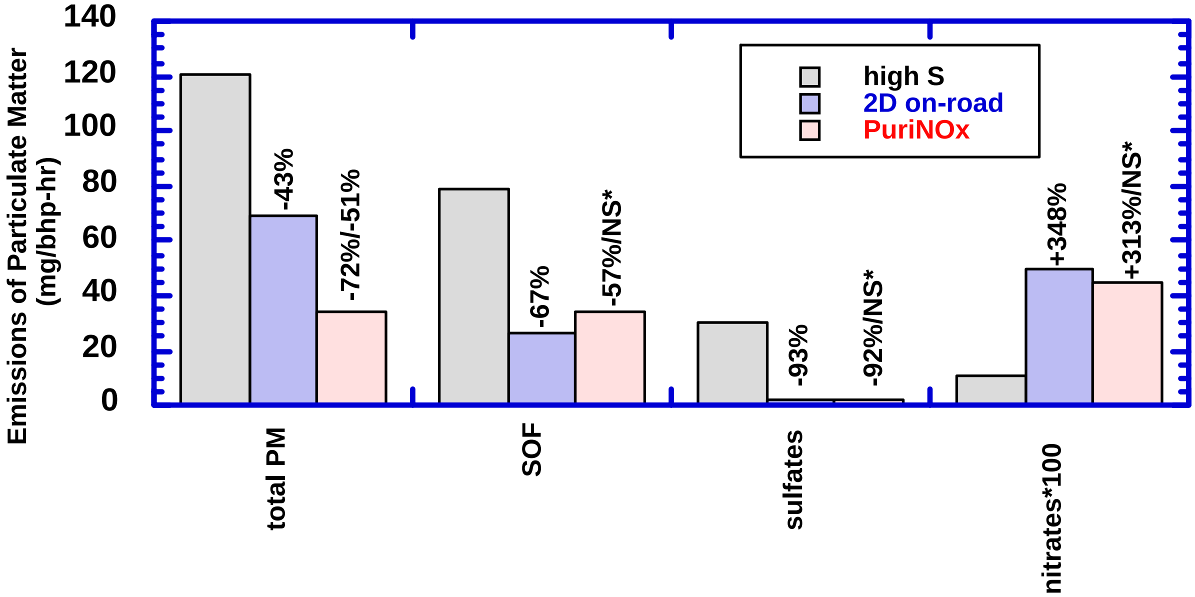
Table B.24 Speciated Emissions from the ISB-190 for the AGC Wheeled Loader Cycle When Operating on Three Different Fuels

Start	Fuel	Torque Map	formal dehyde	acetal dehyde	propion aldehyde	acrolein	MEK	1,3-butadiene	hexane	benzene	toluene	ethyl benzene	m&p xylene	o-xylene	sulfates	nitrates
			mg/hp-hr													
Hot	2D on-rd.	on-rd.	5.6	2.0	1.1	0.5	ND	0.0	ND	0.7	0.8	ND	0.4	ND	2	0.452
Hot	2D on-rd.	on-rd.	5.4	1.9	1.0	0.5	ND	0.6	ND	0.6	0.7	ND	0.0	ND	2	0.531
Average Hot Start			**5.5**	**1.9**	**1.1**	**0.5**	ND	**0.3**	ND	**0.7**	**0.7**	ND	**0.2**	ND	**2**	**0.492**
Hot Start Standard Deviation			0.123	0.072	0.049	0.029		0.405		0.088	0.056		0.273		0.141	0.056
Hot Start CoV (%)			2	4	5	6		141		13	8		141		7	11
Hot	PuriNOx	on-rd.	9.4	3.5	1.1	1.3	0.1	ND	ND	1.2	0.1	ND	0.0	0.5	2	0.361
Hot	PuriNOx	on-rd.	8.9	3.5	1.0	1.1	0.1	ND	ND	1.4	6.7	ND	0.5	0.7	3	0.544
Average Hot Start			**9.2**	**3.5**	**1.0**	**1.2**	**0.1**	ND	ND	**1.3**	**3.4**	ND	**0.3**	**0.6**	**2**	**0.452**
Hot Start Standard Deviation			0.356	0.062	0.004	0.109	0.010			0.106	4.621		0.370	0.172	0.212	0.130
Hot Start CoV (%)			4	2	0	9	8			8	135		141	28	9	29
Hot	hi S	hi S	5.6	2.2	0.9	0.7	0.0	ND	ND	0.9	2.0	0.4	1.5	0.7	34	0.088
Hot	hi S	hi S	6.0	2.2	0.6	0.7	0.1	ND	ND	1.1	2.2	0.6	1.4	0.6	26	0.131
Average Hot Start			**5.8**	**2.2**	**0.8**	**0.7**	**0.0**	ND	ND	**1.0**	**2.1**	**0.5**	**1.4**	**0.7**	**30**	**0.110**
Hot Start Standard Deviation			0.319	0.016	0.219	0.036	0.025			0.151	0.170	0.161	0.090	0.129	5.728	0.031
Hot Start CoV (%)			6	1	28	5	54			15	8	31	6	20	19	28
PuriNOx compared to 2D on-road diesel																
% change: avg. hot start			66	81	-1	150	inf.	-100		98	379		36	inf.	18	-8
95% confidence?			Y	Y	N	Y	Y	N	N	Y	N	N	N	Y	N	N
PuriNOx compared to high sulfur 2D off-road diesel																
% change: avg. hot start			59	62	32	69	160			34	62	inf.	-82	-6	-92	313
95% confidence?			Y	Y	N	Y	Y	N	N	N	N	Y	Y	N	Y	Y
On-road compared to high sulfur off-road 2D diesel																
% change: avg. hot start			-5	-11	34	-33	-100	inf.		-33	-66	-100	-87	-100	-93	348
95% confidence?			N	Y	N	Y	N	N	N	N	Y	Y	Y	Y	Y	Y



*** - emissions difference between the two fuels not statistically significant with 95% confidence**
**** - below detection limit**

Figure B.5.3 Emissions of noncarbonyl TACs for the Cummins ISB-190 operating over the AGC Wheeled Loader Cycle using three different fuels



*** - emissions difference between the two fuels not statistically significant with 95% confidence**

Figure B.5.4 Particulate matter breakdown for the Cummins ISB-190 operating over the AGC Wheeled Loader Cycle using three different fuels

A tandem-axle dump truck was also tested using the high sulfur diesel fuel. Although on-road equipment would not be permitted to use the high sulfur off-road fuel, we wanted to gain additional data regarding the benefits of both PuriNOx and low sulfur on-road fuel compared to the high sulfur diesel. The dump truck that was chosen for these tests was the 1989 GMC-White with the electronically-controlled Cummins L10-300 engine. Comparisons for the two fuels provided to SwRI by Lubrizol were discussed in Section B.4. Results for all three fuels are discussed below.

The regulated emissions and fuel economy are compared in Figure B.5.5 and detailed data are provided in Table B.24. In this case, the only statistically significant differences between the high and low sulfur fuels were a 7% decrease in NOx, a 20% improvement in PM, and a 15% benefit in HCs for the low sulfur diesel. Compared to the high sulfur diesel, PuriNOx provided an 11% benefit in NOx, a 44% benefit in PM, and a 50% benefit in CO along with a 10% fuel economy penalty and a 35% penalty in HC emissions.

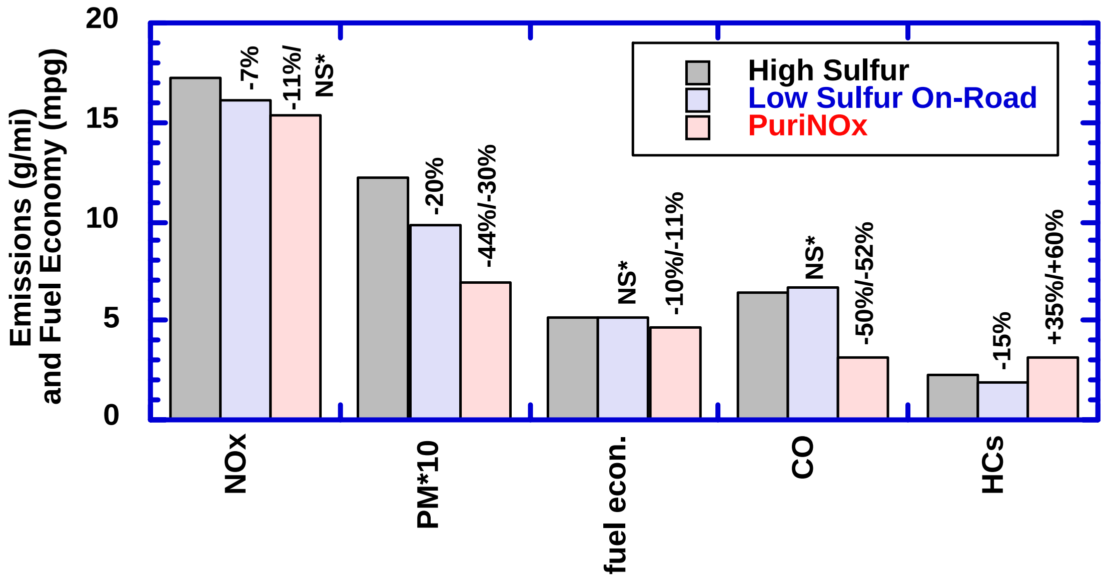


Figure B.5.5 Regulated emissions and fuel economy for the 1989 GMC-White with the Cummins L10-300 engine using three different fuels

Table B.25 Regulated Emissions from the 1989 Cummins L10-300 for Each of the Cold and Hot Start TxDOT Tandem-Axle Dump Truck Cycles for All Three Fuels

Start	HC	PM	NOx	CO2	CO	Fuel Economy	Reference distance	Actual distance	Actual vs. Ref.	Average speed
	g/mile					mpg	miles			mph
2D on-road diesel										
Cold	2.07	1.139	16.89	1962	7.55	4.96	10.58	10.65	0.66	25.22
Hot	1.90	0.956	15.76	1839	6.64	5.29	10.58	10.64	0.57	25.25
Hot	1.95	0.973	15.28	1840	6.24	5.29	10.58	10.64	0.57	25.20
Hot	1.91	0.953	15.96	1866	6.74	5.21	10.58	10.65	0.66	25.24
Hot	1.90	0.942	16.66	1890	6.44	5.15	10.58	10.63	0.47	25.18
avg. hot	1.91	0.956	15.92	1859	6.52	5.24	10.58	10.64	0.57	25.22
composite	**1.94**	**0.982**	**16.05**	**1873**	**6.66**	**5.20**	**10.58**	**10.64**	**0.58**	**25.22**
hot std. dev.	0.02	0.013	0.57	24.67	0.22	0.07		0.01		0.03
hot CoV (%)	1.27	1.34	3.60	1.33	3.41	1.30		0.08		0.14
PuriNOx										
Cold	3.47	0.799	15.48	1897	3.87	4.34	10.58	10.62	0.38	24.98
Hot	2.99	0.650	15.76	1795	3.00	4.59	10.58	10.63	0.47	25.08
Hot	3.01	0.660	15.03	1760	3.11	4.68	10.58	10.63	0.47	25.11
Hot	3.08	0.720	15.03	1734	2.97	4.75	10.58	10.64	0.57	25.12
Hot	3.04	0.656	15.44	1757	3.27	4.69	10.58	10.64	0.57	25.10
avg. hot	3.03	0.672	15.31	1761	3.09	4.68	10.58	10.64	0.52	25.10
composite	**3.09**	**0.690**	**15.34**	**1781**	**3.20**	**4.63**	**10.58**	**10.63**	**0.50**	**25.09**
hot std. dev.	0.04	0.033	0.35	25.49	0.14	0.07		0.01		0.02
hot CoV (%)	1.30	4.85	2.30	1.45	4.42	1.41		0.05		0.07
High S off-road 2D diesel										
Cold	2.64	1.356	17.12	2019	7.29	4.83	10.58	10.64	0.57	25.20
Hot	2.21	1.203	17.16	1891	6.44	5.16	10.58	10.63	0.47	25.21
Hot	2.24	1.223	17.05	1870	5.99	5.23	10.58	10.63	0.47	25.14
Hot	2.24	1.186	17.42	1856	6.24	5.26	10.58	10.65	0.66	25.26
Hot	2.25	1.190	18.626*	1859	6.44	5.25	10.58	10.63	0.47	25.18
avg. hot	2.23	1.201	17.21	1869	6.28	5.23	10.58	10.64	0.52	25.20
composite	**2.29**	**1.223**	**17.20**	**1890**	**6.42**	**5.17**	**10.58**	**10.64**	**0.53**	**25.20**
hot std. dev.	0.02	0.017	0.19	15.96	0.21	0.05		0.01		0.05
hot CoV (%)	0.7	1.4	1.1	0.9	3.4	0.9		0.1		0.2
PuriNOx compared to 2D on-road diesel										
change: avg. hot	58.4	-29.8	-3.8	-5.2	-52.6	-10.6		0.0		-0.5
95% confidence?	Y	Y	N	Y	Y	Y		N		Y
comp. % change	59.9	-29.8	-4.5	-4.9	-52.0	-10.9		-0.1		-0.5
PuriNOx compared to high sulfur 2D off-road diesel										
change: avg. hot	35.8	-44.1	-11.0	-5.8	-50.8	-10.5		0.0		-0.4
95% confidence?	Y	Y	Y	Y	Y	Y		N		Y
comp. % change	35.0	-43.6	-10.8	-5.8	-50.2	-10.4		0.0		-0.4
On-road compared to high sulfur off-road 2D diesel										
change: avg. hot	-14.3	-20.4	-7.5	-0.6	3.8	0.2		0.0		0.1
95% confidence?	Y	Y	Y	N	N	N		N		N
comp. % change	-15.5	-19.7	-6.6	-0.9	3.8	0.5		0.1		0.1

* NOx for this test seems too high, not included in analyses

<u>B.5.B. Low Sulfur Off-Road Diesel</u> – JAM Distributing provided SwRI a low sulfur (~500 ppm by mass) off-road diesel fuel. This fuel is typical of the low sulfur off-road 2D diesel that is used by some members of AGC.

The Cummins 6BTA5.9 used PuriNOx, on-road diesel fuel, and the low sulfur off-road 2D diesel fuel for the tests over the AGC Wheeled Loader Cycle. Comparisons for the first two of these fuels were discussed in Section B.2. Comparisons for all three fuels are discussed below.

This engine did 1.9% less work on PuriNOx, compared to on-road diesel fuel, 2.7% less work for PuriNOx compared to the off-road diesel fuel, and 0.8% less work for on-road versus off-road diesel fuel, as shown in Table B.25. The authors believe that this is acceptable for a valid comparison of these three fuels

The regulated emissions and brake specific fuel consumption for the Cummins 6BTA5.9 operating over the AGC Wheeled Loader Cycle are illustrated in Figure B.5.6 and detailed results are provided in Table B.25.

Compared to the low sulfur off-road diesel, on-road diesel fuel does not produce a statistically significant effect on NOx emissions, but a 43% benefit in PM, a 4% improvement in fuel consumption, and benefits in CO and HC emissions. As illustrated in Figure B.5.6, compared to the low sulfur off-road diesel fuel, PuriNOx provides a 21% benefit in NOx, a 62% benefit in PM, and a 24% penalty in fuel consumption. The effects of PuriNOx on CO and HC emissions are not statistically significant when compared to the off-road diesel.

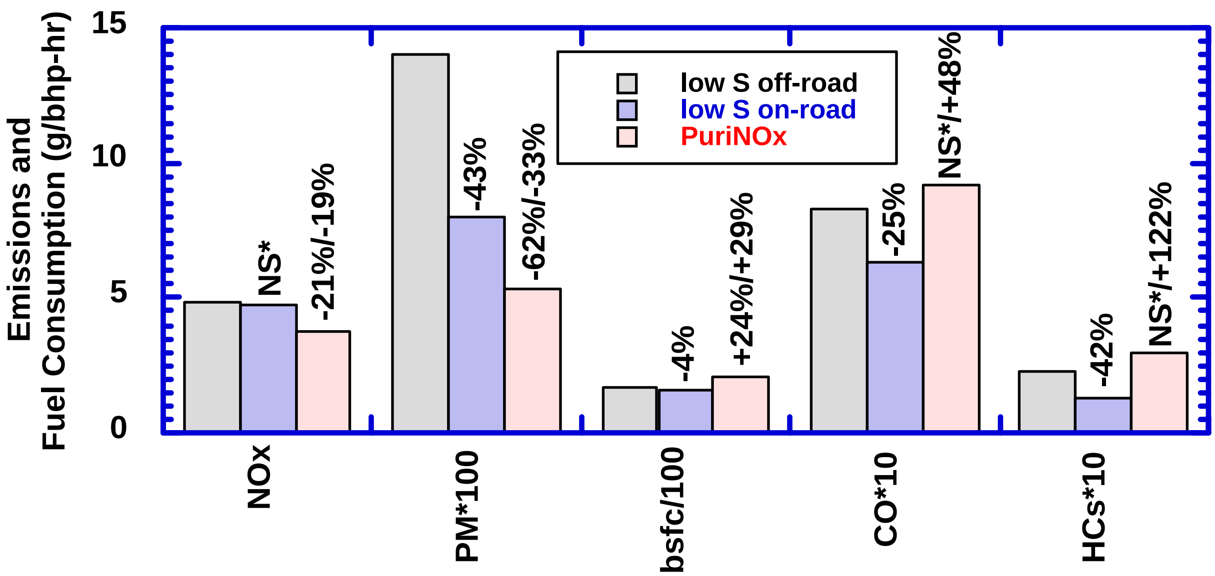


Figure B.5.6 Regulated emissions and fuel consumption for the Cummins 6BTA5.9 operating over the AGC Wheeled Loader Cycle using three different fuels

Table B.26 Regulated Emissions from the 6BTA5.9 for Each of the AGC Wheeled Loader Cycles and Three Different Fuels.

Start	Fuel	Torque Map	HC (g/hp-hr)	PM (g/hp-hr)	NOx (g/hp-hr)	CO2 (g/hp-hr)	CO (g/hp-hr)	BSFC (g/hp-hr)	Ref. Work (hp-hr)	Actual Work (hp-hr)	Actual vs. Ref. (%)
Hot	2D on-road	PuriNOx	0.12	0.079	4.67	519	0.62	163.5	13.47	15.20	12.8
Hot	2D on-road	PuriNOx	0.14	0.081	4.73	519	0.63	163.4	13.47	15.31	13.7
Average Hot Start			**0.13**	**0.080**	**4.70**	**519**	**0.63**	**163.4**	13.47	15.26	13.3
Hot Start Standard Deviation			0.014	0.001	0.047	0.146	0.002	0.031		0.078	0.636
Hot Start CoV (%)			10.7	1.6	1.0	0.0	0.3	0.0		0.5	4.8
Hot	PuriNOx	PuriNOx	0.33	0.056	3.69	542	1.02	212.0	13.47	14.94	10.90
Hot	PuriNOx	PuriNOx	0.26	0.051	3.90	537	0.82	209.9	13.47	14.98	11.20
Average Hot Start			**0.29**	**0.053**	**3.79**	**540**	**0.92**	**211.0**	13.47	14.96	11.05
Hot Start Standard Deviation			0.047	0.004	0.148	3.590	0.141	1.532		0.028	0.212
Hot Start CoV (%)			16.1	7.1	3.9	0.7	15.3	0.7		0.2	1.9
Cold	low S off-road	PuriNOx	0.25	0.15	4.90	559	1.08	176.3	13.53	15.23	12.6
Hot	low S off-road	PuriNOx	0.22	0.14	4.88	542	0.84	170.9	13.53	15.31	13.2
Hot	low S off-road	PuriNOx	0.22	0.14	4.76	541	0.82	170.5	13.53	15.37	13.6
Hot	low S off-road	PuriNOx	0.24	0.14	4.83	540	0.82	170.4	13.53	15.41	13.9
Hot	low S off-road	PuriNOx	0.23	0.14	4.73	539	0.84	170.1	13.53	15.42	14.0
Average Hot Start			**0.23**	**0.14**	**4.80**	**541**	**0.83**	**170.5**	13.53	15.38	13.7
Composite			0.230	0.142	4.815	543	0.865	171.3	13.5	15.4	13.5
Hot Start Standard Deviation			0.007	0.002	0.070	0.593	0.011	0.188		0.007	0.071
Hot Start CoV (%)			3.3	1.4	1.5	0.1	1.3	0.1		0.0	0.5
PuriNOx compared to 2D on-road diesel											
% change: avg. hot start			122	-33.5	-19.3	4.0	47.8	29.1		-1.9	
95% confidence?			Y	Y	Y	Y	Y	Y		Y	
PuriNOx compared to low sulfur 2D off-road diesel											
% change: avg. hot start			29.2	-61.7	-21.0	-0.2	11.4	23.8		-2.7	
95% confidence?			N	Y	Y	N	N	Y		Y	
low sulfur 2D off-road compared to 2D on-road diesel											
% change: avg. hot start			-41.8	-42.5	-2.1	-4.0	-24.6	-4.1		-0.8	
95% confidence?			Y	Y	N	Y	Y	Y		N	

B.5.C. SwRI Test Fuels Compared to TxDOT In-Use Fuels – As noted in the introduction to this section, from the perspective of Cetane Number the fuels provided to SwRI for the tests for this project do not appear to reflect the fuels used by TxDOT. The issue is whether or not the emissions benefits and fuel economy penalties determined from the SwRI tests represent the effects that should be expected from the real world fuels. This issue is explored in this subsection.

A single-axle dump truck was tested using four fuels: the baseline diesel fuel and PuriNOx provided to SwRI by Lubrizol, and samples of 2D diesel fuel and PuriNOx from the Houston District of TxDOT. The dump truck selected for these tests was the 1999 GMC C7500 with an electronically-controlled Cat 3126B. The first two fuels were compared in Section B.3. The two 2D on-road diesel fuels are compared in Table B.26 and the two versions of summer-grade PuriNOx are compared in Table B.27.

As shown in Table B.26, the only statistically significant differences between the two diesel fuels are that the commercial fuel produced ~26% higher emissions of HCs and ~20% higher PM emissions. However, since NOx emissions are the focus of this study, and the difference in NOx emissions is not statistically significant with 95% confidence, it is concluded that the baseline diesel fuel provided to SwRI for the emissions and fuel economy tests is essentially the same as the 2D on-road diesel fuel that is available for TxDOT use in the Houston District.

As shown in Table B.27, the only statistically significant difference between tests using the two versions of PuriNOx is a very small difference in distance traveled over the TxDOT Single-Axle Dump Truck route. Most probably, this is due to natural test-to-test variability. Thus, it is concluded that the PuriNOx provided to SwRI for the emissions and fuel economy tests is essentially the same as the PuriNOx that is sold to TxDOT for use in the Houston District.

Table B.27 Regulated Emissions from the Caterpillar 3126B for Each of the Cold and Hot Start TxDOT Single-Axle Dump Truck Cycles for Commercial 2D On-Road Diesel and for the Baseline Diesel Fuel Provided to SwRI by Lubrizol

Start	HC	PM	NOx	CO2	CO	Fuel Economy	Reference distance	Actual distance	Actual vs. Ref. (%)	Average speed
	g/mile					mpg	miles			mph
SwRI 2D on-road diesel										
Cold	0.19	0.151	22.17	1552	2.22	6.31	8.78	8.80	0.23	24.06
Hot	0.20	0.134	21.23	1398	1.57	7.01	8.78	8.79	0.11	23.95
Hot	0.20	0.128	21.07	1423	1.61	6.88	8.78	8.80	0.23	24.00
Hot	0.21	0.135	21.28	1417	1.66	6.92	8.78	8.80	0.23	24.05
avg. hot	0.20	0.132	21.19	1413	1.61	6.94	8.78	8.80	0.19	24.00
composite	**0.20**	**0.135**	**21.33**	**1432**	**1.70**	**6.85**	**8.78**	**8.80**	**0.20**	**24.01**
hot std. dev.	0.004	0.004	0.110	13.347	0.043	0.067		0.006		0.052
hot CoV (%)	2.05	2.86	0.52	0.94	2.64	0.96		0.07		0.22
TxDOT 2D on-road diesel										
Cold	0.25	0.167	22.09	1513	2.22	6.47	8.78	8.79	0.11	23.99
Hot	0.24	0.156	21.00	1451	1.87	6.75	8.78	8.79	0.11	24.02
Hot	0.27	0.163	20.92	1447	1.84	6.77	8.78	8.80	0.23	24.04
Hot	0.25	0.154	21.57	1418	1.63	6.91	8.78	8.79	0.11	24.03
Hot	0.26	0.165	20.60	1438	1.71	6.81	8.78	8.79	0.11	24.03
avg. hot	0.26	0.160	21.02	1438	1.76	6.81	8.78	8.79	0.14	24.03
composite	**0.25**	**0.161**	**21.17**	**1449**	**1.83**	**6.76**	**8.78**	**8.79**	**0.14**	**24.02**
hot std. dev.	0.011	0.005	0.404	14.727	0.114	0.071		0.005		0.006
hot CoV (%)	4.4	3.3	1.9	1.0	6.5	1.0		0.1		0.0
hot % change	26.1	20.5	-0.8	1.8	9.2	-1.8		0.0		0.1
95% conf?	Y	Y	N	N	N	N		N		N
comp. % change	26.8	18.9	-0.8	1.2	7.5	-1.3		-0.1		0.1

Table B.28 Regulated Emissions from the Caterpillar 3126B for Each of the Cold and Hot Start TxDOT Single-Axle Dump Truck Cycles for Commercial PuriNOx and for the PuriNOx Provided to SwRI by Lubrizol

Start	HC	PM	NOx	CO2	CO	Fuel Economy	Reference distance	Actual distance	Actual vs. Ref. (%)	Average speed
	g/mile					mpg	miles			mph
SwRI PuriNOx										
Cold	0.86	0.143	19.39	1512	1.78	5.45	8.78	8.79	0.11	23.67
Hot	0.93	0.134	19.69	1380	1.52	5.97	8.78	8.78	0.00	23.64
Hot	1.00	0.145	19.22	1373	1.43	6.00	8.78	8.78	0.00	23.68
Hot	1.01	0.149	20.45	1451	1.46	5.67	8.78	8.78	0.00	23.78
Hot	0.99	0.161	18.99	1372	1.27	6.00	8.78	8.79	0.11	23.73
avg. hot	0.98	0.147	19.59	1394	1.42	5.91	8.78	8.78	0.03	23.71
composite	**0.96**	**0.147**	**19.56**	**1411**	**1.47**	**5.84**	**8.78**	**8.78**	**0.04**	**23.70**
hot std. dev.	0.037	0.011	0.642	38.369	0.106	0.161		0.005		0.061
hot CoV (%)	3.8	7.6	3.3	2.8	7.5	2.7		0.1		0.3
TxDOT PuriNOx										
Cold	0.86	0.130	20.03	1488	1.89	5.53	8.78	8.79	0.11	23.99
Hot	0.97	0.130	20.20	1421	1.65	5.79	8.78	8.79	0.11	23.67
Hot	0.99	0.143	20.86	1420	1.43	5.80	8.78	8.79	0.11	23.69
Hot	1.01	0.149	20.45	1451	1.46	5.67	8.78	8.78	0.00	23.78
Hot	1.04	0.144	19.15	1418	1.42	5.81	8.78	8.79	0.11	23.73
avg. hot	1.00	0.142	20.16	1428	1.49	5.77	8.78	8.79	0.09	23.72
composite	**0.98**	**0.140**	**20.14**	**1436**	**1.55**	**5.73**	**8.78**	**8.79**	**0.09**	**23.76**
hot std. dev.	0.029	0.008	0.727	15.770	0.105	0.066		0.005		0.047
hot CoV (%)	2.9	5.7	3.6	1.1	7.0	1.1		0.1		0.2
hot % change	2.1	-3.9	2.9	2.4	5.0	-2.4		0.1		0.0
95% conf?	N	N	N	N	N	N		Y		N
comp. % change	2.0	-4.6	3.0	1.8	5.1	-1.9		0.0		0.2

B.6. Small Utility Engines

TxDOT uses a variety of small diesel engines for their traffic alerting signals, herbicide sprayers, and riding lawn mowers. Therefore, in addition to the heavy equipment testing at SwRI, a 10 hp diesel engine, used in herbicide sprayers, was tested at UT. It was assumed that this single cylinder, 0.418 L engine is generally representative of the small utility engines used for other applications by TxDOT.

This engine was tested to estimate the typical emissions and fuel consumption for these engines. TxDOT estimated that the single cylinder engines used for traffic alerting signals are used at maximum speed, full load 100% of the time; that the single cylinder herbicide sprayer engines are used at maximum speed, full load 50% of the time and half speed, slight load the remaining 50%; and that the two cylinder diesels in riding lawn mowers operate at maximum speed, full load 90% of the time and half speed, slight load the remaining 10% (Nicholes, 2003). This represents only two operating conditions, which we took to be 3550 rpm, full load, and 1500 rpm, 2.5 lb-ft of torque.

The engine was installed in an engine test cell, coupled to an engine dynamometer, and instrumented to measure speed, torque output, fuel consumption, and emissions. NOx was measured using a chemiluminescence analyzer and PM was measured gravimetrically. The results of these tests are discussed in this subsection.

Steady-state emissions and fuel consumption were evaluated using both winter-grade and summer-grade PuriNOx, and compared with operation on 2D on-road diesel fuel and with Texas Low Emissions Diesel (TxLED), an ultra low sulfur diesel fuel. The full-load torque and power curves for the Yanmar using the various fuels are discussed in Appendix C and illustrated in Figure C.2.3.

As noted above, typical TxDOT operation of small utility engines includes only two modes, which we have taken to be 3550 rpm, full load, and 1500 rpm, 2.5 lb-ft of torque. To calculate composite emissions and fuel consumption for these two modes, the weighting factors for the high speed and load point are 0.9 for mowers, 1.0 for traffic alerting signals, and 0.5 for sprayers. The results are provided in Table B.28.

Table B.29 Composite Emissions and Fuel Consumption for Small Utility Engines

	bsNOx	**bsfc**	**bsPM**	**EINOx**	**EIPM**
	g/hp-hr			g/kg	
2D on-road diesel fuel					
high speed & load	5.87	215.9	0.86		
mid-speed, low load	15.04	403.0	8.64		
composite-mowers	6.79	234.6	1.64	28.93	6.99
composite-signals	5.87	215.9	0.86	27.19	3.99
composite-sprayers	10.46	309.5	4.75	33.79	15.35
Summer-grade PuriNOx					
high speed & load	5.66	279.3	0.62		
mid-speed, low load	9.40	434.6	7.37		
composite-mowers	6.03	294.9	1.30	20.46	4.40
composite-signals	5.66	279.3	0.62	20.26	2.22
composite-sprayers	7.53	357.0	4.00	21.08	11.19
Winter-grade PuriNOx					
high speed & load	4.99	288.6	0.40		
mid-speed, low load	12.52	528.6	5.79		
composite-mowers	5.74	312.6	0.94	18.37	3.00
composite-signals	4.99	288.6	0.40	17.29	1.38
composite-sprayers	8.76	408.6	3.09	21.43	7.57
TxLED					
high speed & load	5.40	205.3	0.78		
mid-speed, low load	15.27	385.7	1.31		
composite-mowers	6.39	223.4	0.83	28.60	3.72
composite-signals	5.40	205.3	0.78	26.30	3.79
composite-sprayers	10.33	295.5	1.04	34.97	3.53
% change: SG PuriNOx vs. 2D on-rd diesel					
mowers	-11.1	25.7	-20.9		
signals	-3.6	29.4	-27.8		
sprayers	-28.0	15.4	-15.9		

B.7. Emissions and Fuel Consumption Penalties Associated with Bi-Weekly Starts

TxDOT has found that it must start all engines twice per week due to the hard starting problem associated with PuriNOx. The engines are typically run for 45 minutes during these bi-weekly starts. This procedure is not required with diesel fuel. Therefore, the emissions, fuel consumption, and labor penalties associated with these extra starts should be accounted for in the cost-effectiveness analyses.

The PuriNOx consumption and NOx emissions from the Yanmar at idle (1050 rpm, no load) are illustrated in Figure B.7.1. At idle, the average PuriNOx consumption rate is 160 g/hr (± 14%) and the average NOx production rate is 12.9 grams of NOx produced per kilogram of PuriNOx consumed (± 12%). For the other small utility engines, it will be assumed that the Emissions Index for NOx is the same as that for the Yanmar (12.9 gNOx/kgPuriNOx or ~42 grams of NOx emitted per gallon of PuriNOx consumed) and that the fuel consumption at idle scales with the displacement (383 g/hr/L, or ~0.118 gallons/hr/L). Similarly, the PM emissions rate at idle is ~52 grams per gallon of PuriNOx consumed.

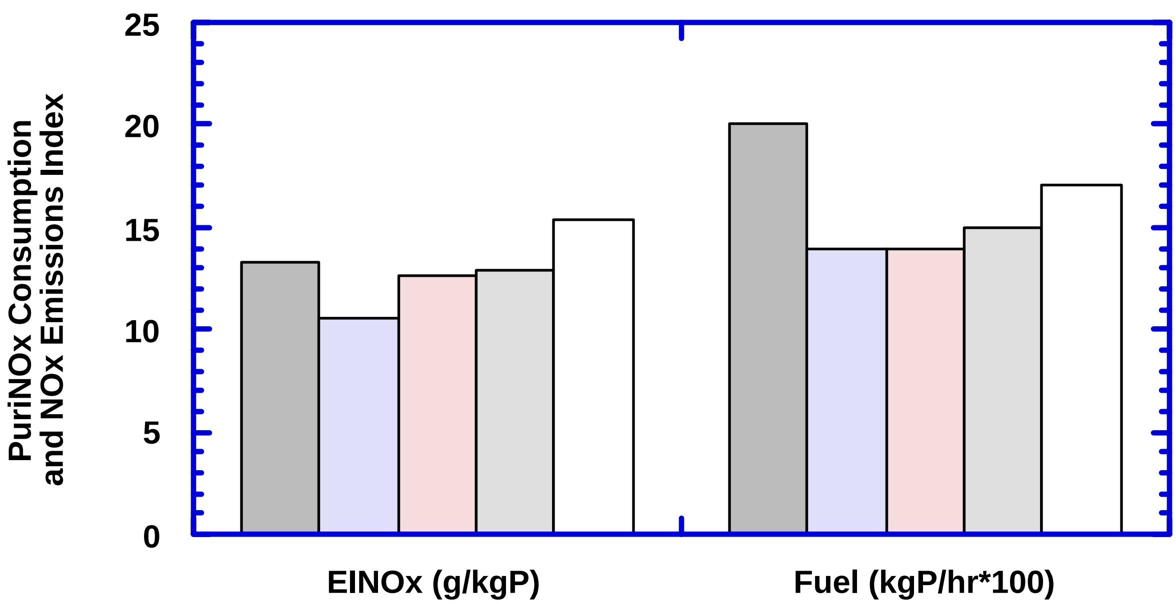


Figure B.7.1 NOx emissions and PuriNOx consumption at idle; results for 5 experimental runs shown, illustrating experimental repeatability

It is known that single cylinder engines generally have higher frictional and parasitic losses per unit displacement than multicylinder engines. Other than the Yanmar engine discussed above, measurements of fuel consumption and emissions at idle were not planned for this project. Thus, it was necessary to estimate the fuel consumption and emissions at idle for the multicylinder engines of interest. These estimates were obtained from several sources, as discussed below.

Sarlo (2001) examined a Detroit Diesel Series 50 operating on PuriNOx and his results were one basis for these estimates. Figure B.7.2 shows his fuel consumption data at 1200 rpm for two sets of tests. As shown in Figure B.7.2, the two sets of data agree closely and both can be fit with a line with a correlation coefficient of >0.99. Both curves indicate a fuel consumption at no load, 1200 rpm of 1330 g/hr. Assuming that the average engine speed – for all of the diesels in the TxDOT fleet - during these starting and extended idling periods is 600 rpm, and that fuel consumption scales linearly with engine speed (Lim, 2003) yields an estimated fuel consumption at idle of ~665 g/hr for this 8.5 L engine. Also assuming that idle fuel consumption scales linearly with displacement yields 0.024 gallons of PuriNOx per hour per liter of engine displacement.

Lim (2003) provided diesel consumption data, in gallons per hour, for 8 heavy-duty diesels at idle. Most of these engines idled at 600 rpm, but a few idled at higher speeds, up to 1000 rpm. For these, the fuel consumption at 600 rpm was estimated by assuming a linear dependence, as shown via Lim's results. For each of the 8 engines, the PuriNOx consumption at idle was estimated by accounting for the difference in the density between PuriNOx and diesel fuel, plus accounting for the mass fraction of water in the PuriNOx (20%), and assuming a 1% efficiency benefit in consumption of the diesel fraction of PuriNOx.

The assumption that is used for the cost-effectiveness analyses is the average for the 8 engines examined by Lim plus the engine examined by Sarlo. Specifically, it is estimated that the PuriNOx consumption rate at idle is 0.04 gallons of PuriNOx per hour per liter of engine displacement.

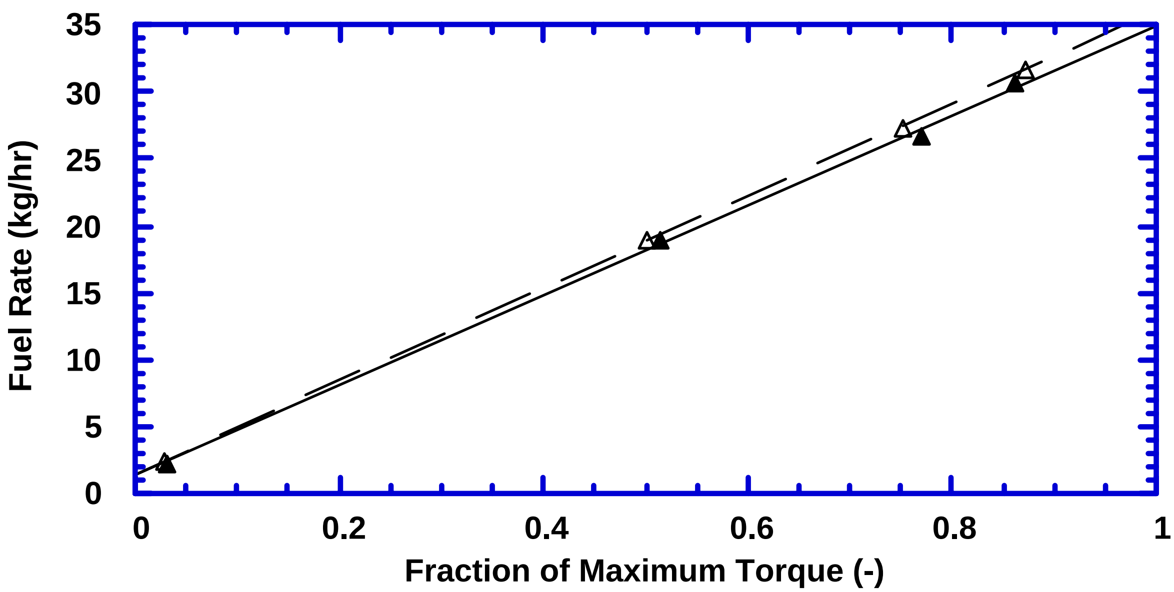


Figure B.7.2 PuriNOx consumption at 1200 rpm for a DDC Series 50 (Sarlo, 2001)

Figure B.7.3 shows Sarlo's data for NOx emissions at 1200 rpm. In this case, the agreement between the two sets of data is not as good and linear fits are poor. Figure B.7.4 presents these results on an Emissions Index basis. Use of the Emissions Index allows extrapolation to other engines, via the fuel consumption. It was estimated that the NOx emission rate at idle is 25 g/kg of PuriNOx.

The results for a 1999 calibration 15 L engine at idle (Roberts, 2003) were about the same: 24.2 g/kg of PuriNOx, after assuming a 48% NOx benefit at idle (Musculus et al. 2002) and accounting for the differences in properties between diesel fuel and PuriNOx.

Storey and coworkers (2003) examined the fuel consumption, NOx emissions, and PM emissions for 5 heavy-duty diesels at idle. The Emissions Index for NOx was calculated for each of these engines for idle operation on diesel fuel. The EINOx for idle with PuriNOx was then calculated by assuming the 48% NOx benefit at idle found by Musculus and coworkers (2002), and accounting for the different properties of the two fuels. The results ranged from 26.1-54.1 gNOx/kg of PuriNOx.

For the cost-effectiveness analyses, the average of these 7 was used, yielding 117 grams of NOx per gallon of PuriNOx consumed at idle.

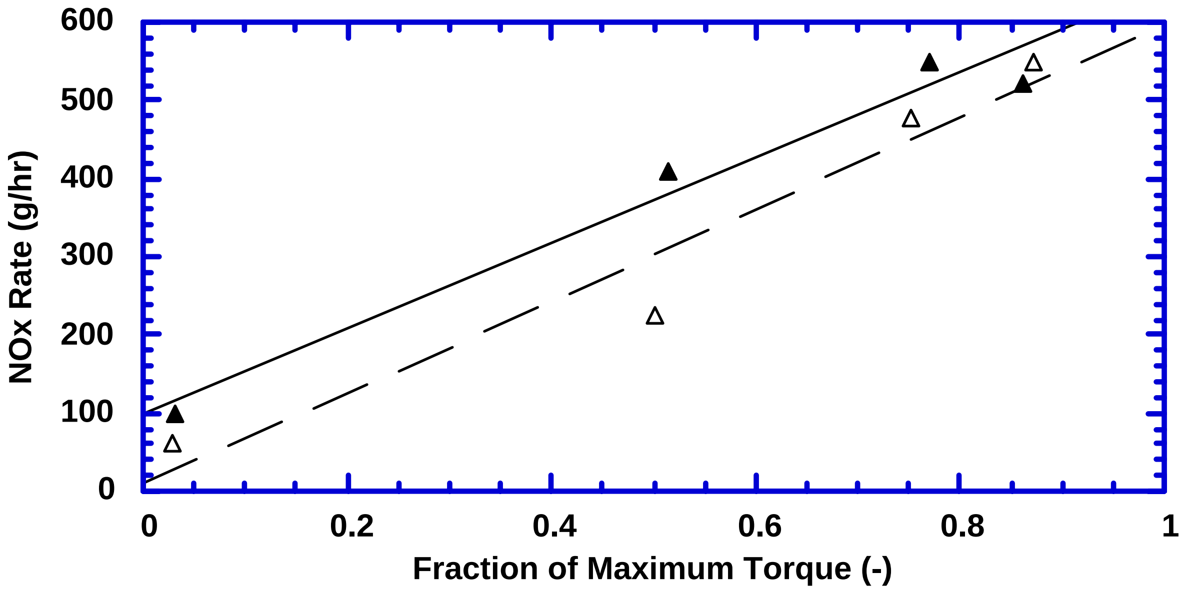


Figure B.7.3 NOx emissions rate at 1200 rpm for a DDC Series 50 operating on PuriNOx (Sarlo, 2001)

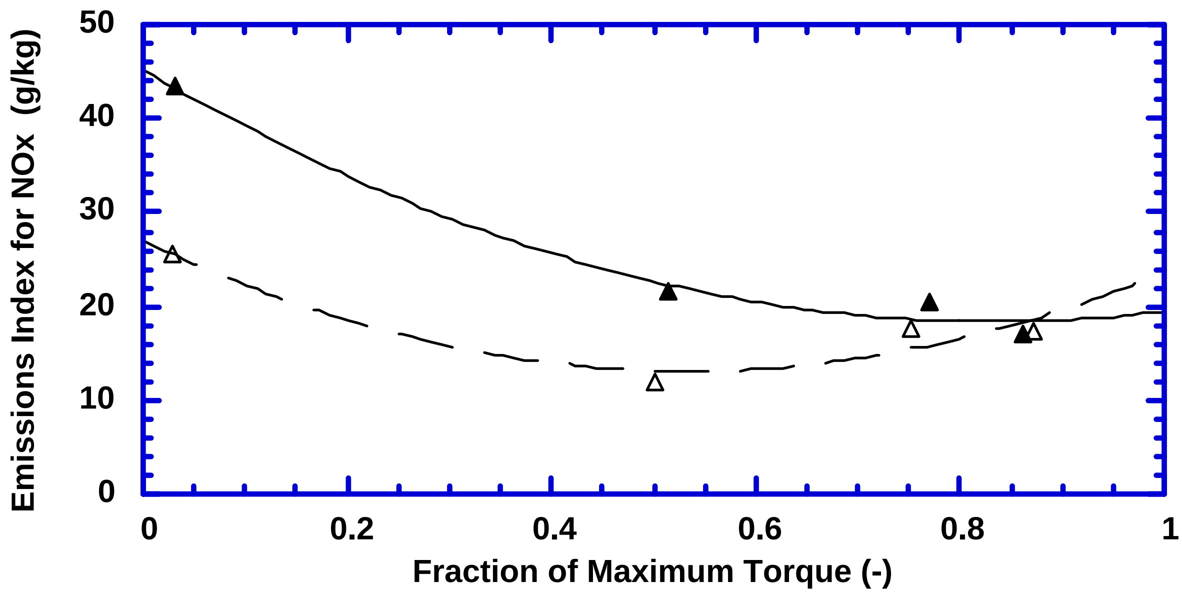


Figure B.7.4 NOx Emissions Index for a DDC Series 50 operating on PuriNOx at 1200 rpm (Sarlo, 2001)

Figure B.7.5 shows Sarlo's data for PM emissions at 1200 rpm. In this case, the agreement between the two sets of data is good and second order fits have correlation coefficients of >0.99. Figure B.7.6 presents these results on an Emissions Index basis. Again, the Emissions Index allows extrapolation to other engines.

The average EIPM for the 8.5 L engine examined by Sarlo is much lower than for the engine examined by Roberts (2003) or the 5 engines examined by Storey and coworkers (2003), especially if the PuriNOx penalty of a 580% increase in PM at idle, as found by Musculus and coworkers (2002), is used for the calculations. In this case, the results ranged from about 3-8 gPM/kg of PuriNOx. However, the PM mass emissions at idle are so low that it makes essentially no difference whether a PM penalty or a PM benefit is assumed for the extra starts.

The average for these 7 engines, including the 580% PM penalty at idle, was used for the cost-effectiveness analyses. Specifically, it was estimated that the PM emission rate at idle is 15 grams of PM per gallon of PuriNOx consumed at idle.

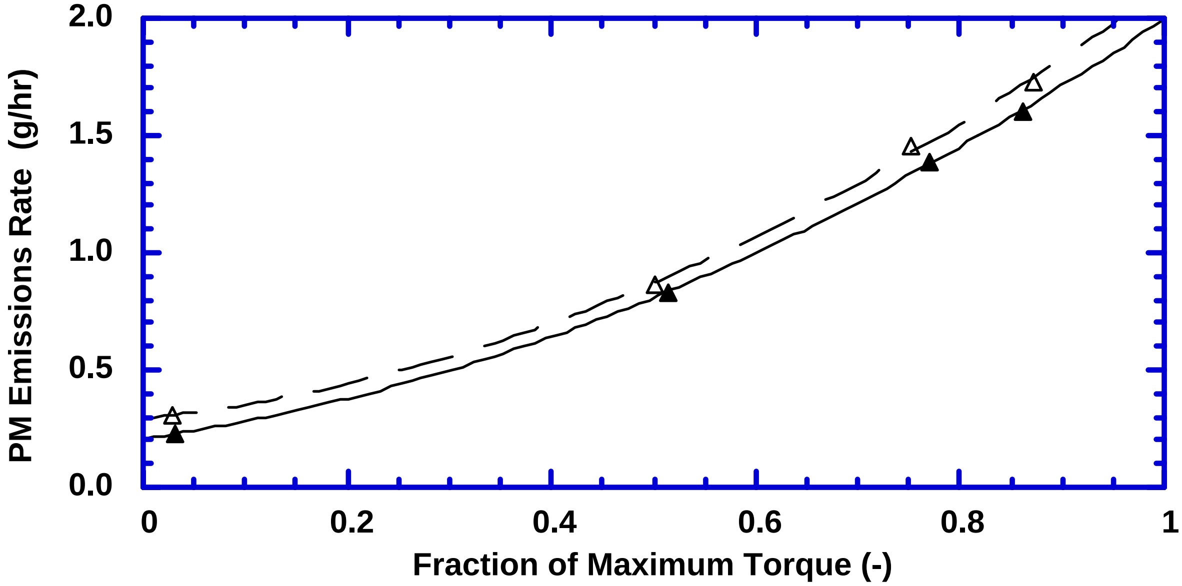


Figure B.7.5 PM emissions rate at 1200 rpm for a DDC Series 50 operating on PuriNOx (Sarlo, 2001)

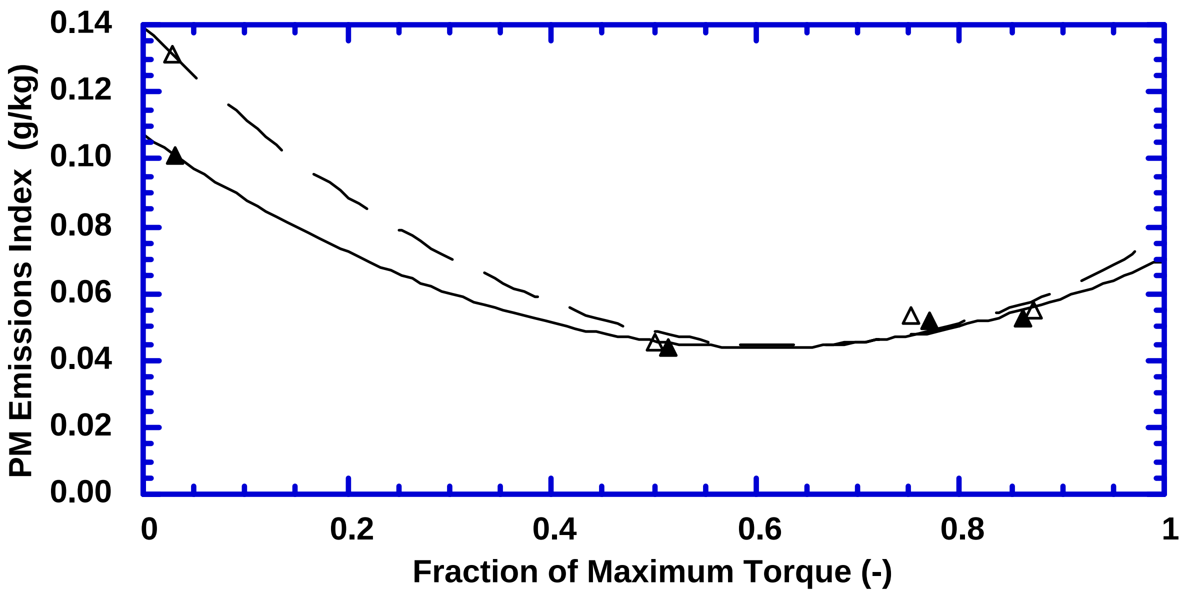


Figure B.7.6 PM Emissions Index for a DDC Series 50 operating on PuriNOx at 1200 rpm (Sarlo, 2001)

TxDOT provided complete records of the FY01 gallons of diesel consumed and the hours or miles of use for each of the 386 pieces of equipment that were converted to PuriNOx in 2002. These records were used to estimate the number of extra starts required annually to prevent the separation problems associated with PuriNOx. For most of the equipment, including much of the on-road equipment, the TxDOT records showed the total number of hours each was used in FY01. When a piece of equipment is in use, it is typically used for 6 hours per day by TxDOT. This allowed us to estimate the number of days each piece of equipment was used during the year. The most conservative estimate of the number of weeks each year that a piece of equipment must be started when otherwise not needed results from assuming each is used 2 days per week (since the equipment is started twice per week when not otherwise needed). The difference between 52 weeks per year and the number of weeks when the equipment is used for normal service equals the number of weeks the equipment must be started when not otherwise needed. During these weeks, each is started and allowed to warm-up for 45 minutes twice. This yields the number of "extra starts" required for each piece of equipment.

$$\text{ExtraStarts / year} = 2\frac{\text{starts}}{\text{week not used}}\left\{52\frac{\text{weeks}}{\text{yr}} - \left[\text{X}\frac{\text{hours used}}{\text{yr}} / (6\frac{\text{hrs}}{\text{day}}2\frac{\text{days}}{\text{week}})\right]\right\} \quad \text{(B.2)}$$

The result from the right hand side of Equation B.2 was rounded down to the nearest even number. For example, if the result was that 15.9 extra starts were required, this was rounded to 14 (seven weeks worth of extra starts, twice per week).

The equipment that was converted to PuriNOx for which the annual miles rather than hours were recorded included 5 light-duty trucks, 7 truck tractors, 3 medium-duty trucks, 82 single-axle dump trucks, 44 tandem-axle dump trucks, and 14 other trucks in various categories. For these, miles used can be converted to hours used if the average speed is known. Equation B.2 is then applied to determine the number of extra starts required annually. For the single-axle and tandem-axle dump trucks, the data that was logged to develop the test cycles (Appendix A) was interrogated to determine the average speeds: ~14 mph for the single-axle dump trucks and ~16 mph for the tandems. Because average speeds were not available for the remaining 29 trucks, it was assumed that these did not require any extra starts even though some of these had logged very few miles.

Some of this equipment has an auxiliary engine. During periods when not in use, both engines must be started twice per week. This was accounted for in the calculations. The results of these calculations revealed an estimated 24,328 extra starts per year for the 386 pieces of equipment in the 6 Sections that make up the Houston District. This is an average of 468 extra starts per week. If it is assumed that 5 minutes are required to go to each piece of equipment, start it, and let it warm-up a bit before leaving for the next piece of equipment, and another 5 minutes to reverse this process for each piece of equipment, a total of 78 hours is required each week for the extra starts (13 hours per week per section). TxDOT had independently estimated that they devote 65 hours per week to these extra starts. These two estimates of the hours required for the extra starts agree quite well. However, to be conservative, our calculations for the NOx, PM, and fuel consumption penalties, were multiplied by the ratio 65/78.

To estimate the extra gallons of fuel consumed by each piece of equipment for these extra starts, the idle fuel consumption per liter of displacement was multiplied by the displacement (D) of the engine (or the sum of the engines for equipment that has an auxiliary engine). The resulting fuel consumption in gallons per hour was multiplied by 0.75 hours of warm-up for each start and by the number of extra starts per year. For the large engines, this equation is:

$$\text{ExtraGallons/year} = Z\frac{\text{extra starts}}{\text{year}}0.04\frac{\text{gallons}}{\text{hr}-\text{L}}D[\text{L}]45\frac{\text{minutes}}{\text{start}}\frac{1}{60}\frac{\text{hour}}{\text{minutes}} \quad \text{(B.3)}$$

For the small utility engines, the equation is:

$$\text{ExtraGallons/year} = Z\frac{\text{extra starts}}{\text{year}}0.118\frac{\text{gallons}}{\text{hr}-\text{L}}D[\text{L}]45\frac{\text{minutes}}{\text{start}}\frac{1}{60}\frac{\text{hour}}{\text{minutes}} \quad \text{(B.4)}$$

The extra NOx emissions associated with the need to start these engines twice per week when not otherwise needed was calculated from the fuel consumed during these starts plus the estimated NOx emissions at idle. For the large engines, the resulting equation is:

$$\text{ExtraNOx/year}\left[\frac{g_{NOx}}{\text{yr}}\right] = G\frac{\text{extra gallons}}{\text{year}}117\frac{g_{NOx}}{\text{gal}} \quad \text{(B.5)}$$

For the small utility engines, the equation is:

$$\text{ExtraNOx / year}\left[\frac{g_{NOx}}{\text{yr}}\right] = G\frac{\text{extra gallons}}{\text{year}}42\frac{g_{NOx}}{\text{gal}} \quad \text{(B.6)}$$

The extra PM emissions were calculated in a similar manner, using the estimates of the grams of PM emitted per gallon of PuriNOx consumed at idle, as discussed above.

The methods used to account for the fuel consumed and the emissions of NOx and PM during these extra starts and extended warm-ups do not account for differences between the fully-warmed up engine tests used for the estimates and conditions for cold starting and warm-up. During a cold start, the oil viscosity is high, resulting in high engine friction and the need for additional fueling. Also, diesels emit white smoke when first starting. Thus, our estimates for the starting penalty are believed to be conservative.

The emissions and fuel consumption penalties associated with the extra starts resulting from the tendency of the emulsion to separate are quantified in Section 5.

B.8. Concluding Remarks

The emissions and fuel consumption data acquired as part of this study are presented and discussed in this appendix. The emissions of the Toxic Air Contaminants, as measured as part of the present study, are relevant to the health risks analysis, as discussed in Section 4.A. The remaining emissions and fuel consumption results that are discussed in this appendix are summarized in Section 5.B. The methods developed to use these results to calculate the anticipated annual decrease in NOx and PM emissions are also discussed in Section 5.B. These values are then used in the cost-effectiveness analyses that are discussed in Section 5.C.

Appendix C. Torque and Power Loss

The torque and power loss associated with the water in emulsified diesel fuel was assessed from data available in the literature (Section C.1) and from the present testing (Section C.2). The torque loss inferred from comparisons between dyno data and a data logger that read the torque calculated by the on-board computer is discussed in Section C.3. The results are summarized in Section C.4.

C.1 From the Literature

Two complete full-load torque curve comparisons were available from the literature. The results from these tests are discussed in this subsection.

Southwest Research Institute (Khalek et al. 2000) performed a study of the effects of PuriNOx on emissions, fuel consumption, and performance of a 1991 Detroit Diesel Series 60. The fuels tested were a CARB reference diesel fuel and the PuriNOx was made from this diesel fuel. The full-load torque curve was measured for each fuel seven times. The average results are presented in Figure C.1.1. The coefficient of variation (the standard deviation normalized by the mean) was within 1% at each speed for the diesel fuel and within 2% for the PuriNOx tests. Thus, the differences shown in Figure C.1.1 are statistically significant. The torque loss is speed dependent, ranging from approximately 11% to approximately 19%, with a loss of approximately 13% at peak torque speed (1,200 RPM). The loss in peak power (power at the rated speed of 1,800 RPM) is approximately 12%.

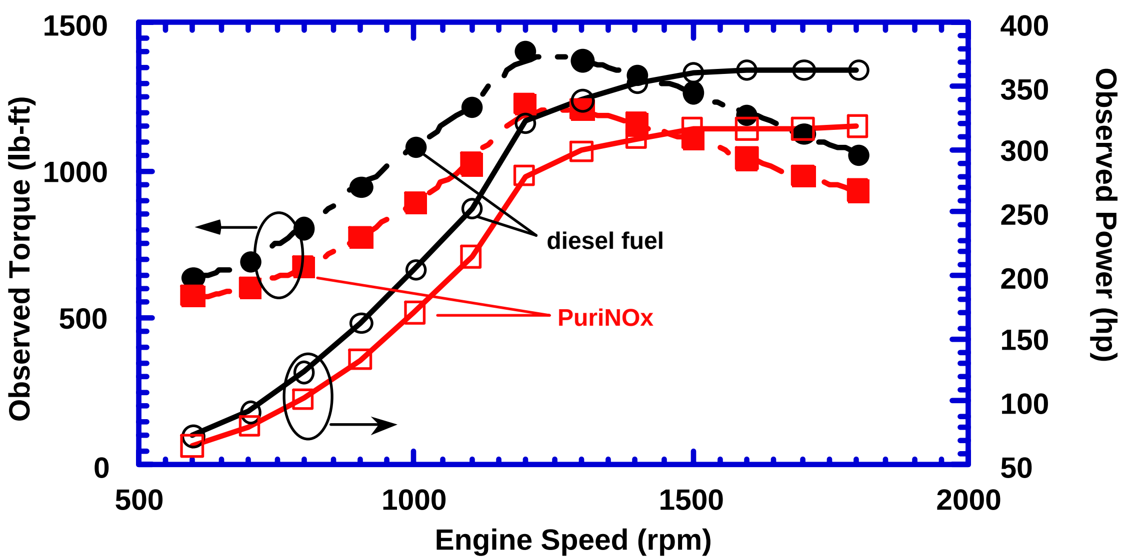


Figure C.1.1 Full-load torque and power curves for a 1991 Detroit Diesel Series 60 (Khalek et al. 2000)

In late 2001, PerkinElmer Automotive Research (Zaiontz, 2002) performed a 1,000 hour durability test on PuriNOx using a Euro II Caterpillar C12 engine. At the beginning of the test, full-load torque curves were measured using 2D diesel fuel and PuriNOx. The results are provided in Figure C.1.2. Again, the torque loss is speed dependent, ranging from approximately 13% to approximately 18%. The loss at peak torque speed is approximately 16%, and the loss in peak power is approximately 13%.

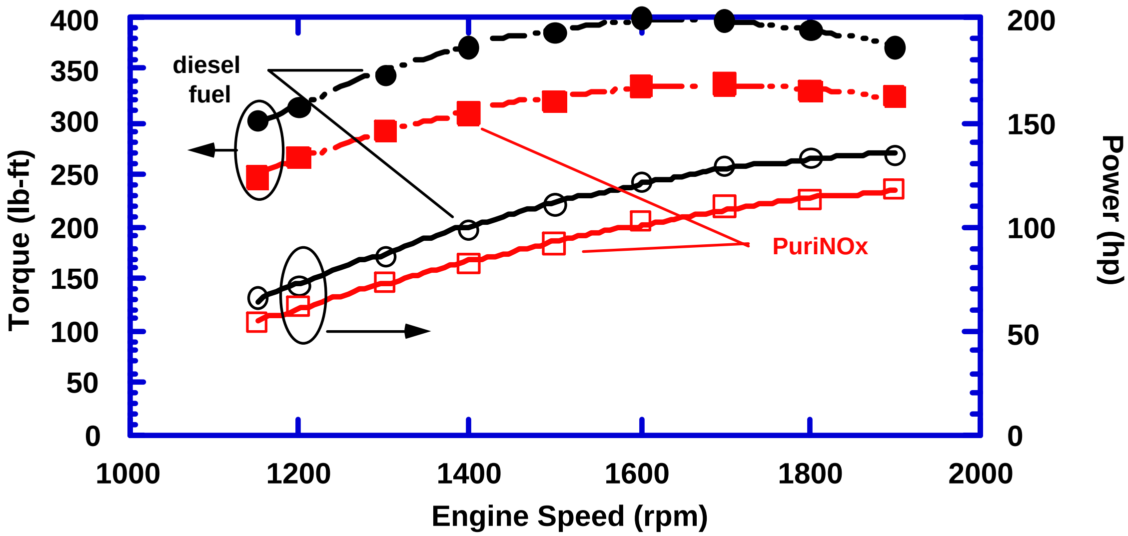


Figure C.1.2 Full-load torque and power curves for a Caterpillar C12 (Zaiontz, 2002)

C.2. From the Present Engine Dyno Tests

Three full-load torque comparisons were generated as part of the present study. The results from these tests are discussed in this subsection.

Prior to running the transient engine cycle tests with the Cummins ISB-190, SwRI measured the full-load torque curves. These results are presented in Figure C.2.1. Compared with 2D on-road diesel fuel, PuriNOx produces a torque loss of approximately 12% at peak torque speed, and a torque and power loss of approximately 14% at rated speed. Compared with the high-sulfur diesel fuel, PuriNOx produces a torque loss of approximately 17% at peak torque speed and approximately 19% at rated speed.

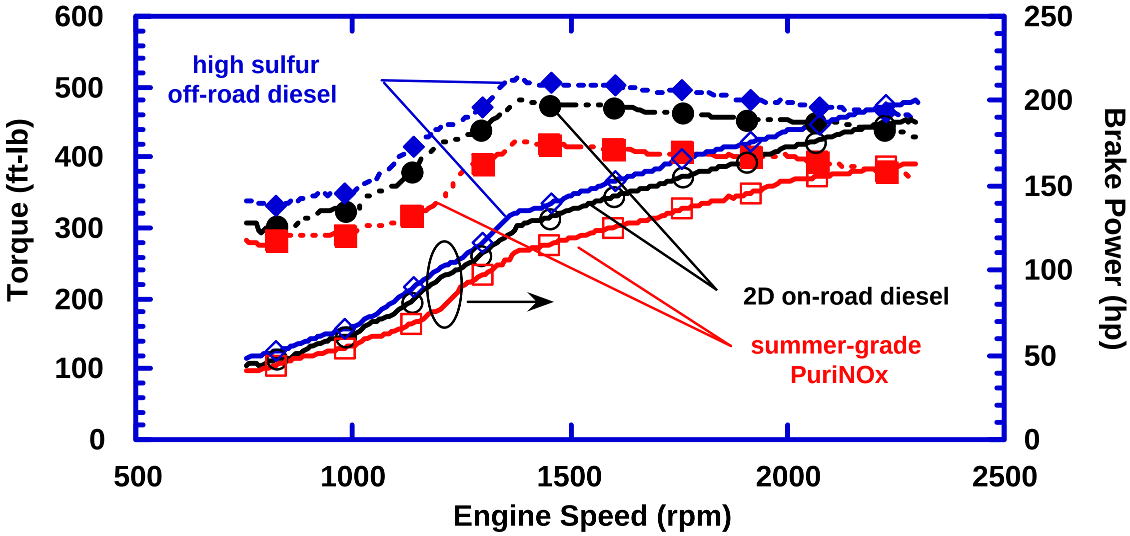


Figure C.2.1 Full-load torque and power curves for a 2000 Cummins ISB-190 from the present tests

The full-load torque and power curves for the Cummins 6BTA5.9 are compared in Figure C.2.2. Compared with 2D on-road diesel fuel, PuriNOx produces a torque loss of approximately 16% at peak torque speed, and a torque and power loss of approximately 15% at rated speed.

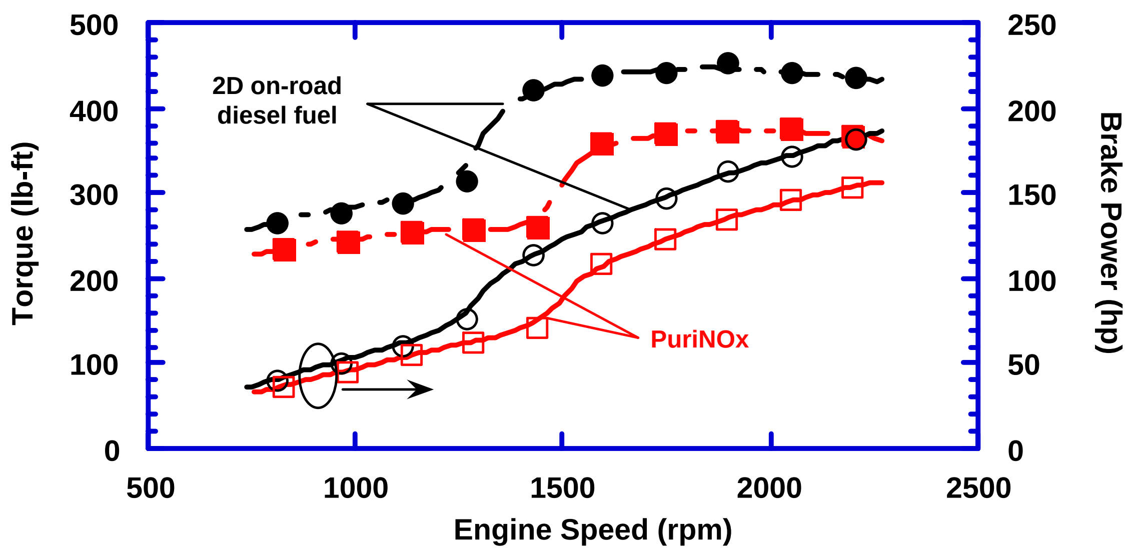


Figure C.2.2 Full-load torque and power curves for a 1997 Cummins 6BTA5.9 from the present tests

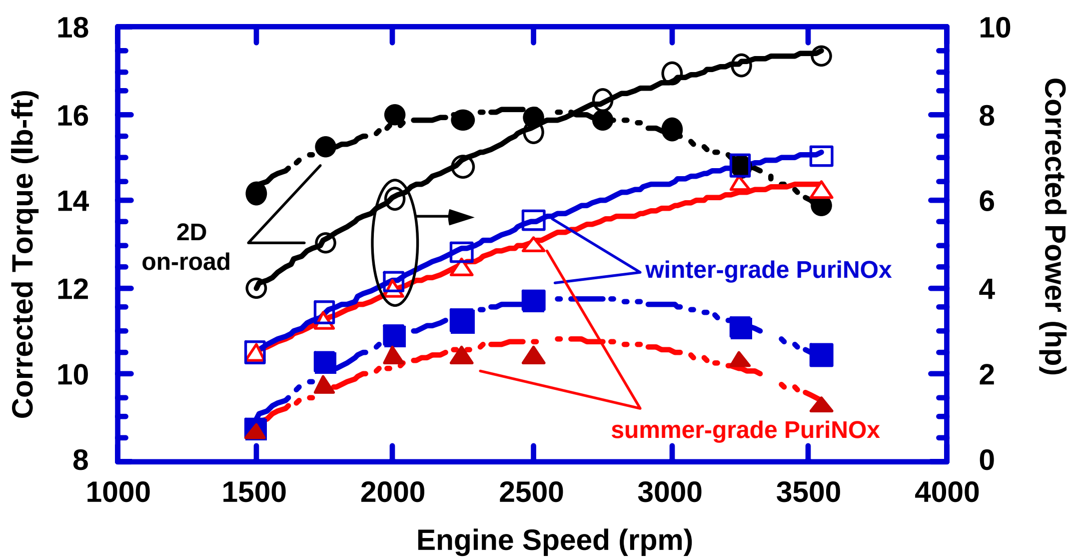


Figure C.2.3 Full-load torque and power curves for a 2002 Yanmar L100EE from the present tests

The full-load torque and power curves for the 2002 Yanmar L100EE single-cylinder diesel are compared in Figure C.2.3. In this figure, comparisons are made among 2D on-road diesel fuel and both summer-grade and winter-grade PuriNOx. Summer-grade PuriNOx produces a torque loss of approximately 58% at peak torque speed, and a torque and power loss of approximately 50% at rated speed. Winter-grade PuriNOx produces a torque loss of approximately 34% at peak torque speed, and a torque and power loss of approximately 35% at rated speed. The improvement for winter-grade relative to summer-grade PuriNOx is due to the methanol in winter-grade PuriNOx. The Yanmar engine is a "low-tech" engine that was designed to produce a small utility diesel at the lowest possible cost. The results for this herbicide sprayer engine may be generally representative of those for other small diesel engines, such as those used in traffic-alerting signals, but should not be expected to reflect the behavior of more sophisticated diesel engines.

C.3. Torque Loss Measures Using QuickCheck Data and Dyno Data

During the SwRI engine dynamometer testing of the Cummins ISB-190 engine, which is the engine used in the Gradall XL3100, the QuickCheck datalogger was installed on the engine. By means of comparisons of the QuickCheck data and the data obtained for engine operation from the dynamometer, the accuracy of the load on the engine as measured by the QuickCheck datalogger and the effect of PuriNOx on engine torque can be determined.

Figure C.2.1, discussed above, shows the full-load torque curves measured by SwRI on the Cummins ISB-190 engine (Serial Number 46109691) when using 2D on-road diesel fuel and when using PuriNOx. This figure illustrates the loss in torque for the engine when using PuriNOx, as compared with 2D on-road diesel fuel.

The emissions of the ISB-190 engine were measured using 2 test cycles (Telescoping Boom Excavator and Wheeled Loader), 2 different temperature modes (Cold Start, Hot Start 1, and Hot Start 2), 3 different fuels (2D on-road, high-sulfur, and PuriNOx), and 3 different dynamometer engine full-load torque maps (1 for each of the 3 fuels). The different dynamometer engine maps were simply the result of applying the percent load and percent RPM test points specified by the test cycle to the different full-load torque curves produced by each of the 3 fuels at each engine speed. This procedure converts the percent torque and percent RPM versus time specification for the cycle into absolute torque and absolute RPM versus time.

In the analysis in this section, we compare the measured torque as determined by the dynamometer measurements with the inferred torque as calculated by multiplying the maximum measured torque at each engine speed (as is shown in Figure C.2.1) times the percent load inferred by the engine computer and recorded on the QuickCheck datalogger. The engine computer does not measure the percent load of the engine but instead infers it from the measured values of engine RPM, accelerator position, and possibly other sensors on the engine. Because the percent load is not measured by the engine computer, we wanted to compare the inferred torque based on the engine computer output with the measured torque from the dynamometer test. If the measured and inferred torques agree reasonably well for operation on 2D diesel fuel, then we could conclude that the dynamometer and chassis test cycles developed for emissions testing, which were based on data collected in the field using the QuickCheck datalogger, were reasonably accurate. In addition, the comparison of measured and inferred torques is a means of determining the torque loss produced by the PuriNOx fuel throughout the operating range of the engine, not simply at full load.

To accomplish this comparison, we matched the second-by-second QuickCheck logged data with the 0.1-second-by-0.1-second dynamometer data. The results of these comparisons indicated no difference in the relationship of the measured and inferred torques as a result of test cycle, temperature mode, and dynamometer map; however, differences were observed for the 3 different test fuels. Figures C.3.1, 2, and 3 show these differences.

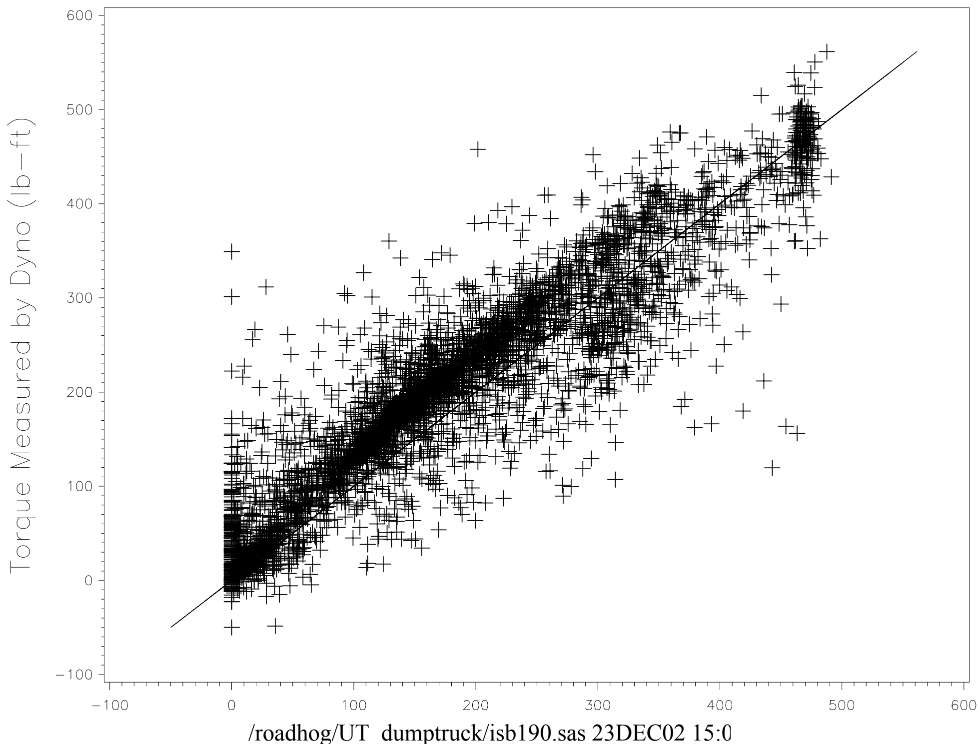


Figure C.3.1 Measured versus inferred torque using high sulfur diesel fuel

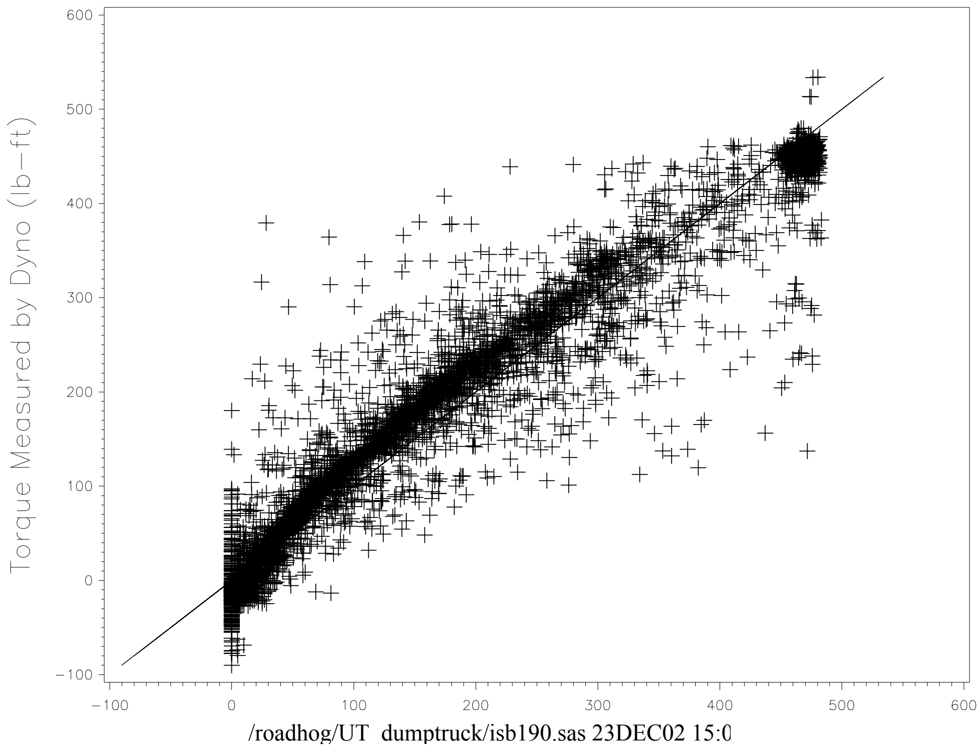


Figure C.3.2 Measured versus inferred torque using 2D on-road diesel fuel

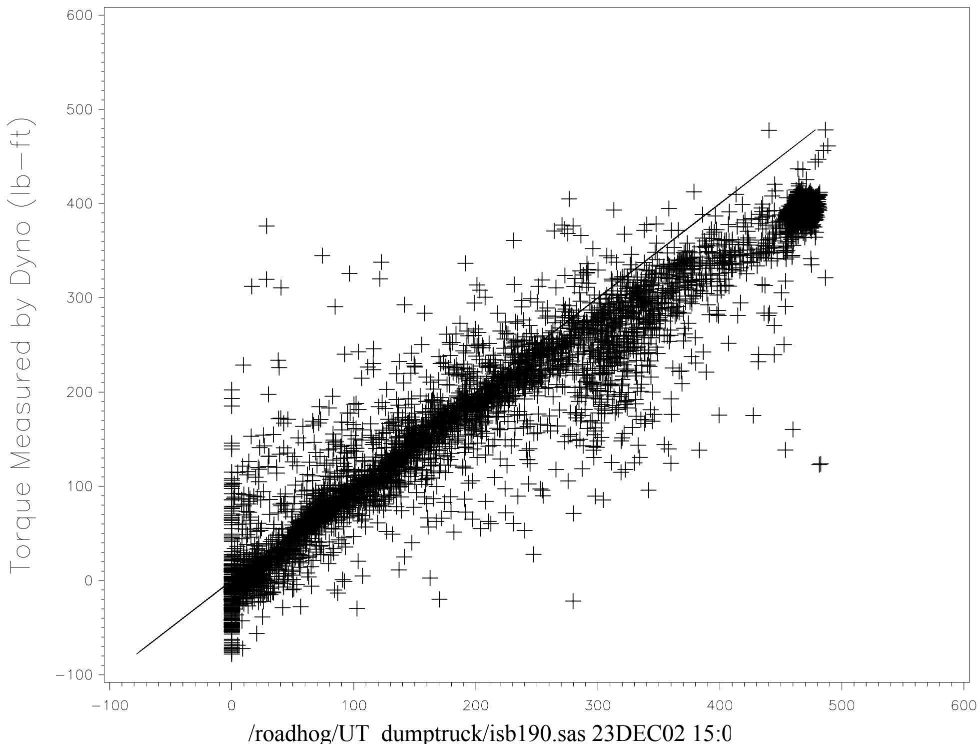


Figure C.3.3 Measured vs. inferred torque using PuriNOx

We used the torque inferred by the engine computer as the means of comparing the effect of fuels because the engine computer does not have the capacity to know the composition of the fuel that is being used by the engine. Figure C.3.1 shows the comparison of measured and inferred torque for high-sulfur diesel fuel. At low torques and high torques, the inferred torque and the dynamometer torque are in good agreement. However, for middle torques, the inferred torques are slightly lower than the measured dynamometer torque. A similar, but not exactly the same, trend is seen in Figure C.3.2 for the low-sulfur diesel fuel. The small differences in the trends may be the result of the somewhat different compositions of low- and high-sulfur diesel fuels as a result of diesel fuel blending and hydrotreating. In the process of hydrotreating diesel fuel blending components, the structure of the hydrocarbon molecules is slightly altered at the same time that sulfur is removed.

Figure C.3.3 shows the comparison of measured and inferred torque when PuriNOx fuel was used. A comparison of this trend with the trends in Figures C.3.1 and C.3.2 indicates that at a given inferred torque, the torque as measured by the dynamometer is approximately 20% lower throughout the range of torques.

Overall, the comparisons of the measured dynamometer torque and the inferred engine torque indicate that, as expected, the PuriNOx fuel reduces the torque of the engine throughout its operating range, not simply at the maximum torque. In addition, the comparisons indicate that the QuickCheck datalogger technique is able to record engine loads that are reasonably accurate.

C.4. Summary of Torque and Horsepower Losses

The torque loss from use of summer-grade PuriNOx, as compared with 2D on-road diesel fuel, is illustrated in Figure C.4.1 and Table C.1. In addition to the results presented in Sections C.1 and C.2, Figure C.4.1 and Table C.1 include data for a 2001 DDC Series 50 engine that was tested at SwRI (Sarlo, 2001). For this 1,000 hour durability test, the torque for PuriNOx and diesel fuel were compared only at peak torque speed and at rated speed.

The Yanmar engine is a "low-tech" engine that was designed to produce a small utility diesel at the lowest possible cost. The results for this herbicide sprayer engine, as discussed in Section C.2, may be generally representative of those for other small diesel engines, such as those used in traffic-alerting signals, but should not be expected to reflect the behavior of more sophisticated diesel engines. Thus, the results for the Yanmar are not included in Table C.1 and are not discussed further.

Table C.1 shows that the torque loss at peak torque speed ranges from approximately 12 to 16%, and the loss of torque at rated speed ranges from approximately 12 to 15%. Because maximum power occurs at rated speed, this torque loss at rated speed corresponds to a loss of maximum power of approximately 12 to 15%. However, Figure C.4.1 shows that there is, in general, a peak in the torque loss, up to 39%, near mid-speed. This torque loss, plus that at peak torque speed, affects acceleration, whereas the loss of peak power is related to maximum possible cruising speed or load lifting capacity.

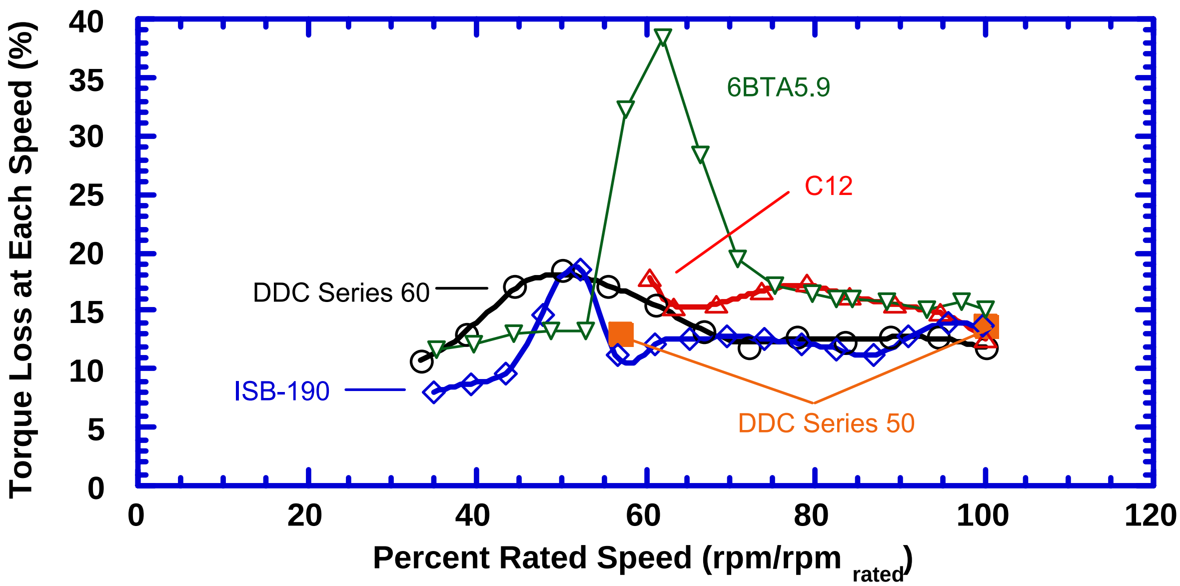


Figure C.4.1 Torque loss for PuriNOx compared with diesel fuel as a function of speed for a variety of engines

Table C.1 PuriNOx Torque Loss for a Variety of Diesel Engines

		Percent Torque Loss at		Max. Torque Loss	
Engine	**Control**	**Peak Torque Speed**	**Rated Speed**	**%**	**at RPM**
01 DDC Series 50	elect.	13.1	13.7	18.5	900
91 DDC Series 60	elect.	13.3	11.8	NA	
96 Cat C12	elect.	16.3	12.7	17.3	1500
00 Cummins ISB-190	elect.	12.1	13.7	19.5	1170
97 Cummins 6BTA5.9	mech	16.1	15.1	39.0	1380

Appendix D. Effects on Operations

Detailed results regarding the effects of PuriNOx on operations of TxDOT equipment are discussed in this appendix. The surveys of TxDOT drivers and operators from the Houston District are discussed in Section D.1. The double-blind testing at the Roadeo is discussed in Section D.2. Cabin noise is discussed in Section D.3. Section D.4 covers TxDOT's experiences with PuriNOx in specific pieces of equipment for which this fuel was found to be unsuitable.

D.1. Houston Driver Surveys

The objective of surveying PuriNOx users in Houston was to determine what the performance effects or issues associated with the use of PuriNOx-fueled vehicles/equipment were, and in which kinds of vehicles/equipment, if any, the use of PuriNOx was deemed problematic.

D.1.A. Survey Instrument and Pilot - A survey instrument was developed consisting of 18 statements regarding the perceived effect of using PuriNOx on the operation of the Houston vehicles/equipment. More than one question was included to evaluate the perceived performance of particular performance attributes. These questions were asked in different ways to test consistency among the responses. The respondents were asked to circle the option that best described how they feel on a scale from 1 to 5, where 1 meant disagreement and 5 meant agreement to the statement/question. Also the respondents were given the opportunity to raise additional concerns in the "any other comments" section.

An initial copy of the questionnaire was piloted in Hempstead. The questionnaire was modified based on the received Hempstead responses (see Text box for a copy of the questionnaire). Also the responses were used to determine the sample size required to facilitate statistical analysis at 1% significance level.

Two rounds of surveys were conducted. The first round of operator surveys was conducted at four sites in West Harris, North Harris, Montgomery, and Fort Bend during late August and early September – approximately two to three months after the vehicles/equipment were converted to PuriNOx. A second round of surveys were conducted at the same sites during November to determine if the perceptions changed once the operators became more familiar and gained more experience with PuriNOx. CTR personnel, with extensive experience in heavy equipment operations, administered the surveys.

Center for
Transportation Research
The University of Texas at Austin
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Phone: (512) 232-3100 • *Fax:* (512) 232-3153 • *Website:* www.utexas.edu/research/c

Dear Sir:

The Texas Department of Transportation (TxDOT) is conducting field tests with PuriNOx that promises to offer emissions benefits. TxDOT contracted with the University of Texas at Austin to conduct extensive experiments to determine the benefits, detriments, and real-world operational characteristics of this fuel when applied to TxDOT's on-road and off-road equipment.

You are part of a sample of carefully selected operators that have used PuriNOx over the past five months. The objective of the attached questionnaire is to gain your perceptions on the effect of this particular fuel on the operation of the vehicle/ equipment compared to diesel fuel. For each of the statements, please ***circle*** the option that best describes how you feel. Your honest response is essential to the success of the study, but please remember that there is no "right" or "wrong" answer.

Your participation is completely voluntary. Please be assured that your responses will be treated as confidential and will be used solely for the study purpose. **It will not be provided to anyone outside the study team and will never be reported in a manner in which could identify you.**

Thank you in advance for completing the survey. If you have any questions, please do not hesitate to ask the surveyor or contact Ms. Jolanda Prozzi at (512) 232 3079.

Operator Assessment

Date:
Surveyor:
Name:
Location:
Vehicle/ equipment used:
Type of Engine:
Tasks performed:

1. I noticed a substantial improvement in the performance of my vehicle/ equipment.

   1 2 3 4 5 ☐6
   Disagree Agree Not Applicable

2. I had more tasks in the past eight weeks than on average.

   1 2 3 4 5 ☐6
   Disagree Agree Not Applicable

3. Even at full throttle, it took me longer than normal to perform the same task when using the hydraulics.

   1 2 3 4 5 ☐6
   Disagree Agree Not Applicable

4. My vehicle/ equipment used more fuel than before.

   1 2 3 4 5 ☐6
   Disagree Agree Not Applicable

5. I asked a mechanic to check my vehicle/ equipment during the past eight weeks.

   1 2 3 4 5 ☐6
   Disagree Agree Not Applicable

6. I was able to do all my usual tasks faster than before.

1	2	3	4	5	☐6
Disagree			Agree		Not Applicable

7. The engine of the vehicle/ equipment was noticeably noisier than before.

1	2	3	4	5	☐6
Disagree			Agree		Not Applicable

8. I suffered from more backaches, sore muscles, and headaches than usual.

1	2	3	4	5	☐6
Disagree			Agree		Not Applicable

9. I changed my driving/ operating behavior over the past eight weeks.

1	2	3	4	5	☐6
Disagree			Agree		Not Applicable

10. I moved heavier loads over the past eight weeks than normally.

1	2	3	4	5	☐6
Disagree			Agree		Not Applicable

11. I experienced some of the following symptoms over the past eight weeks: runny nose, nausea, hair loss, or skin rash.

1	2	3	4	5	☐6
Disagree			Agree		Not Applicable

12. I noticed that my vehicle/ equipment had less power than before.

1	2	3	4	5	☐6
	Disagree		Agree		Not Applicable

13. I had a problem starting my vehicle/ equipment early in the morning.

1	2	3	4	5	☐6
Disagree			Agree		Not Applicable

14. My vehicle was accelerating faster than before.

1	2	3	4	5	☐6
Disagree			Agree		Not Applicable

15. My vehicle/ equipment smelled better than before.

1	2	3	4	5	☐6
Disagree			Agree		Not Applicable

16. I noticed more smoke coming from my vehicle/ equipment.

1	2	3	4	5	☐6
Disagree			Agree		Not Applicable

17. I had to shift gears more often when doing my work.

1	2	3	4	5	☐6
Disagree			Agree		Not Applicable

18. My vehicle/equipment was vibrating more than before.

1	2	3	4	5	☐6
Disagree			Agree		Not Applicable

19. Any other comments:

D.1.B. Houston Driver Surveys: August/September - In late August and early September a total of 44 drivers/operators were surveyed in West Harris, North Harris, Montgomery, and Fort Bend (see Table D.1). The response was almost uniformly negative, although the intensity of the responses varied depending on the criteria tested. At the same time, some of the drivers/operators raised the following specific concerns in the comment section of the questionnaire about using PuriNOx:

- a 10 to 15% loss of power,
- acceleration problems, particularly operators felt unsafe when required to merge onto the freeway,
- required frequent shift points,
- slower hydraulic movement,
- difficulty starting vehicles/equipment in the morning,
- excessive pollution if vehicles/equipment are started only once a week,
- maximum speed which can be reached is 55 miles/hour, which impacts traffic,
- uses more fuel,
- dies when idling (e.g., when stopping at traffic lights),
- smells bad, and
- noisy.

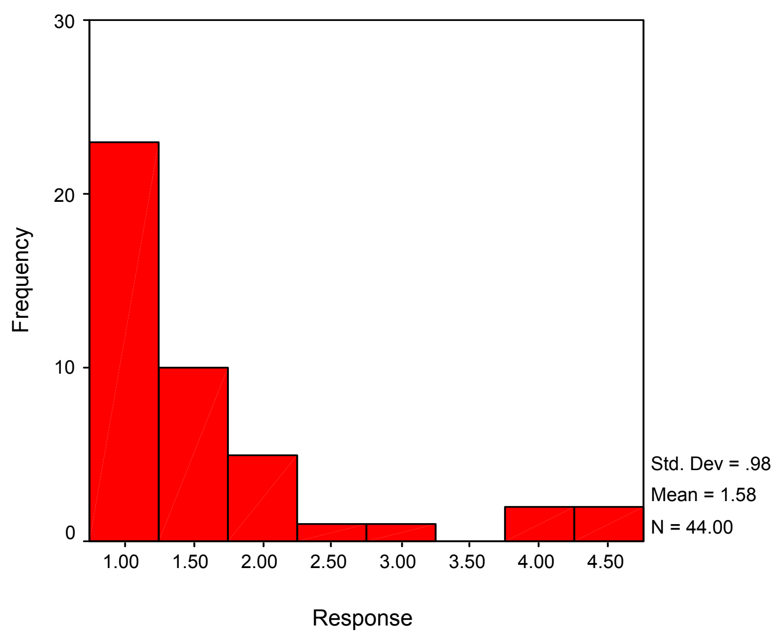
Table D.1 Number of Survey Responses (August/September)

	Total Responses	Valid Driver/Operator Responses	Mechanic Responses
Fort Bend	9	9	0
Conroe	14	13	0
West Harris	8	7	0
Humble	18	15	2
Total	**49**	**44**	**2**

Frequency Distribution of Houston Responses: August/September

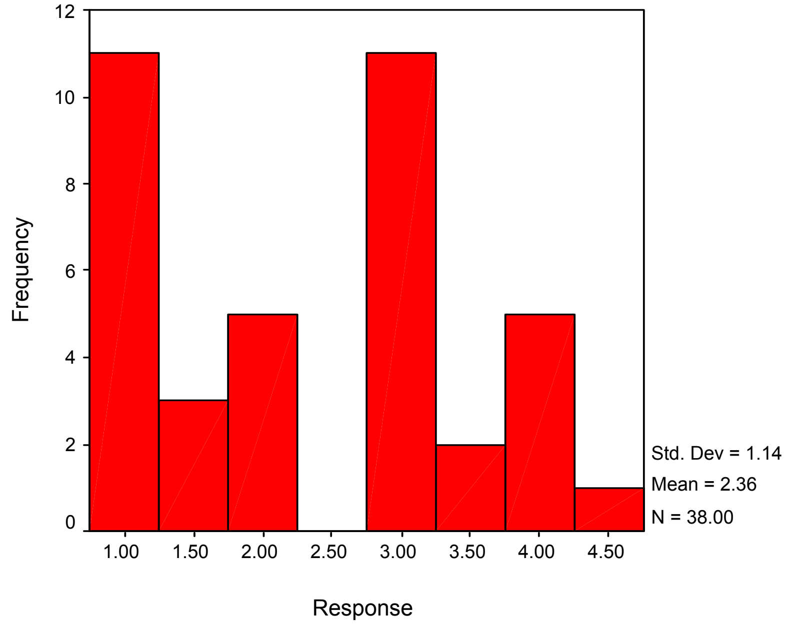
This section graphs the frequency distribution of the responses to each question and lists the mean response and the standard deviation. Some of the questions resulted in stronger and more uniform responses from the drivers/operators than others. These cases are highlighted.

I noticed a substantial improvement in the performance of my vehicle/equipment.



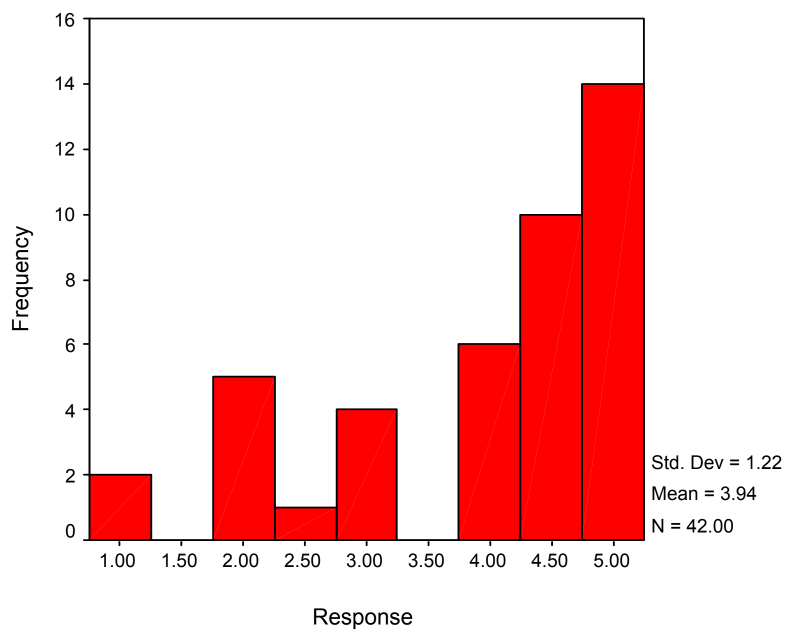
84.1 % of the 44 operators who answered this question, circled/checked a number less than or equal to 2. This indicates that the drivers/operators did not perceive any improvement in the performance of the vehicles/equipment.

I had more tasks in the past few weeks than on average.



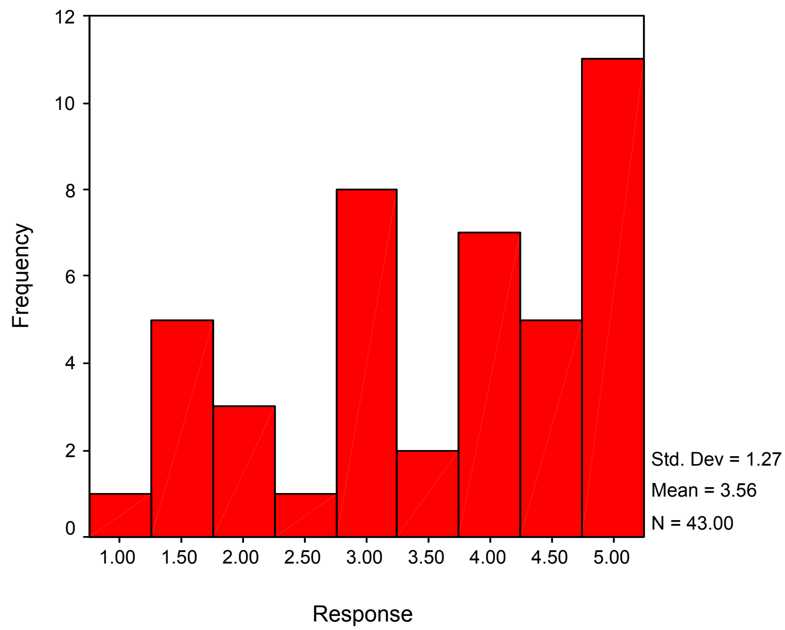
Most of the responses circled/checked seem to indicate that the perceptions of the drivers/operators regarding PuriNOx were not influenced by a higher than average task load. Questions such as these were included to identify possible biases.

Even at full throttle, it took me longer than normal to perform the same task when using the hydraulics



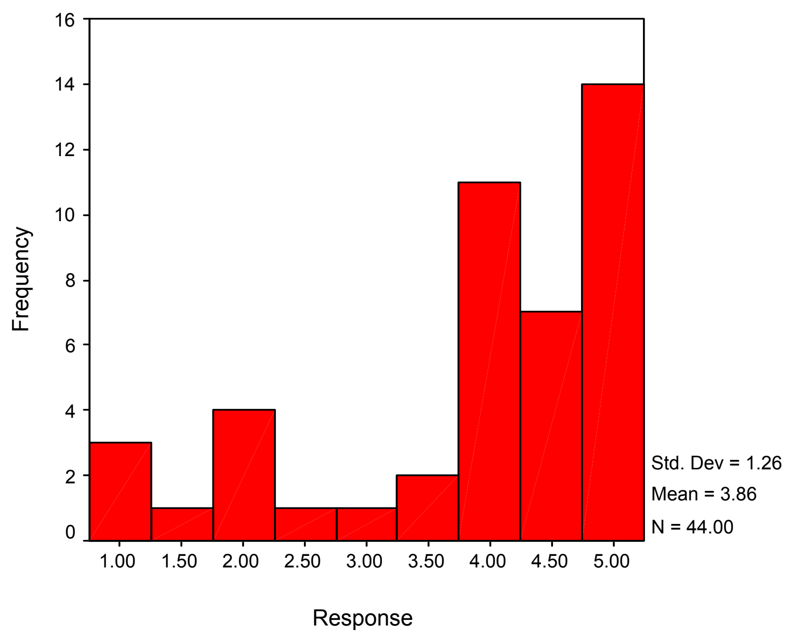
Most of the respondents that used hydraulics felt that it took them longer to perform the same task using PuriNOx compared to conventional diesel.

My vehicle/equipment used more fuel than before.



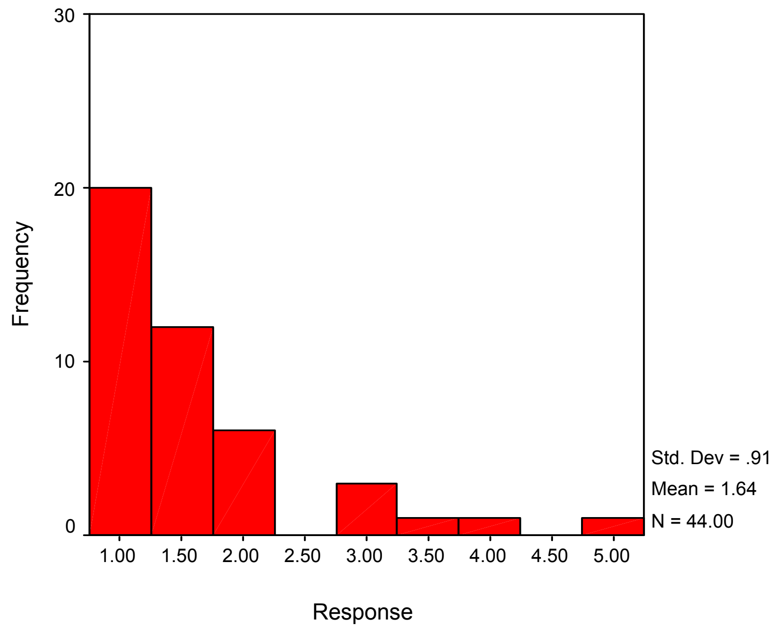
Although most of the responses ranged from neutral to agree with this statement, the mean suggests that the response from the population would be neutral to somewhat agree.

I asked a mechanic to check my vehicle/equipment during the past few weeks



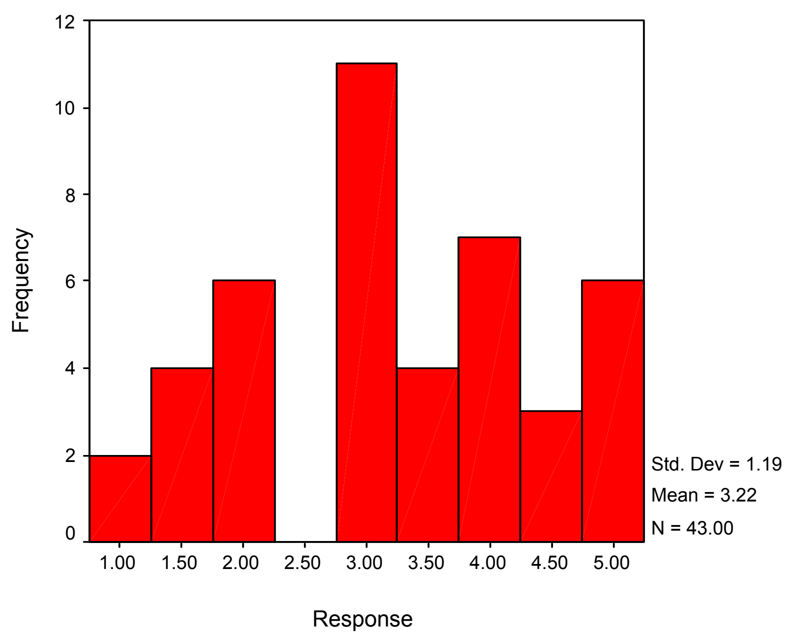
From these responses, it is obvious that the drivers/operators noticed a change in the performance of their vehicles/equipment to the extent that more than half of the respondents asked a mechanic to look at their vehicles/equipment after switching to PuriNOx

I was able to do all my usual tasks faster than before.



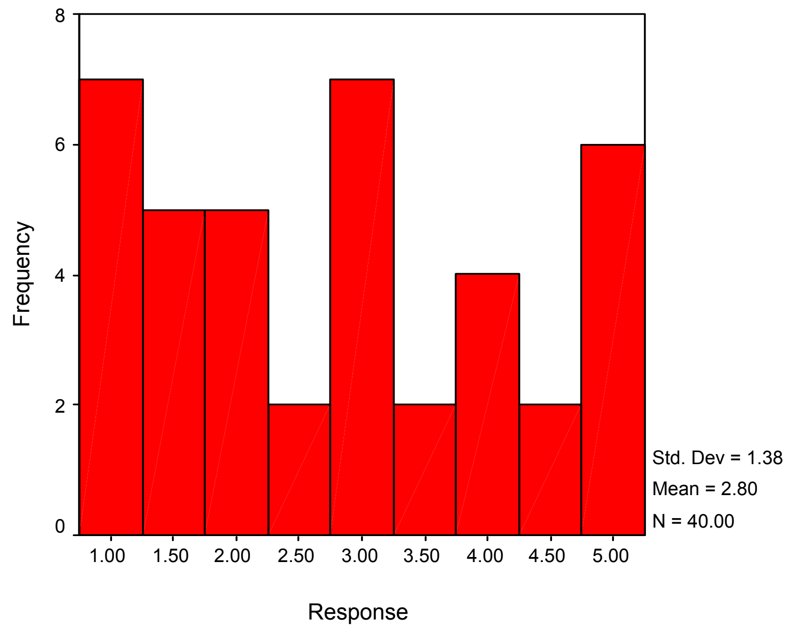
38 out of the 44 operators responded negatively to this statement, clearly showing that the operators did not perceive an increase in the performance of their vehicles/equipment that allowed them to do their tasks faster than before.

The engine of the vehicle/equipment was noticeably noisier than before.



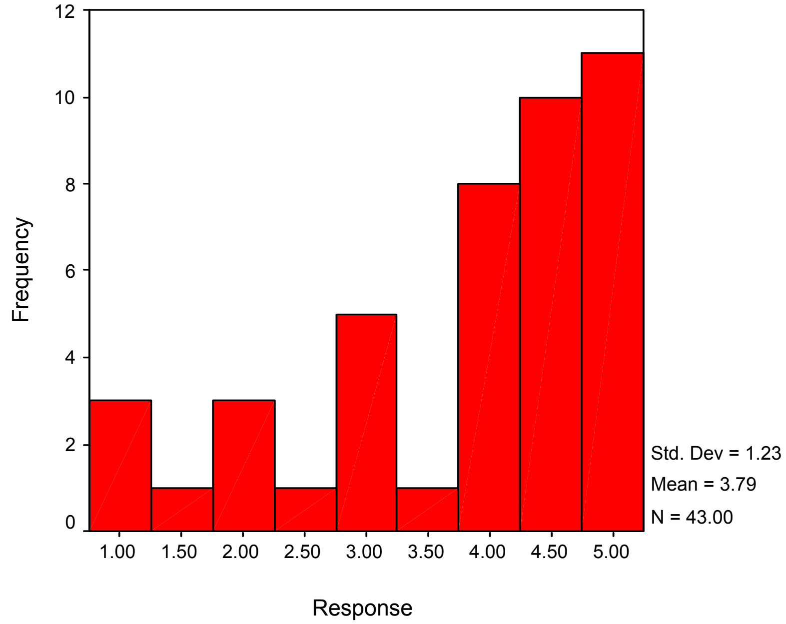
The responses to this statement were more varied, but a significant number of the respondents seemed to be neutral to this statement.

I suffered from more backaches, sore muscles, and headaches than usual.



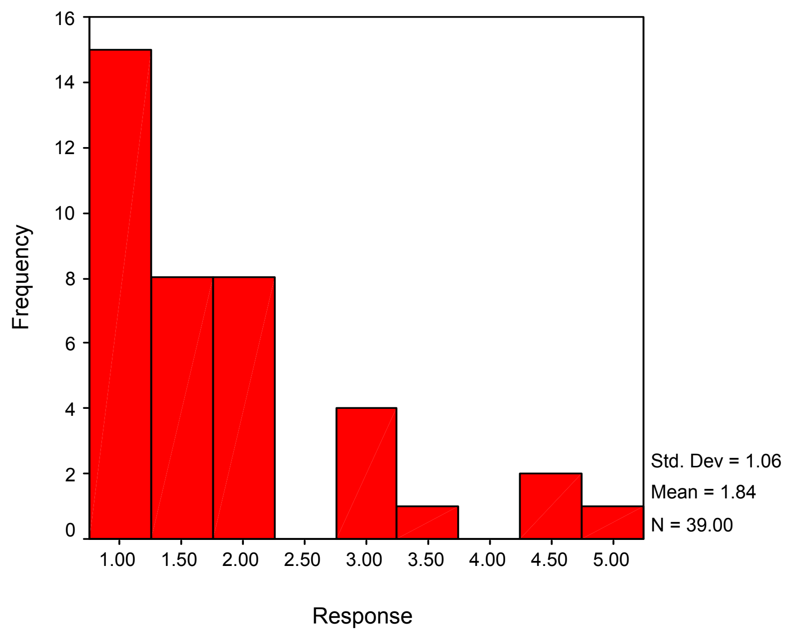
The calculated mean indicates that the response from the population would be neutral to somewhat disagree. This seems to suggest that the respondents did not perceive an association between an increase in adverse health affects (i.e. backaches, sore muscles and headaches) and using PuriNOx.

I changed my driving/operating behavior over the past weeks.



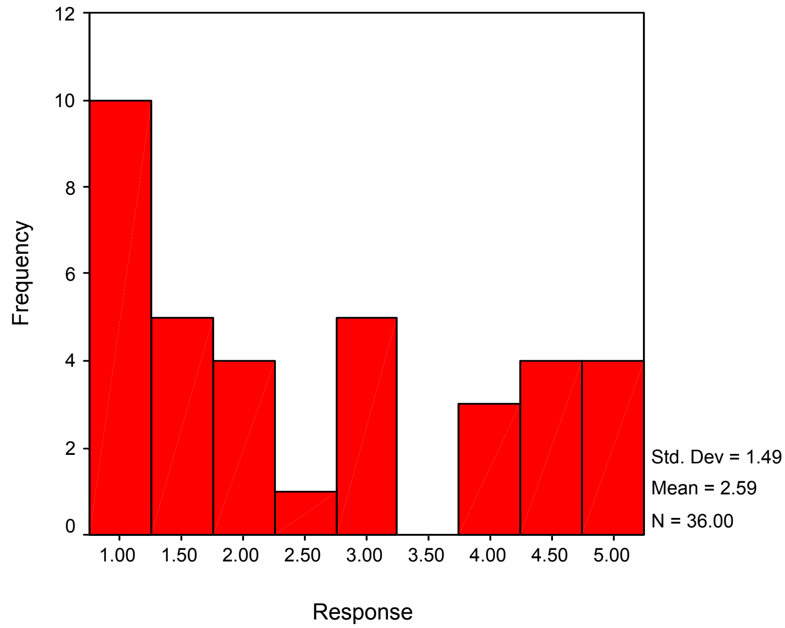
Most of the respondents indicated that they changed their driving/operating behavior since switching to PuriNOx.

I moved heavier loads over the past few weeks than normally.



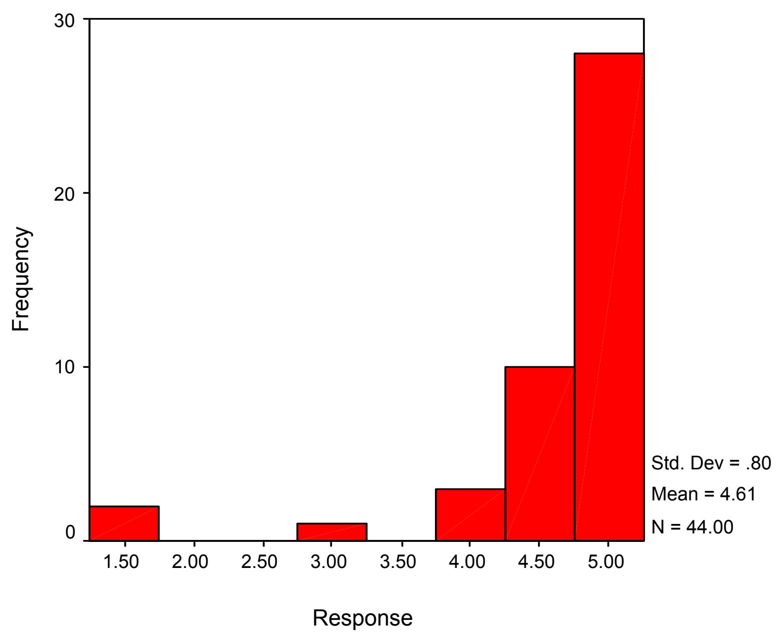
The responses to this statement indicated that the drivers/operators did not have to move heavier loads than normal since switching to PuriNOx.

I experienced some of the following symptoms over the past weeks: runny nose, nausea, hair loss, and skin rash.



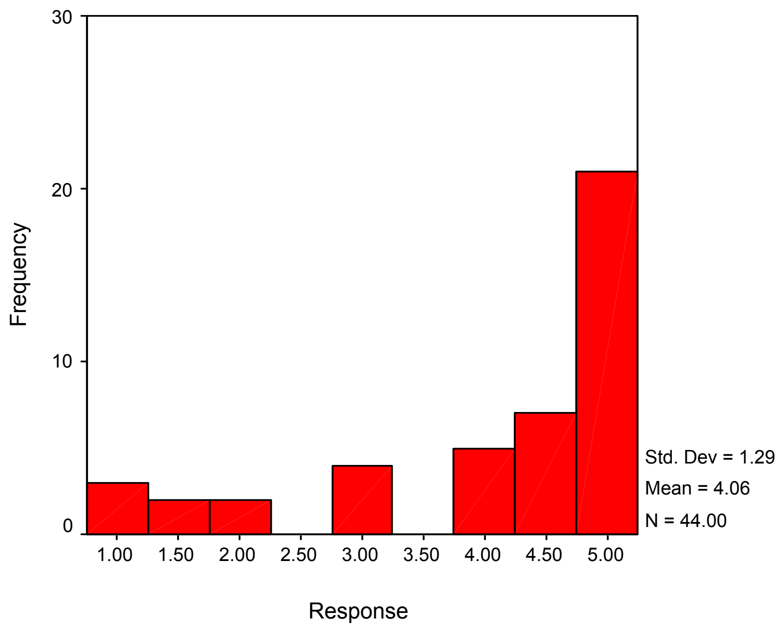
The responses to this statement were consistent with the responses to statement 8 (I suffered from more backaches, sore muscles, and headaches than usual), suggesting that the respondents did not perceive an association between an increase in adverse health affects and using PuriNOx.

I noticed that my vehicle had less power than before.



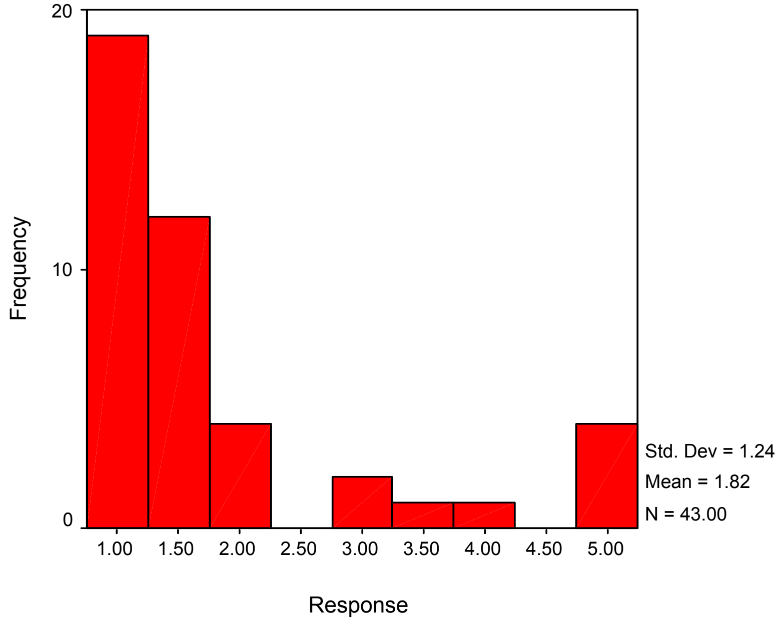
93% of the respondents stated a reduction in the power of their vehicles/equipment. Furthermore, statistical analysis showed that, at 99% confidence level, the mean response of the population would be at least 4.33 on a scale of 1 to 5 (with 1 being disagreement and 5 being agreement with the statement that the power of the vehicle/equipment reduced due to the use of PuriNOx). This strong uniform response indicates that loss of power was a noticeable concern for most of the drivers/operators.

I had a problem starting my vehicle/equipment early in the morning.



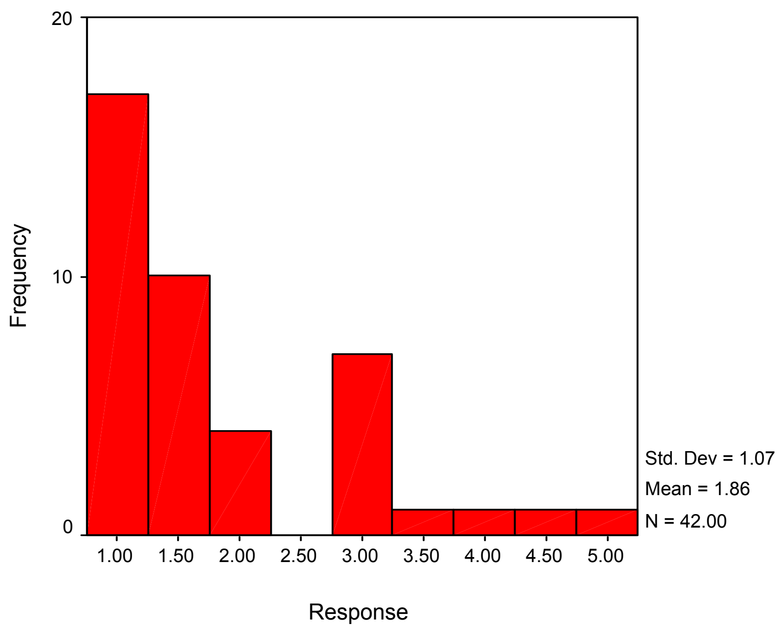
Given the number of respondents who agreed with this statement and the calculated mean, the starting of vehicles/equipment early in the morning is also a perceived concern for the Houston PuriNOx users.

My vehicle was accelerating faster than before.



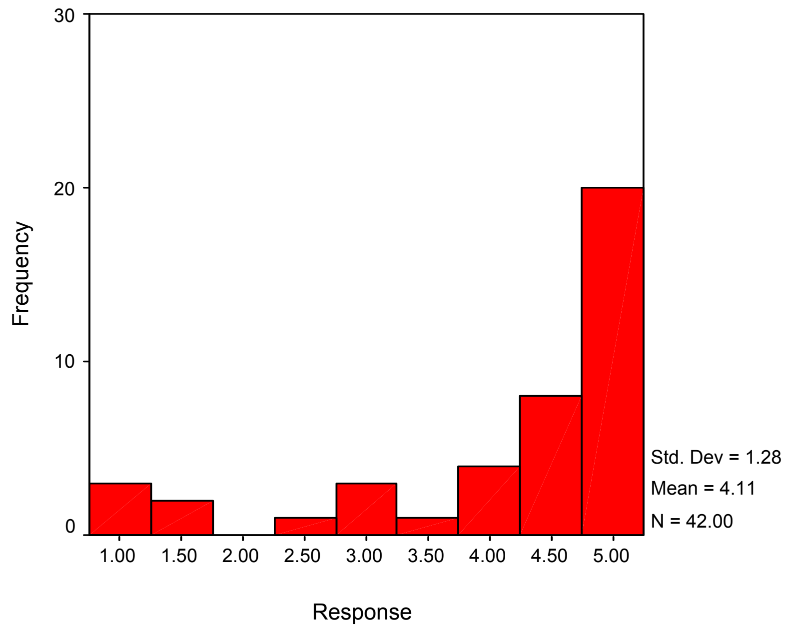
35 out of the 43 respondents disagreed with the statement that the vehicles were accelerating faster than before.

My vehicle/equipment smelled better than before.



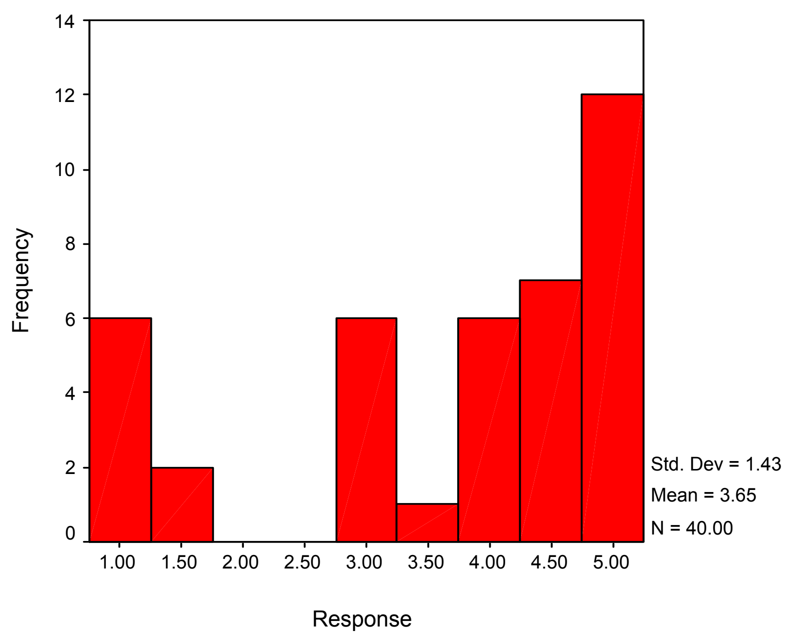
Most of the respondents disagreed with the statement that their vehicles/equipment smelled better than before.

I noticed more smoke coming from my vehicle/equipment.



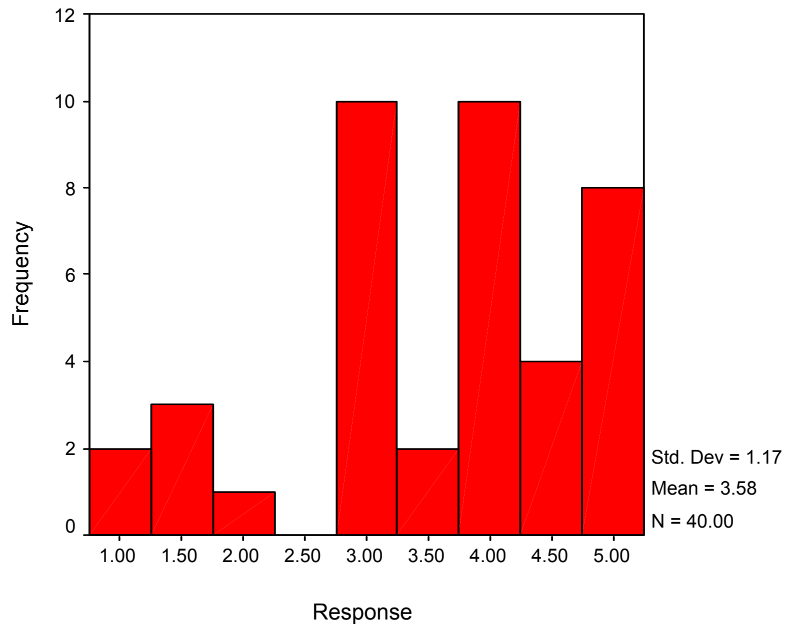
Given the number of respondents who agreed with this statement and the calculated mean, Houston PuriNOx users perceived a noticeable increase in the smoke coming from their vehicles/equipment.

I had to shift gears more often when doing my work.



More than half of the respondents indicated that they had to shift gears more often when doing their work.

My vehicle/equipment was vibrating more than before.



The responses to this question varied a lot, but more than half of the responses are between neutral and somewhat agree.

Statistical Analyses

Since the number of responses to each question was more than 30, a normal distribution was assumed and hypothesis tests were performed on each of them. The statistical analysis was conducted in two stages. Initially a two-sided test was performed to test the null hypothesis that the "true" mean of the responses was 3. In other words, the null hypothesis was that the operators were neutral towards each of the statements – suggesting no perceived difference between the performance attributes of the vehicles/equipment with PuriNOx and conventional diesel. If the two-sided test revealed that the null hypothesis had to be rejected for any statement – thus meaning that the operators were not neutral – a second test (a one-sided test) was performed to determine if the operators agreed or disagreed with that statement.

These tests allowed for the calculation of a confidence interval for the population mean for each of the statements (attributes). All the tests were performed at 1% significance level.

Two-Sided Test Results

First the two-sided tests were thus performed to test:

Null Hypothesis: $\mu = 3$
Alternative Hypothesis: $\mu \neq 3$

The results of the two-sided tests are summarized in Table D.2.

Table D.2 Two-Sided Test Results (August/September)

Statement	Reject Null?	Confidence Interval	
		Lower limit	Upper limit
I noticed a substantial improvement in the performance of my vehicle/equipment.	Yes	1.20	1.96
I had more tasks in the past few weeks than on average.	Yes	1.88	2.84
Even at full throttle, it took me longer than normal to perform the same task when using hydraulics.	Yes	3.46	4.42
My vehicle/equipment used more fuel than before.	Yes	3.07	4.06
I asked a mechanic to check my vehicle/equipment during the past few weeks.	Yes	3.38	4.35
I was able to do all my usual tasks faster than before.	Yes	1.28	1.99
The engine of the vehicle/equipment was noticeably noisier than before.	No	2.75	3.68
I suffered from more backaches, sore muscles, and headaches than usual.	No	2.24	3.37
I changed my driving/operating behavior over the past weeks.	Yes	3.31	4.27
I moved heavier loads over the past few weeks than normally.	Yes	1.40	2.28
I experienced some of these symptoms: runny nose, nausea, hair loss, skin rash.	No	1.95	3.23
I noticed that my vehicle had less power than before.	Yes	4.30	4.92
I had a problem starting my vehicle/equipment early in the morning.	Yes	3.55	4.56
My vehicle was accelerating faster than before.	Yes	1.34	2.31
My vehicle/equipment smelled better than before.	Yes	1.44	2.29
I noticed more smoke coming from my vehicle/equipment.	Yes	3.60	4.62
I had to shift gears more often when doing my work.	Yes	3.06	4.23
My vehicle/equipment was vibrating more than before.	Yes	3.11	4.05

As can be seen from Table D.2, the null hypothesis was not rejected for only three of the statements (attributes): (1) The engine of the vehicle/equipment was noticeably noisier than before; (2) I suffered from more backaches, sore muscles, and headaches than usual, and (3) I experienced some of these symptoms: runny nose, nausea, hair loss, skin rash. This means that the respondents did not perceive any change in engine noise or health effects associated with the use of PuriNOx. It can be concluded at a 99 % confidence level that the population mean response of PuriNOx users to the "noise" statement lies between 2.75 and 3.68. Similarly, the true mean response to "occurrence of backaches, sore muscles and headaches" lies between 2.24 and 3.37, and for "occurrence of runny nose, nausea, hair loss, skin rash, etc' between 1.95 and 3.23.

Two questions were included in the questionnaire to determine if the respondents' working conditions were perceived different since the switching to PuriNOx. For example, respondents were asked to respond to a statement that they had more tasks on average since switching to PuriNOx. No additional statistical analysis was performed for these two questions.

The fact that the null hypothesis was rejected for all the remaining statements indicate that the Houston PuriNOx users perceived a difference in the performance of their vehicles/equipment when using PuriNOx. A one-sided test was performed on each statement to determine whether the perceived impact was positive or negative.

One-Sided Test Results

The remaining statements were divided into two groups: "negative statements" and "positive statements". The null and the alternative hypotheses for the first group of questions were:

Null Hypothesis: $\mu = 3$
Alternative Hypothesis: $\mu > 3$

If the null hypothesis is rejected, then the "true" mean response is greater than 3, meaning that the respondents agreed with the statement. Table D.3 summarizes the attributes tested, whether the null hypothesis was rejected, and the confidence intervals for the mean responses of the population of PuriNOx users.

Table D.3 Negative PuriNOx Statements

Statement	Reject Null?	Confidence Interval
Even at full throttle, it took me longer than normal to perform the same task when using hydraulics.	Yes	≥ 3.50
My vehicle/equipment used more fuel than before.	Yes	≥ 3.11
I asked a mechanic to check my vehicle/equipment during the past few weeks.	Yes	≥ 3.42
I noticed that my vehicle had less power than before.	Yes	≥ 4.33
I had a problem starting my vehicle/equipment early in the morning.	Yes	≥ 3.60
I noticed more smoke coming from my vehicle/equipment.	Yes	≥ 3.65
I had to shift gears more often when doing my work.	Yes	≥ 3.12
My vehicle/equipment was vibrating more than before.	Yes	≥ 3.15

From Table D.3, it is evident that loss of power was a major concern. This was also evident from statements to the open-ended question in the questionnaire. Other significant concerns include:

- starting the vehicle/equipment early in the morning,
- more smoke coming from the equipment, and the
- inability to perform tasks as quickly when using the hydraulics.

The requirements for additional shift points, fuel usage and vibration seem to be of lesser concern.

The null and the alternative hypotheses for the second group of questions were:

$$\text{Null Hypothesis: } \mu = 3$$
$$\text{Alternative Hypothesis: } \mu < 3$$

If the null hypothesis is rejected, then the "true" mean response is less than 3, meaning that the respondents disagreed with the statement. Similar to the first group, the statements, whether the null hypothesis was rejected and the confidence intervals have been presented in Table D.4.

Table D.4 Positive PuriNOx Statements

Statement	Reject Null?	Confidence Interval
I noticed a substantial improvement in the performance of my vehicle/equipment.	Yes	≤ 1.93
I was able to do all my usual tasks faster than before.	Yes	≤ 1.96
My vehicle was accelerating faster than before.	Yes	≤ 2.26
My vehicle/equipment smelled better than before.	Yes	≤ 2.25

From Table D.4, it is evident that the respondents disagreed about increases in performance and ability to do their tasks faster than before. The respondents somewhat disagreed with the statements implying faster acceleration and that the vehicles/equipment smelled better.

Concluding Remarks

It can be concluded from the statistical analysis of the survey data that the drivers/operators were concerned about a loss of power, starting the vehicles/equipment in the morning, and more smoke (at a 99% confidence level). Specific concerns in the comment section of the questionnaire about using PuriNOx included: poor acceleration, loss of power, the inability to reach highway speeds and poor idling performance. There was no statistical evidence to suggest perceived health effects associated with the use of PuriNOx.

D.1.B. Houston Driver Surveys: November - In late November a total of 55 drivers/operators were surveyed in West Harris, North Harris, Montgomery, and Fort Bend (see Table D.5). Two of the driver/operator questionnaires had to be excluded from the statistical analyses, because of invalid responses. The overall response from the second round of surveys was - as in the first round - uniformly negative. In addition, many more drivers/operators used the opportunity to raise their concerns about using PuriNOx in the space provided for in "any other comments". Some of the comments are included in the Text Box below.

Table D.5 Number of Survey Responses (November)

	Total Responses	**Valid Driver/Operator Responses**	**Mechanic Responses**
Fort Bend	14	14	0
Conroe	18	18	0
West Harris	8	8	0
Humble	16	13	1
Total	**56**	**53**	**1**

"Any Other Comments"

"To put it into perspective, this stuff is a bunch of bull crap that is going to get somebody killed because there is no power to the engine for take off when needed on very busy highways…"

"Sign truck does not have enough power to pull itself out of a ditch and back onto hard surface. Have to call for a truck to pull … back onto the road when I have to get off hard surface to do sign work …"

"The change of fuel has done nothing but make daily operations more dangerous than usual. The motor grader I operate will barely drive 12 mph on the road due to PuriNOx; I've almost had several vehicles rear end me due to being so slow on the road. It also takes several passes to move the same amount of material now that one could do without PuriNOx earlier. Engines have no power. Smoke excessively, runs rough, stalls and takes an act of God to start."

"The fuel is a waste of time and money for everybody in Texas."

"A very expensive screw up."

"This fuel is dangerous to use. Our machine will not run with enough power to get into flowing traffic at their rate of speed. All equipment has at least 30% less power than before."

"Truck often dies when the engine is idling and often is hard to start. Severe problems starting equipment even on a warm day till you run down the battery. Leaves bad taste in your mouth when you stand in smoke for a while. Notice constant runny nose and trouble with sinuses and headaches and backaches. Severe loss of power with equipment and a lot harder to get it started. Uses more fuel and smokes a lot more."

"Being around the fumes my eyes water a lot. Had more headaches. Taste in mouth that won't go away. Less power than before. Takes longer to do my work. Uses more fuel than before. Smokes more than before. Takes longer to warm up. I think we need to go back to the old fuel before someone gets sick bad or get hurt from the lack of power."

"In my opinion, these vehicles are hazardous for the flow of traffic, especially on highways and expressways. The exhaust looks like it causes more pollution and would expect more complaints."

"Vehicle idle is lower than normal. Engine vibrating more at idle. Engine smokes more. Engine power is weaker. Truck is about 10 mph slower. Slower take off."

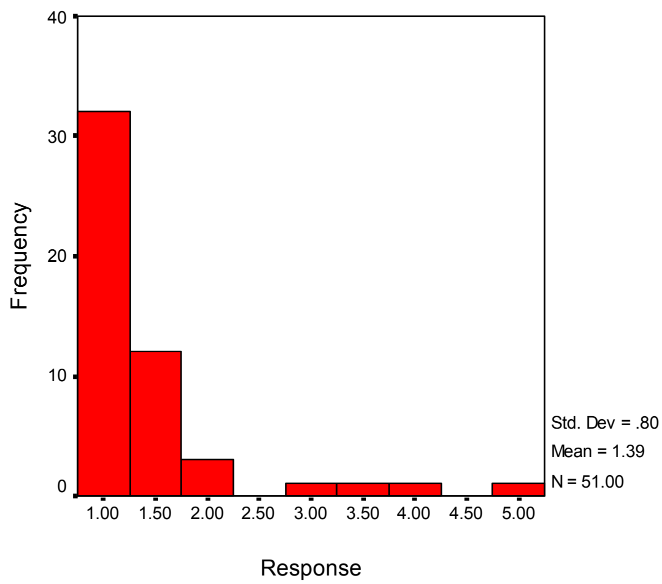
"My truck did not respond with even enough power to perform simple tasks when using PuriNOx fuel."

"When driving the badget down the highway, it does not have no pickup power. It has less lifting power."

Frequency Distribution of Houston Responses: November

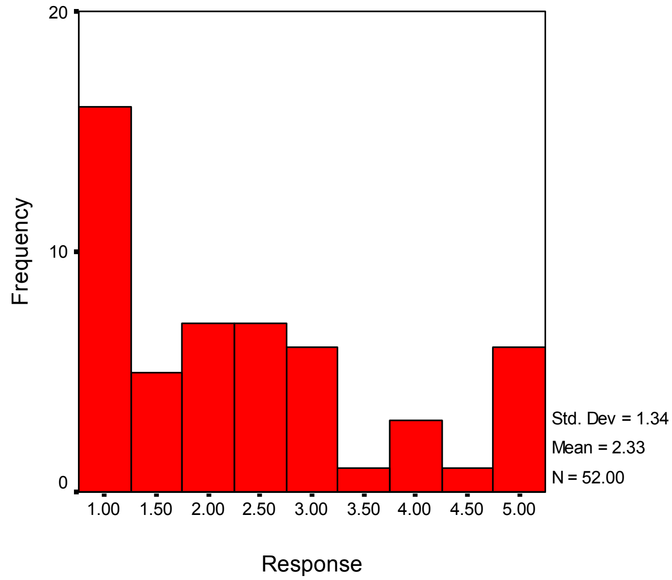
This section graphs the frequency distribution of the November responses to each question and lists the mean response and the standard deviation. As was the case during the first round of surveys in August/September, some of the questions resulted in stronger and more uniform responses than others. These cases are highlighted.

I noticed a substantial improvement in the performance of my vehicle/equipment.



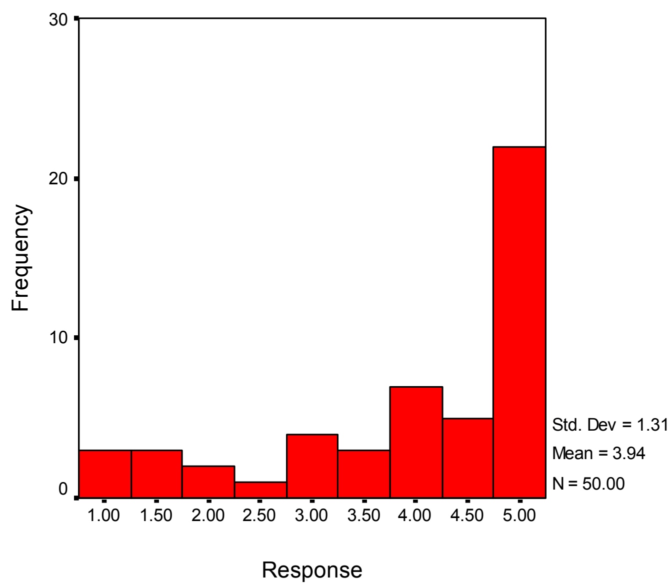
As opposed to the 84.1 % of the operators during the first round, 92.2 % circled/checked a number less than or equal to 2 during the second round. This indicates that the drivers/operators did not perceive any improvement in the performance of the vehicles/equipment.

I had more tasks in the past few months than on average.



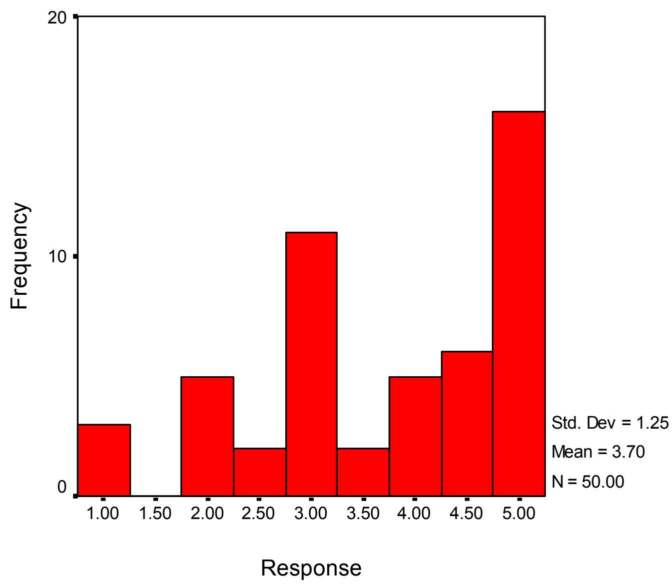
Most of the responses circled/checked seem to indicate that the perceptions of the drivers/operators regarding PuriNOx were not influenced by a higher than average task load.

Even at full throttle, it took me longer than normal to perform the same task when using the hydraulics



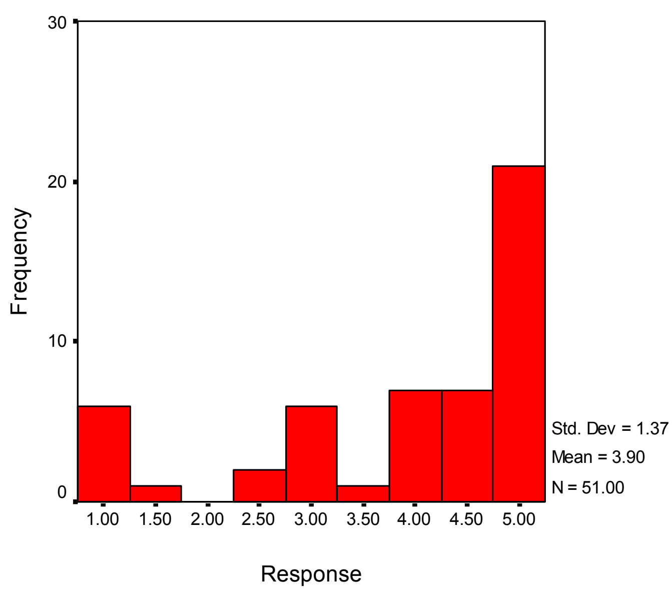
Similar to the August/September respondents, most of the November respondents who used hydraulics felt that it took them longer to perform the same task using PuriNox compared to conventional diesel.

My vehicle/equipment used more fuel than before.



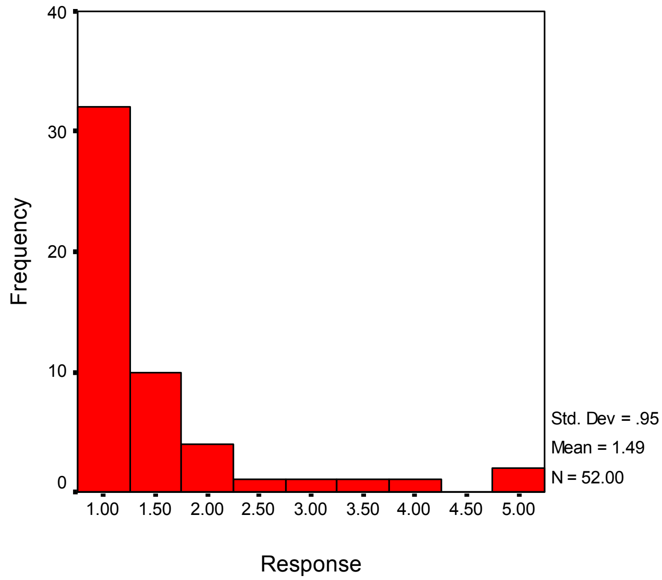
Most of the responses ranged from "neutral" to "agree" for this statement, but the calculated mean suggests that the overall response is neutral to somewhat agree.

I asked a mechanic to check my vehicle/equipment during the past few months



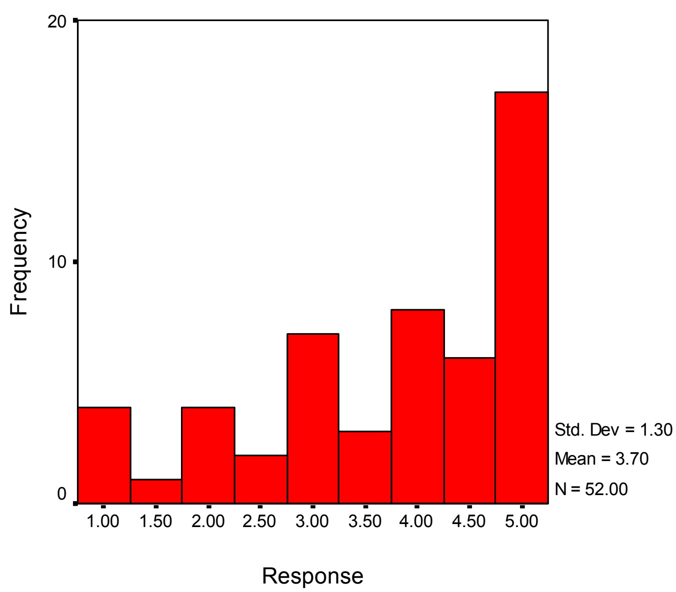
The respondents again indicated a noticeable change in the performance of their vehicles/equipment to the extent that a significant number asked a mechanic to look at their vehicles/equipment after switching to PuriNOx.

I was able to do all my usual tasks faster than before.



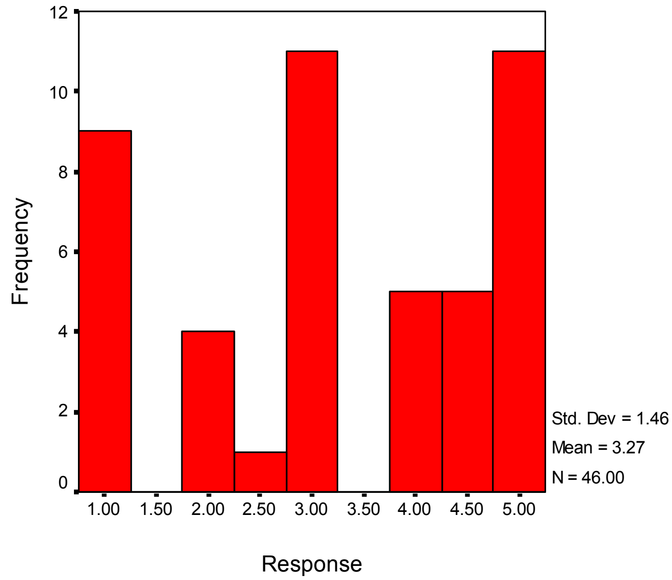
45 out of the 52 operators responded negatively to this statement, clearly showing that the operators did not perceive an increase in the performance of their vehicles/equipment that allowed them to do their tasks faster than before.

The engine of the vehicle/equipment was noticeably noisier than before.



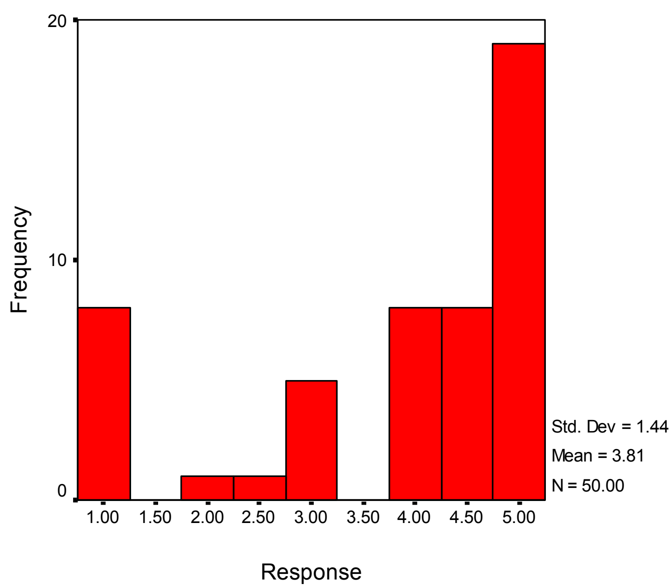
A larger number of respondents indicated during this survey that their vehicles were noisier compared to operating with conventional diesel. The mean response to this question accordingly changed from 3.22 in the first round of surveys to 3.7 in the second round of surveys.

I suffered from more backaches, sore muscles, and headaches than usual.



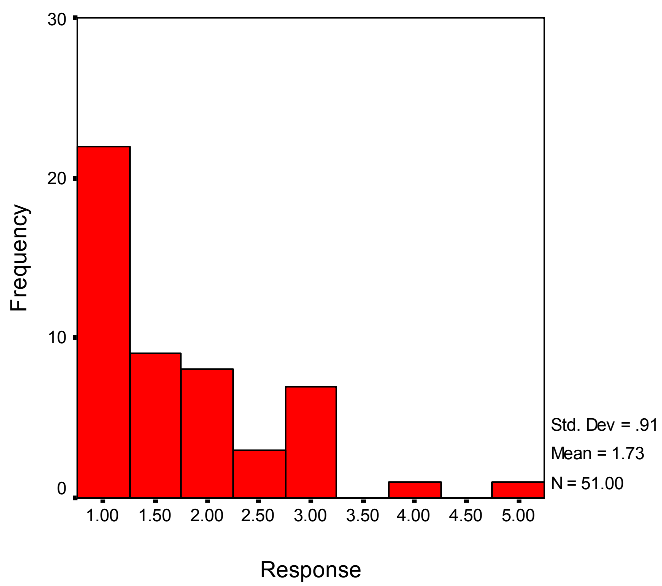
A larger percentage of the respondents agreed with this statement compared to the first round of surveys – 45.7% compared to 30%. The calculated mean, however, indicates that the overall response is "neutral" to "somewhat agree". This is contrary to the first round results where the mean was 2.8. This suggests that more respondents perceived an association between an increase in adverse health effects (i.e. backaches, sore muscles and headaches) and using PuriNOx.

I changed my driving/operating behavior over the past months.



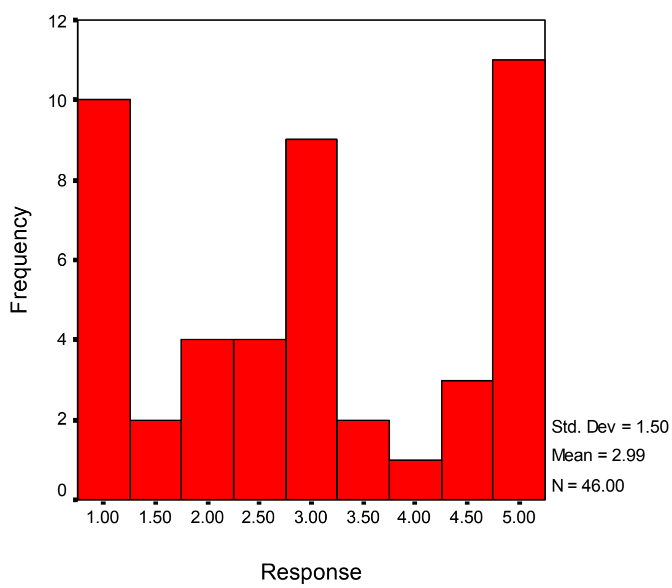
Most of the respondents indicated that they changed their driving/operating behavior since switching to PuriNOx. The average response to this question was thus similar for both survey rounds – 3.79 compared to 3.81.

I moved heavier loads over the past few months than normally.



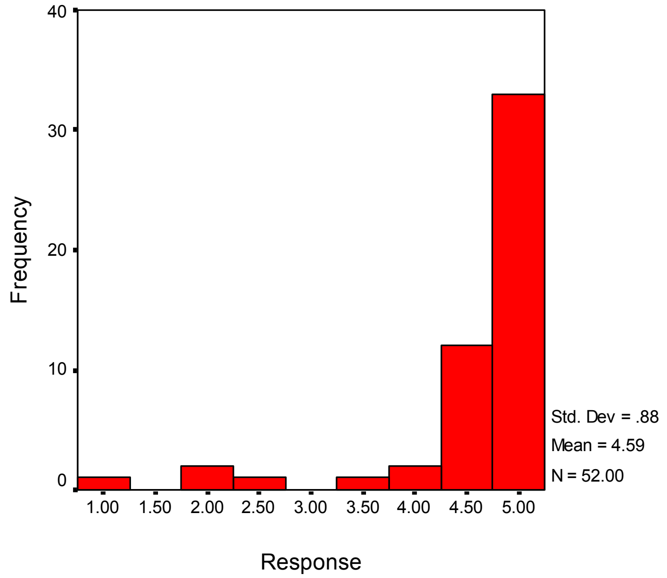
The responses to this statement indicated that the drivers/operators did not have to move heavier loads than normal since switching to PuriNOx.

I experienced some of the following symptoms over the past months: runny nose, nausea, hair loss, and skin rash.



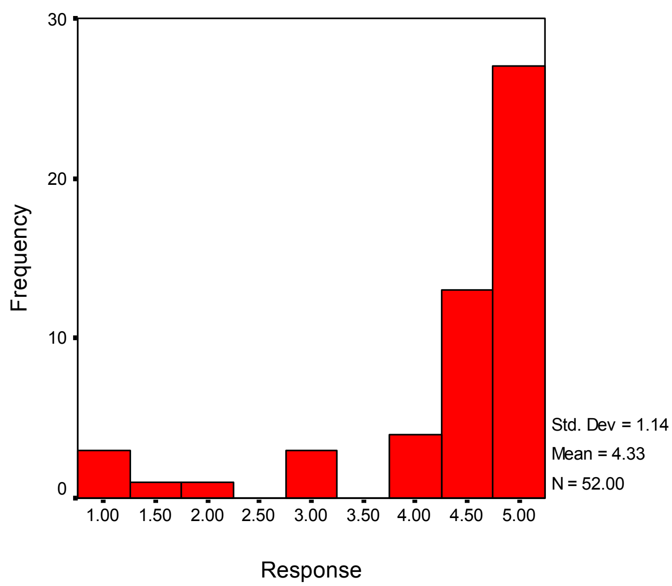
The mean response was slightly lower for this question compared to statement 8 (I suffered from more backaches, sore muscles, and headaches than usual). However, as was the case for statement 8, a higher percentage of the respondents (23.9%) had checked "agree" compared to the first round (11.1%).

I noticed that my vehicle had less power than before.



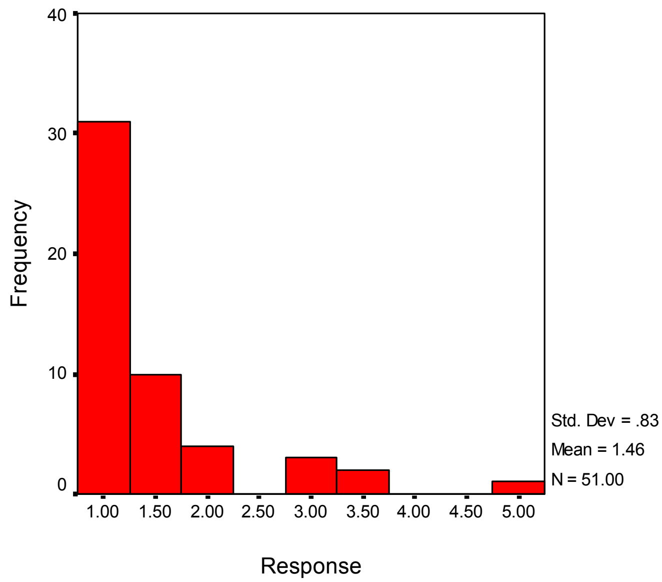
90.4% of the respondents stated a reduction in the power of their vehicles/equipment, compared to 93% during the first round of surveys. This strong uniform response indicates that loss of power was again a noticeable concern for most of the drivers/operators.

I had a problem starting my vehicle/equipment early in the morning.



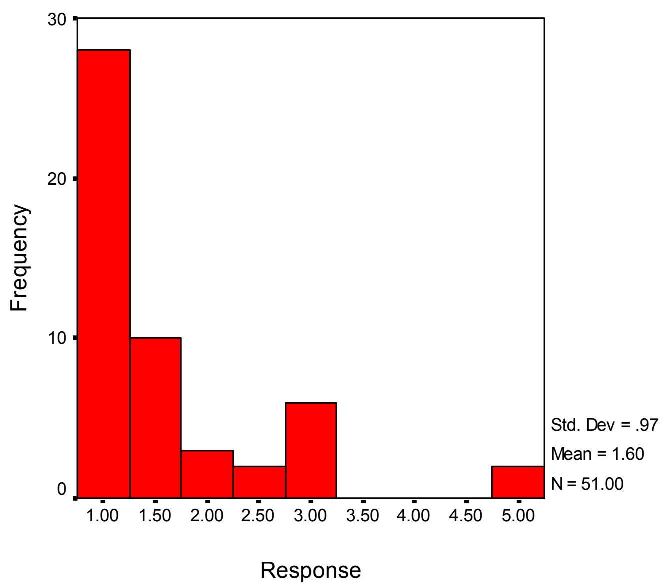
Given the number of respondents (84.62%) who agreed with this statement and the calculated mean, the starting of vehicles/equipment early in the morning remains a concern for the Houston PuriNOx users.

My vehicle was accelerating faster than before.



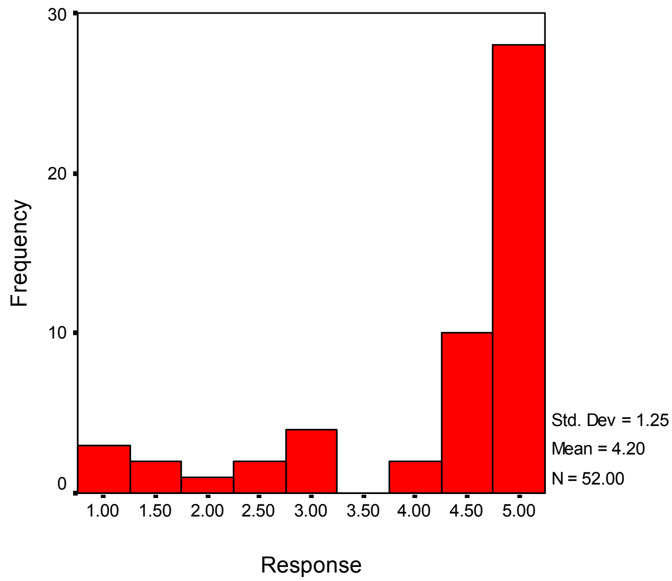
88.2% of the respondents, compared to the first round of surveys (81.4%), disagreed with the statement that the vehicles/equipment were accelerating faster than before.

My vehicle/equipment smelled better than before.



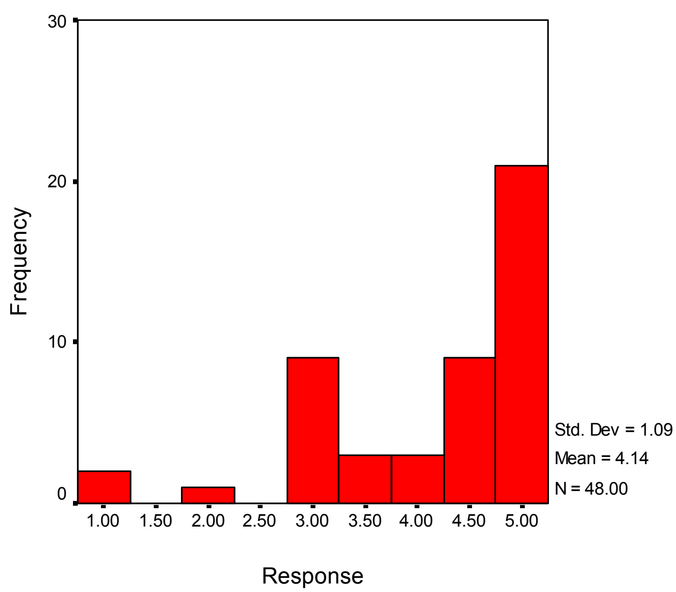
Again, most of the respondents disagreed with the statement that their vehicles/equipment smelled better than before.

I noticed more smoke coming from my vehicle/equipment.



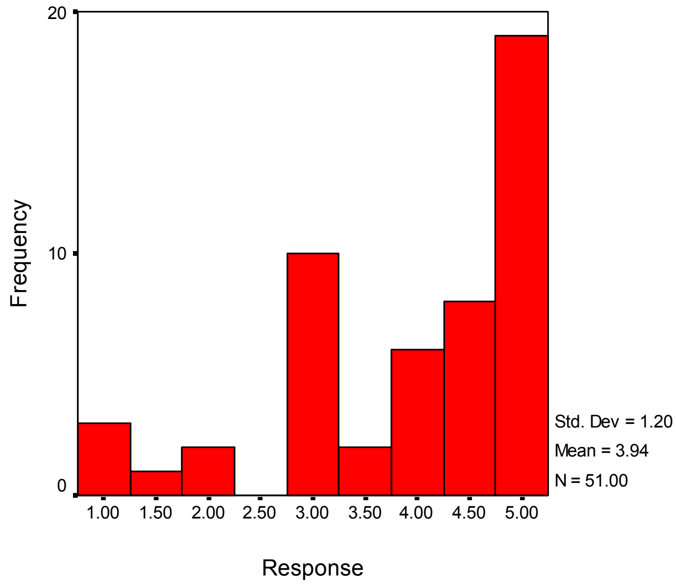
Given the number of respondents who agreed with this statement and the calculated mean, Houston PuriNOx users continue to perceive a noticeable increase in the smoke coming from their vehicles/equipment.

I had to shift gears more often when doing my work.



More than half of the respondents indicated that they had to shift gears more often when doing their work.

My vehicle/equipment was vibrating more than before.



Most of the November responses are between "neutral" and "agree" resulting in mean response of 3.94 compared to 3.58 during the first round of surveys.

Statistical Analyses

The same statistical tests were performed for the November survey data as for the August/September data: first a two-sided test was performed to test the null hypothesis that the "true" mean of the responses was 3, and secondly if the two-sided test revealed that the null hypothesis had to be rejected for any statement, a one-sided test was performed to determine if the operators agreed or disagreed with that statement. These tests allowed for the calculation of a confidence interval for the population mean for each of the statements (attributes). All the tests were again performed at 1% significance level.

Two-Sided Test Results

First the two-sided tests were thus performed to test:

Null Hypothesis: $\mu = 3$
Alternative Hypothesis: $\mu \neq 3$

The results of the two-sided tests are summarized in Table D.6.

Table D.6 Two-Sided Test Results: November

Statement	Reject Null?	Confidence Interval	
		lower limit	upper limit
I noticed a substantial improvement in the performance of my vehicle/equipment.	Yes	1.10	1.68
I had more tasks in the past few weeks than on average*	Yes	1.86	2.81
Even at full throttle, it took me longer than normal to perform the same task when using hydraulics.	Yes	3.46	4.42
My vehicle/equipment used more fuel than before.	Yes	3.25	4.16
I asked a mechanic to check my vehicle/equipment during the past five months	Yes	3.41	4.39
I was able to do all my usual tasks faster than before.	Yes	1.15	1.83
The engine of the vehicle/equipment was noticeably noisier than before.	Yes	3.24	4.17
I suffered from more backaches, sore muscles, and headaches than usual.	No	2.72	3.83
I changed my driving/operating behavior over the past five months.	Yes	3.28	4.33
I moved heavier loads over the past five months than normally*.	Yes	1.40	2.05
I experienced some of these symptoms: runny nose, nausea, hair loss, skin rash.	No	2.42	3.56
I noticed that my vehicle had less power than before.	Yes	4.28	4.90
I had a problem starting my vehicle/equipment early in the morning.	Yes	3.93	4.74
My vehicle was accelerating faster than before.	Yes	1.16	1.76
My vehicle/equipment smelled better than before.	Yes	1.25	1.95
I noticed more smoke coming from my vehicle/equipment.	Yes	3.75	4.64
I had to shift gears more often when doing my work.	Yes	3.74	4.54
My vehicle/equipment was vibrating more than before.	Yes	3.51	4.37

* These two questions were included to determine if the respondents' working conditions were perceived different since switching to PuriNOx. No additional statistical analysis was performed for these questions.

As can be seen from Table D.6, the null hypothesis was not rejected for only two of the statements (attributes): (1) I suffered from more backaches, sore muscles, and headaches than usual, and (2) I experienced some of these symptoms: runny nose, nausea, hair loss, skin rash. This means that even after five months the respondents did not perceive any statistically significant change in health effects associated with the use of PuriNOx. Furthermore, it can be concluded at a 99 % confidence level that the population mean response of PuriNOx users to the "occurrence of backaches, sore muscles and headaches" lies between 2.72 and 3.83, and for "occurrence of runny nose, nausea, hair loss, skin rash, etc' between 2.42 and 3.56. A number of the respondents, however, reported health effects in the open-ended section of the questionnaire, indicating that some respondents might be more sensitive to PuriNOx than others.

As indicated before, analysis of the first round of survey data revealed that the respondents were neutral – thus they neither agreed nor disagreed – with the statement that "the engine of the vehicle/equipment was noticeably noisier than before. Analysis of the November survey data, however, resulted in the rejection of the null hypothesis for this attribute, indicating that the operators were not neutral. A one-sided test was thus performed to determine whether the operators agreed or disagreed with the statement.

The fact that the null hypothesis was rejected for all the remaining statements indicates that the Houston PuriNOx users continue to perceive a difference in the performance of their vehicles/equipment when using PuriNOx. A one-sided test was performed on each statement to determine whether the perceived impact was positive or negative.

One-Sided Test Results

The remaining statements were divided into two groups: "negative statements" and "positive statements". The null and the alternative hypotheses for the first group of questions were:

Null Hypothesis: $\mu = 3$
Alternative Hypothesis: $\mu > 3$

If the null hypothesis is rejected, then the mean response is greater than 3, meaning that the respondents agreed with the statement. Table D.7 summarizes the attributes tested, whether the null hypothesis was rejected, and the confidence intervals for the mean responses of the population of PuriNOx users.

Table D.7 Negative PuriNOx Statements

Statement	**Reject Null?**	Confidence Interval
Even at full throttle, it took me longer than normal to perform the same task when using hydraulics.	Yes	**≥ 3.51**
My vehicle/equipment used more fuel than before.	Yes	**≥ 3.29**
I asked a mechanic to check my vehicle/equipment during the past five months.	Yes	**≥ 3.45**
The engine of the vehicle/equipment was noticeably noisier than before.	Yes	**≥ 3.28**
I noticed that my vehicle had less power than before.	Yes	**≥ 4.31**
I had a problem starting my vehicle/equipment early in the morning.	Yes	**≥ 3.97**
I noticed more smoke coming from my vehicle/equipment.	Yes	**≥ 3.79**
I had to shift gears more often when doing my work.	Yes	**≥ 3.77**
My vehicle/equipment was vibrating more than before.	Yes	**≥ 3.55**

Comparing the confidence intervals calculated for each of these attributes for the August/September data (Table D.3) with the confidence intervals for the November data (Table D.7), it is evident that the interval bands are narrower overall. This indicates a more negative response than during the first round of surveys.

Loss of power remains the most pressing concern, but starting the vehicles/equipment early in the morning, the need to shift gears more often and vibration were more of a concern during the second round of surveys compared to the first. Smoke from the vehicles/equipment and the hydraulic performance were again somewhat of a concern. Fuel usage and engine noise was of lesser concern.

The null and the alternative hypotheses for the second group of questions were:

Null Hypothesis: $\mu = 3$
Alternative Hypothesis: $\mu < 3$

If the null hypothesis is rejected, then the mean response is less than 3, meaning that the respondents disagreed with the statement. Similar to the first group, the statements, whether the null hypothesis was rejected and the confidence intervals have been presented in Table D.8.

Table D.8 Positive PuriNOx Statements

Statement	**Reject Null?**	**Confidence Interval**
I noticed a substantial improvement in the performance of my vehicle/equipment.	Yes	≤ 1.65
I was able to do all my usual tasks faster than before.	Yes	≤ 1.80
My vehicle was accelerating faster than before.	Yes	≤ 1.73
My vehicle/equipment smelled better than before.	Yes	≤ 1.92

As is the case with the Negative PuriNOx statements, a comparison between Table D.4 and Table D.8 reveals that the confidence interval bands are narrower for the

November survey data than for the August/September survey data – indicating a more negative perception about the performance of PuriNOx. From Table D.8, it is evident that operators disagree with the statements about increases in performance and faster acceleration. The operators disagree somewhat less with the statements that they could do all their usual tasks faster than before and that the vehicles/equipment smelled better.

Concluding Remarks

It can be concluded from the statistical analysis of the survey data that the drivers/operators remained concerned about loss of power, starting the vehicles/equipment in the morning, and more smoke (at a 1% significance level). Engine noise, the need to shift gears more often and vibration were more of a concern during the second round of surveys compared to the first. Despite numerous comments in the open-ended section of the questionnaire noting health effects, there was no statistical evidence for the perceived health effects associated with the use of PuriNOx.

Analysis of Variance (ANOVA)

From the statistical analyses of the surveys from August/September and from November, it was evident that the driver/operator perceptions were more negative about the performance impacts of using PuriNOx when surveyed in November. The objective of the Analysis of Variance (ANOVA) was to determine whether the changed perceptions were statistically significant. ANOVA was performed to test the hypothesis that the means of the two samples were the same. The ANOVA results are summarized in Table D.9.

Table D.9 ANOVA Results

Statement	F-value	P-value	Significance
I noticed a substantial improvement in the performance of my vehicle/equipment.	1.1440	0.2876	No
I had more tasks in the past few weeks than on average.	0.0090	0.9245	No
Even at full throttle, it took me longer than normal to perform the same task when using the hydraulics.	0.0000	0.9991	No
My vehicle/equipment used more fuel than before.	0.2745	0.6016	No
I asked a mechanic to check my vehicle/equipment during the past five months	0.0169	0.8970	No
I was able to do all my usual tasks faster than before.	0.5877	0.4452	No
The engine of the vehicle/equipment was noticeably noisier than before.	3.5573	0.0624	No
I suffered from more backaches, sore muscles, and headaches than usual.	2.3361	0.1302	No
I changed my driving/operating behavior.	0.0043	0.9477	No
I moved heavier loads over the past five months than normally.	0.3075	0.5807	No
I experienced some of the following symptoms over the past weeks: runny nose, nausea, hair loss, skin rash.	1.4605	0.2304	No
I noticed that my vehicle had less power than before.	0.0132	0.9088	No
I had a problem starting my vehicle/equipment early in the morning.	1.2479	0.2668	No
My vehicle was accelerating faster than before.	2.8728	0.0935	No
My vehicle/equipment smelled better than before.	1.5220	0.2205	No
I noticed more smoke coming from my vehicle/equipment.	0.1057	0.7459	No
I had to shift gears more often when doing my work.	3.3486	0.0707	No
My vehicle/equipment was vibrating more than before.	2.0739	0.1533	No

As can be seen from Table D.9, there is no statistically significant difference (at 5% significance level), between the means of the two samples with respect to each of the attributes tested. It can thus be concluded that there was no statistically significant change in the perceptions of the Houston PuriNOx users after a period of approximately five months during which it was assumed that the drivers/operators would become more familiar with the PuriNox-fueled equipment/vehicles.

Conclusions

The statistical analysis (at 1% significance level) revealed that the drivers/operators perceived performance impacts associated with the use of PuriNOx relating to a loss of power, starting problems, and more smoke. Engine noise, vibration and the need to shift gears more often were more of a concern during the second round of surveys compared to the first. In addition, there was no evidence from the first round of surveys to suggest a perceived performance impact with respect to engine noise, but during the second round of surveys the statistical evidence suggested that the respondents agreed that the engine was noisier fueling with PuriNOx as compared to conventional diesel.

Specific concerns in the comment section of the questionnaire about using PuriNOx included: loss of power, the inability to reach and maintain highway speeds, poor idling performance, and engine smoke. Despite numerous comments in the open-ended section of the questionnaire noting health effects, there was no statistical evidence for the perceived health effects associated with the use of PuriNOx.

Although there was some evidence to suggest that the driver/operator perceptions was more negative about the performance impacts of using PuriNOx when surveyed in November compared to August/September, the statistical analysis (ANOVA) revealed no statistically significant change in the perceptions of the Houston PuriNOx users (at 5% significance level).

D.2. Double-Blind Testing

A double-blind assessment of the use of PuriNOx relative to conventional diesel fuel was accomplished via an "Alternative Fuels Roadeo". Details about the Roadeo are provided in Subsection D.2.A. The Roadeo exercises were evaluated in two ways. First, the perceptions of the test vehicle drivers were determined through the use of surveys immediately after the drivers drove the test vehicles. The detailed results of the surveys are discussed Subsection D.2.B. Second, each of the test vehicles was equipped with a datalogger to determine the details of the operation of each test vehicle while the drivers were operating them. Details from the quantitative analyses of the data from the dataloggers is discussed in Subsection D.2.C.

D.2.A. Roadeo Details - The Roadeo was conducted November 13–14 at two Houston sites: Hempstead and La Marque. The Hempstead site was chosen to control for the impacts of traffic congestion that could bias the time to complete particular "Roadeo" events since Hempstead is situated in an area that does not experience severe traffic congestion. The La Marque site was chosen because it had a large stockpile necessary to test the performance of the loaders. – more specifically the size of the stockpile allowed for three loaders to be tested at the same time.

Roadeo Equipment

To account for both fuel performance and vehicle performance differences, three pieces of each equipment type (identical in terms of model, year, engine size, etc.) were needed. The researchers analyzed TxDOT's equipment database and identified the various types of equipment that met this criterion. Once identified, the researchers consulted the Houston District to confirm the final selection and ensure that the chosen equipment types were representative of TxDOT's fleet and included equipment types that seemed to be negatively affected according to the Houston PuriNOx users. Table D.10 describes the equipment that was tested in the Roadeo:

Table D.10 Roadeo Equipment Description

	Vehicle Type																	
	Telescoping Cranes			**Telescoping Boom Excavators**			**Single-Axle Dump Trucks**			**Tandem-Axle Dump Trucks**			**Forklifts**			**Loaders**		
Roadeo ID	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B***	**C***	**A**	**B**	**C**	**A**	**B**	**C**
TxDOT ID Number	12-6210-G	12-6211-G	12-6212-G	11-9828-G	20-9826-G	N/A - Rented	12-5218-G	12-5219-G	12-5221-G	12-4456-G	12-4457-G	12-4521-G	12-6414-A	12-6417-A	12-6418-A	12-6702-A	12-6703-A	12-6704-A
VIN	2FZAAKBV42AJ86318	2FZAAKBV72AJ86314	2FZAAKBV92AJ86315				1GDM7H1C1XJ509518	1GDM7H1C8XJ517244	1GDM7H1CXXJ517343	1HTGGATRXWH557960	1HTGGATR4WH557971	1HTGGATR2WH557970						
Vehicle Serial Number				*0313329*	*0313319*	*0314301*							9PG00545	9PG00546	9PG00439			
Vehicle Model Year	2002			2002			1999			1998			1993			1995		
Vehicle Mfr / Make	Freightliner Sterling			Gradall			GMC			International			Caterpillar			Fiat - Hitachi		
Vehicle Model	Acterra			XL3100			C7500			2574 6X4			V50E, Type D			FR90		
Vehicle Weight													9555 lbs.			10,000 kg		
Engine Manufacturer	Cummins			Cummins			Caterpillar			Caterpillar			Caterpillar			Fiat-Allis		
Engine Model/Series	ISB225			ISB190			3126 B			C10			XD3P			8045T		
Engine Cylinders	6			6			6			5			4			4		
Engine Displacement	5.9 L			5.9 L			7.2 L			10.3 L								
Engine Aspiration	Single Turbo			Single Turbo			Single Turbo			Single Turbo						Single Turbo		

* Initial designation. See text in Section D.2.C for changes that occurred in the middle of Roadeo testing.

To ensure a complete double-blind test in which neither the operators nor the UT researchers knew which fuel was being used in which vehicle/equipment, TxDOT employees from the Houston District (which did not otherwise take part in the Roadeo) fueled the vehicles/equipment in advance.

Each vehicle of a specific type was marked with the letters A, B or C to facilitate the evaluation. The researchers only received information on which vehicles were fueled with PuriNOx after the Roadeo. Table D.11 summarizes the fuel used in each vehicle/equipment.

Table D.11 "Roadeo" Fueled Vehicles/Equipment

Vehicle/Equipment Type	Fuel Used
Telescoping cranes/bucket trucks	
A	PuriNOx
B	#2 Diesel
C	#2 Diesel
Telescoping boom excavators	
A	PuriNOx
B	#2 Diesel
C	#2 Diesel
Single-axle dump trucks	
A	PuriNOx
B	#2 Diesel
C	PuriNOx
Tandem-axle dump trucks	
A	#2 Diesel
B	PuriNOx
C	PuriNOx
Forklifts	
A	PuriNOx
B	#2 Diesel
C	PuriNOx
Loaders	
A	PuriNOx
B	PuriNOx
C	#2 Diesel

“Roadeo” Events

The research team, together with the Houston District, designed a series of Roadeo events, which aimed to assess the concerns raised by the Houston PuriNOx users. Figures D.2.1 to D.2.4 summarize the routes and activities for the telescoping boom excavators, the telescoping cranes, single-axle, and tandem-axle dump trucks respectively.

The single-axle dump trucks used the route shown in Figure D.2.1. The route is 18.5 miles long. Single-axle dump trucks traveled the route in a counter-clockwise direction. The trucks exited the TxDOT Hempstead facility and turned right. At 0.5 miles, the route turned left onto Business Route 290 going east. At 9.0 miles, the route turned left onto FM 362 going north. At 9.8 miles, the route turned left onto Highway 290 going west. At 17.3 miles, the route turned left onto FM 1488 going south. The route ended at 18.5 miles by returning to the TxDOT facility. The tandem-axle dump trucks followed the same route except, as is shown in Figure D.2.2, they drove the route in the clockwise direction.

The telescoping cranes and telescoping boom excavators used a different, but common, route which is shown in Figures D.2.3 and D.2.4. These vehicles turned right as they exited the TxDOT Hempstead facility. At 1.0 mile, the route turned right onto Business Route 290 going north and continued straight onto Highway 6 going north. At 10.4 miles, the route turned around to head south on Highway 6. At 18.3 miles, the route turned right onto Highway 290 going west. At 25.3 miles, the route exited into the crossover where the vehicle stopped and performed its work activity. After the work activity was completed, the route turned back east onto Highway 290. At 32.0 miles, the route exited Highway 290 at Exit 6. At 33.2 miles, the route turned left onto State Highway 159 going east. At 33.7 miles, the route turned left onto FM1488 and at 34.3 miles, the route ended after returning to the TxDOT facility.

The loader operators were required to fill as many dump trucks as possible in 30 minutes with material that needed to be loosened from a densely packed stockpile. The forklift operators were required to move a pallet of cement between two lines, approximately 50 yards apart. The number of completed trips conducted in 20 minutes was recorded for each forklift.

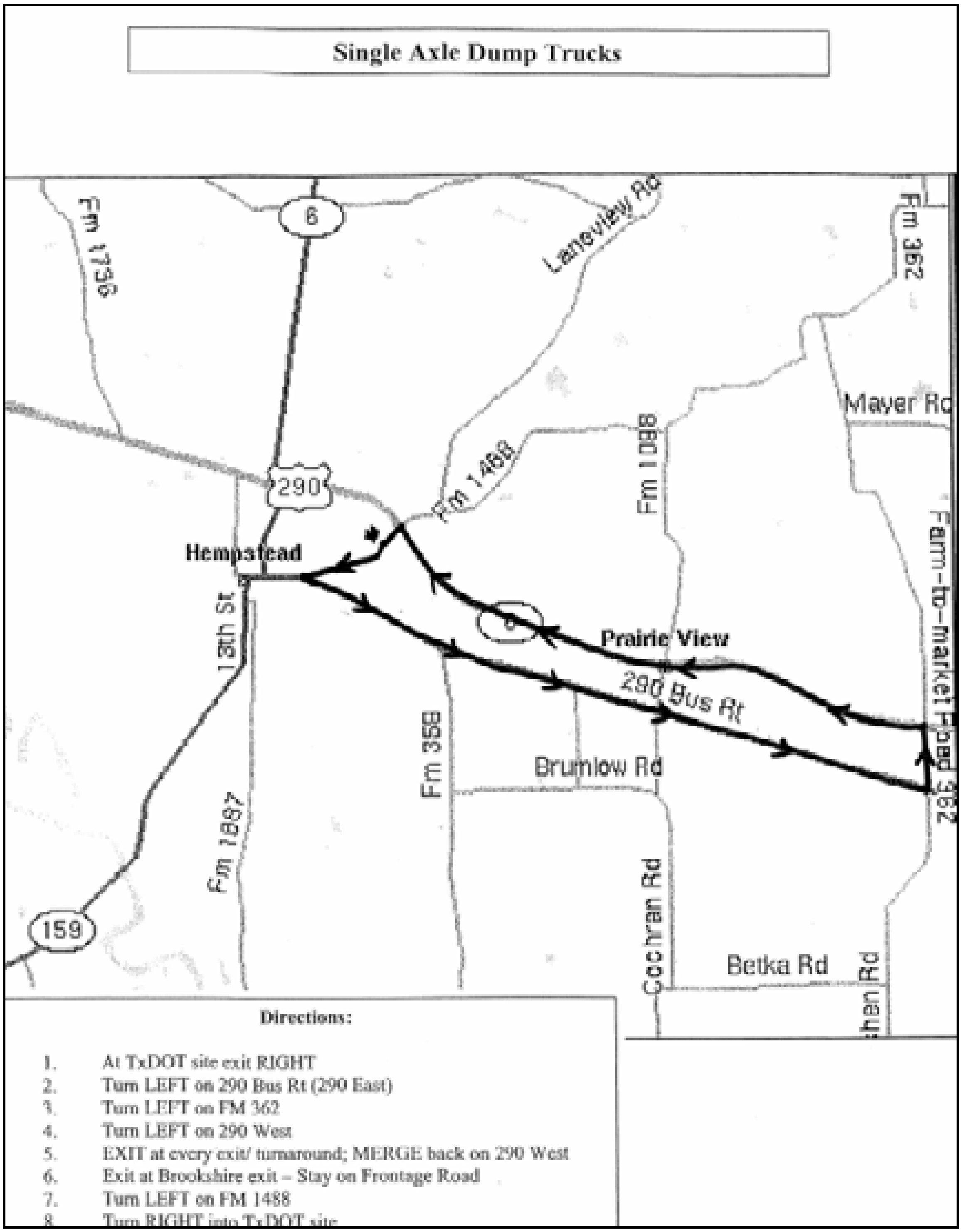


Figure D.2.1 Single-axle dump truck activity

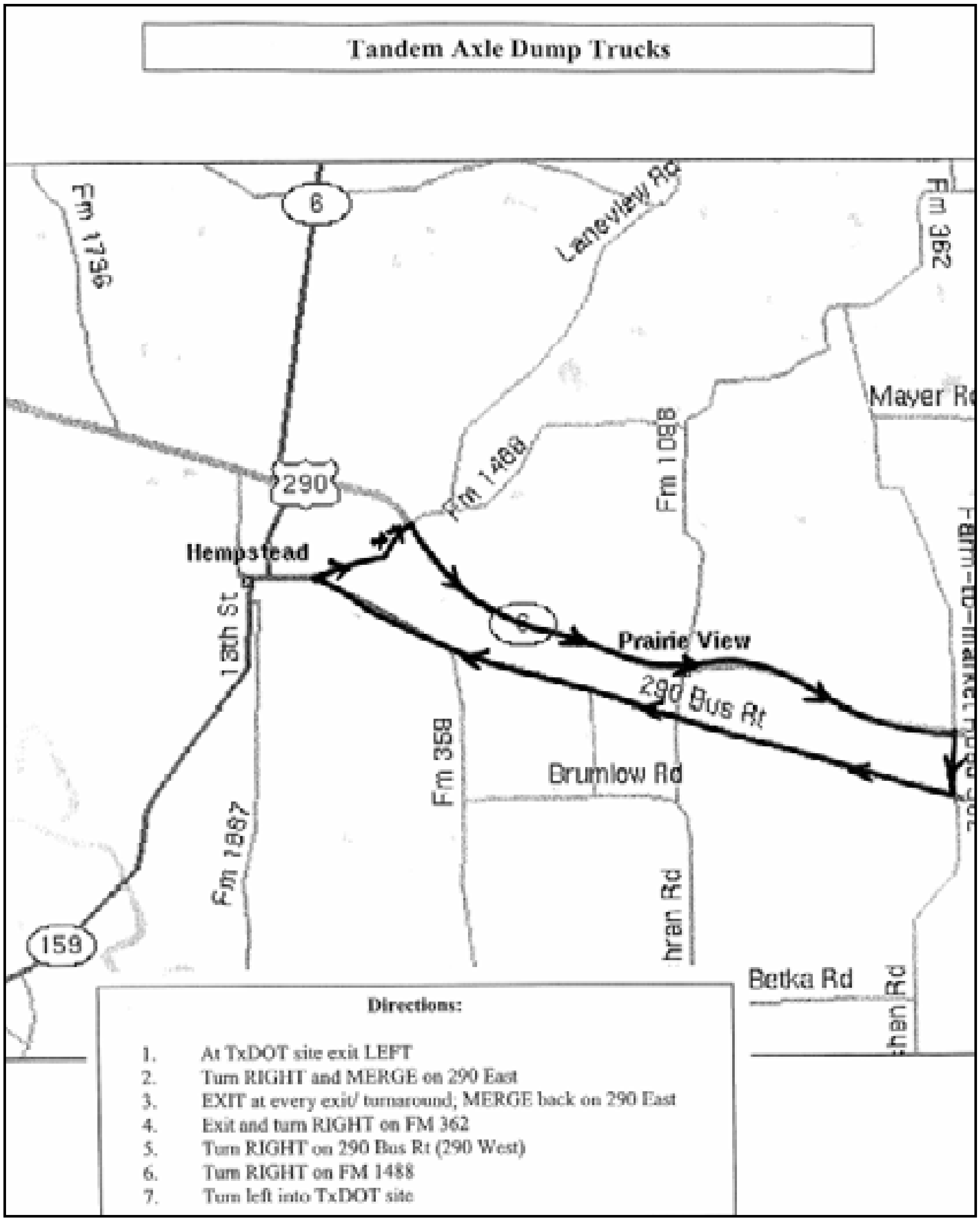


Figure D.2.2 Tandem-axle dump truck activity

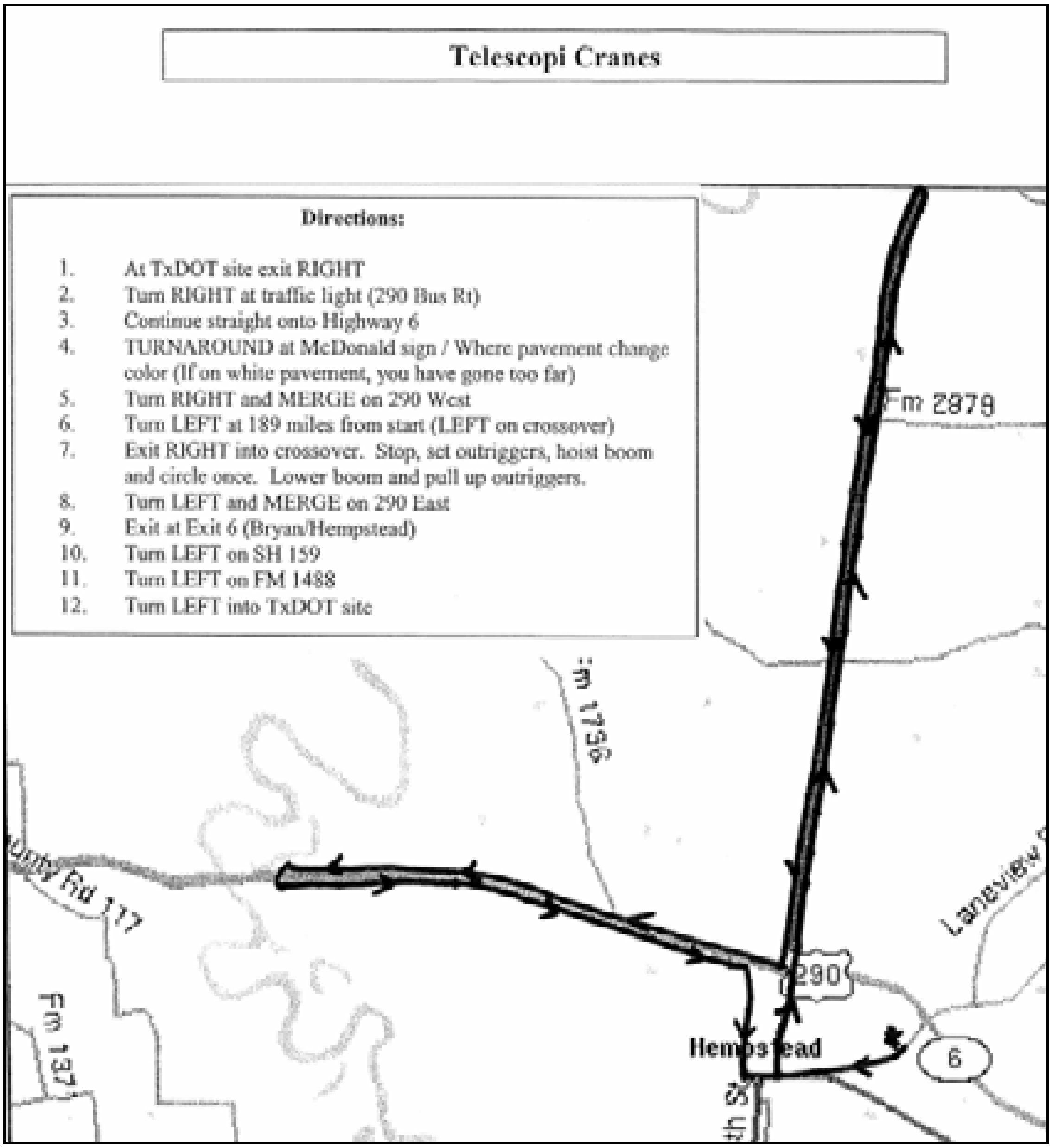


Figure D.2.3 Telescoping crane activity

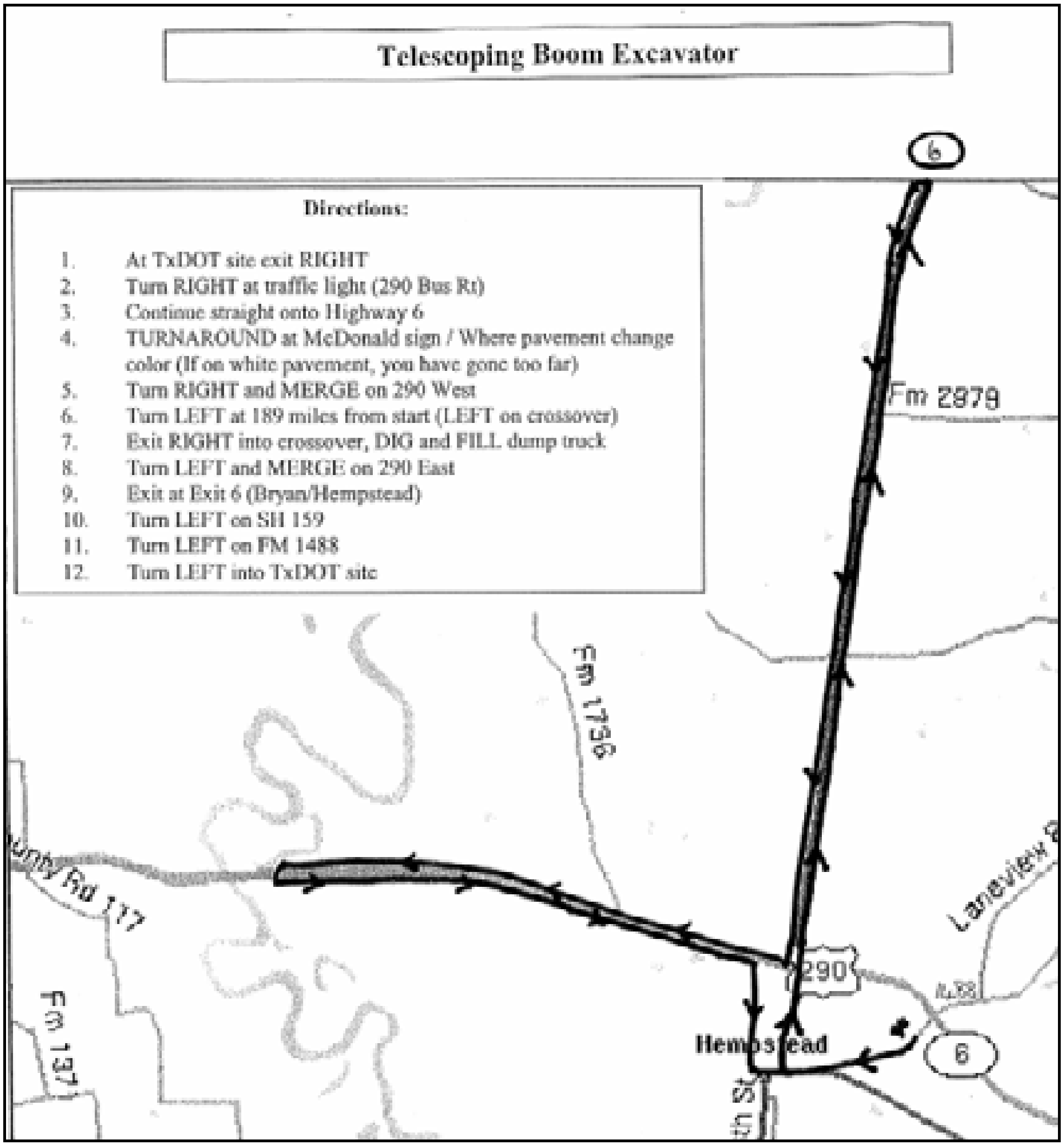


Figure D.2.4 Telescoping boom excavator activity

Roadeo Participants

Volunteer TxDOT drivers/operators from outside the Houston District in which PuriNOx is used, were asked to participate in the Roadeo. Participating districts included: GSD fleet, Bryan, Lufkin, Fort Worth, Pharr, Dallas, Waco, Tyler, Yoakum and Corpus Christi.

One week before the Roadeo, a memo was sent to each participating district to confirm the district's participation in terms of the number of volunteers, the equipment/ vehicles they were qualified to operate/drive and to provide information to the participants on when, where and what they could expect on the day of the Roadeo (see Text Box for an example of the memo).

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To: TxDOT Supervisor: Bryan

From: Jolanda Prozzi
Randy Machemehl

Date: 12/9/02

Subject: ROADEO Participation on November 13, 2002

Thank you for your support and willingness to participate in TxDOT's Alternative Fuels ROADEO on November 13, 2002 at Hempstead. The objective of the ROADEO is to test and determine the effects on vehicle/equipment performance when fueled with an alternative fuel.

The participants from Bryan are scheduled as follows:

- 5 x 10 yard dump truck drivers/operators
- 1 x observer

Although participation is only required on **November 13,** all participants are advised to arrange to stay in a hotel the night before (**November 12**) and **November 13** in the event the schedule runs late. The nearest hotel to the site is Motel 8 located at 51325 Highway 290, Hempstead, Texas 77445 (see attached information on hotel amenities). The participants are encouraged to make reservations as soon as possible.

The ROADEO program is as follows:

07:15 AM All ROADEO participants are requested to arrive at the TxDOT site in Hempstead at **07:15 AM** (see the attached map for location).
Upon arrival, participants are requested to gather in the meeting room and complete a registration form. Participants will then be divided into two groups.

07:20 AM Group 1 will be briefed on the routes and activities.

08:00 AM Participants will be briefed on the purpose of the event and the associated logistics.

08:30 AM The ROADEO is scheduled to start**.** Please note that since the events are staged, some participants will complete the ROADEO earlier than others. Upon completion of the ROADEO activity, a participant will not be able to join his colleagues again in the meeting room. Participants are encouraged to wait for their colleagues at the Mexican restaurant across from the TxDOT site.

The Center for Transportation Research at the University of Texas, Austin looks forward to collaborating with TxDOT in conducting this assessment. Please confirm your participation by e-mailing the names of the drivers/operators, the type of vehicle/equipment they are qualified to drive/operate and a telephone number where they can be contacted to **jpprozzi@mail.utexas.edu.** If you have any questions or concerns, please do not hesitate contacting Ms. Jolanda Prozzi (512) 232 3079 or Dr. Randy Machemehl (512) 232 3100.

Based on the information obtained, a schedule was developed for each type of equipment and operator. On the days of the Roadeo, participants were assigned to two groups: (1) operators/drivers and (2) observers according to the prepared schedule for the equipment/vehicles and the operator/driver qualifications. Each driver/operator was given a specific number at sign in, for example the crane operators were assigned numbers C1 to C5, the single-axle dump trucks were assigned numbers S1 to S5. Both the drivers/operators and the observers were given a questionnaire at sign-in. Tables D.12-D.14 provides a summary of the participating districts, the number of participants, and the equipment operated over the two Roadeo days.

Table D.12 Roadeo Participation at Hempstead
(November 13, 2002)

Participating District	**Number of Participants**
Single-Axle Dump Truck	
Tyler	2
Waco	2
Lufkin	1
Tandem-Axle Dump Truck	
Bryan	3
Dallas	2
Telescoping Boom Excavator	
Fort Worth	2
Dallas	1
Telescoping Cranes	
Tyler	2
Waco	1
Fort Worth	1
Lufkin	1
Observers	
Lufkin	6
Waco	3
Tyler	2
Dallas	2
Fort Worth	3
Bryan	3
Total Participants	**37**

The duration of the telescoping boom excavator activity prevented all the excavators from being evaluated on the same day. Three excavator operators thus participated on Wednesday and two on Thursday at Hempstead. This required participation of four of the Lufkin and two of the GSD fleet representatives on both November 13 and 14 at Hempstead.

Table D.13 Roadeo Participation at Hempstead
(November 14, 2002)

Participating District	**Number of Participants**
Telescoping Boom Excavator	
Lufkin	2
Observers	
Lufkin	2
GSD Fleet	2
Total Participants	**6**

Table D.14 Roadeo Participation at La Marque
(November 14, 2002)

Participating District	**Number of Participants**
Loader	
Pharr	2
Yoakum	2
Corpus Christi	1
Forklift	
Pharr	2
Yoakum	2
Corpus Christi	1
Observers	
Yoakum	2
GSD Fleet	1
University of Texas	2
Eastern Research Group	1
Total Participants	**16**

To ensure that the events were undertaken in a safe manner and in an effort to control the test, observers accompanied the drivers/operators during the activities. The observers were tasked to note any events that might bias or influence the results, for example, slow traffic and any unusual driver behavior, such as frustration (see Text Box for a copy of the observer form). Prior to initiation of testing, the Hempstead observers were driven on the routes/activities they oversaw to ensure that they could give appropriate guidance to the drivers/operators.

All the participants were briefed on the day of the Roadeo by the Research Supervisor and Lenert Kurtz from the Houston District. To circumvent any speculation that the performance of PuriNOx was being tested during the Roadeo, the participants were told that the performance of THREE alternative fuels was being tested.

The performance of each equipment type was evaluated by five drivers/operators. The driver/operator performed a specific activity with all three pieces of identical equipment. Upon completing the specific event, the driver/operator was asked to rank the performance of the three vehicles/equipment in terms of certain performance criteria, including power, acceleration, idling, required shift points, hydraulic movements, engine sounds, etc.

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Observers accompany the drivers/operators to ensure that speed limits are obeyed; activities are undertaken in a safe manner and as a control measure. As such observers are asked to ***note*** any events that might bias or influence the results obtained (e.g. slow traffic, accidents), and any unusual driver behavior (such as frustration, unusual number of shifts required, etc.)

Driver/Operator Number:
Equipment Type:

A

Start Time:
End Time:
Notes:

B

Start Time:
End Time:
Notes:

C

Start Time:
End Time:
Notes:

Roadeo Questionnaires

The questionnaire contained 13 questions pertaining to the performance of the vehicles/equipment (see Text Box for a copy of the questionnaire). To simplify the Roadeo logistics, one questionnaire was used with the result that all the questions did not pertain to all the equipment types. For example, a question regarding the ability of a vehicle to dig was included in the questionnaire although only the telescoping boom excavators and loaders performed any digging. One of the responses to each question was thus 'Not Applicable'. Each driver was asked to rank the three vehicles/equipment they drove/operated 1, 2 and 3 in terms of the performance attributes, where '1' referred to the best and '3' the worst of the three vehicles.

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Did you perceive a difference in the performance of the vehicles/equipment?

Yes ____ **No** ____

If **yes**, please rank the vehicles in terms of the following aspects based on your driving experience.

1. Rank the three vehicles 1, 2 and 3 based on *acceleration performance* with **1** meaning **best** and **3** meaning **worst acceleration**.

A ____ **B** ____ **C** ____ **NA** ____

2. Rank the three vehicles 1, 2 and 3 based on *the level of engine noise* with **1** meaning **least** and **3** meaning **most noise**.

A ____ **B** ____ **C** ____ **NA** ____

3. Rank the three vehicles 1, 2 and 3 based on *the power of the vehicle* with **1** meaning **most** and **3** meaning **least power**.

A ____ **B** ____ **C** ____ **NA** ____

4. Rank the three vehicles 1, 2 and 3 based on *the level of vibration experienced* with **1** meaning **least** and **3** meaning **most vibration**.

A ____ **B** ____ **C** ____ **NA** ____

5. Rank the three vehicles 1, 2 and 3 based on *the number of shift points required when negotiating a hill* with **1** meaning the **least** and **3** meaning the **most**.

A ____ **B** ____ **C** ____ **NA** ____

6. Rank the three vehicles 1, 2 and 3 based on the *performance when lifting loads* with **1** meaning the **best** and **3** meaning the **worst power**.

A ____ **B** ____ **C** ____ **NA** ____

7. Rank the three vehicles 1, 2 and 3 based on the *impact on hydraulic movements* with **1** meaning the **fastest** and **3** meaning **slowest movement**.

A ____ **B** ____ **C** ____ **NA** ____

8. Rank the three vehicles 1, 2 and 3 based on *the power when digging* with **1** meaning the **most** and **3** meaning the **least power**.

A ____ **B** ____ **C** ____ **NA** ____

9. Rank the three vehicles 1, 2 and 3 based on *the time it takes to reach the desired/ highway speed from a dead stop* with **1** meaning the **shortest** and **3** meaning the **longest time**.

A ____ **B** ____ **C** ____ **NA** ____

10. Rank the three vehicles 1, 2 and 3 based on *the performance when required to operate with a load* with **1** meaning the **best** and **3** meaning the **worst**.

A ____ **B** ____ **C** ____ **NA** ____

11. Rank the three vehicles 1, 2 and 3 based on *the ability to maintain desired/ highway speeds* with **1** meaning the **best** and **3** meaning the **worst able**.

A ____ **B** ____ **C** ____ **NA** ____

12. Rank the three vehicles 1, 2 and 3 based on *idling performance when stopped* with **1** meaning the **best** and **3** meaning the **worst**.

A ____ **B** ____ **C** ____ **NA** ____

13. Rank the three vehicles 1, 2 and 3 based on *the overall performance of the vehicle* with **1** meaning the **best** and **3** meaning the **worst**.

A ____ **B** ____ **C** ____ **NA** ____

Any other comments: ____

____

____

D.2.B. Roadeo Driver Surveys – The analyses of the surveys of the drivers and operators from the Roadeo are discussed in this subsection.

Statistical Analysis

Kendall's Coefficient of Concordance (W) was calculated to determine whether the level of agreement, if any, among the rank responses of the drivers/operators for a particular performance attribute (e.g., acceleration) was statistically significant (for more details see Text box).

The responses in terms of each attribute tested were considered separately. Kendall's Coefficient of Concordance, W, its significance and estimates of the true rank order given a significant W was calculated for each attribute (question). In terms of the rank order, 1 represents the best vehicle with respect to that particular attribute and 3 means the worst.

The statistical results are subsequently summarized and presented: first in terms of the ranked responses for each attribute, and secondly in terms of each vehicle/equipment type. This allows for the evaluation of the impact of PuriNOx on different attributes and also on the performance of the vehicle/equipment included in the Roadeo.

Kendall Coefficient of Concordance (W)

Kendall Coefficient of Concordance is statistically defined as:

$$W = \frac{s}{\left(\frac{1}{12}\right)k^2\left(N^3 - N\right)}$$

Where

s = sum of squares of the observed deviations from the mean of Rj, i.e., s = $\sum\left(R_j - \frac{\sum R_j}{N}\right)^2$

k = number of sets of rankings, i.e. number of drivers
N = number of entities ranked, i.e. number of vehicles ranked

$\frac{1}{12}k^2(N^3 - N)$ = Maximum possible sum of the squared deviations, i.e., the sum s which would occur with perfect agreement among k rankings.

W indicates the level of agreement. W = 1 means 100% agreement while W = 0 means 100% disagreement.

If two vehicles/equipment are ranked the same, the observations are assigned the average of the ranks they would have been assigned had no ties occurred. In this case W is computed by:

$$W = \frac{s}{\left(\frac{1}{12}\right)k^2\left(N^3 - N\right) - k\sum_T T}$$

$T = \frac{\sum(t^3 - t)}{12}$, where

t = number of observations tied for a given rank in a group.
$\sum_T T$ is the sum of the values of T for all the k rankings.

The objective is to test the hypothesis that the agreement, if any, among the rankings of the performance of the vehicles/equipment in terms of a given attribute is due to chance. To test the significance of the computed W-value, the probability associated with the occurrence of a value as large as the "s" with which it is associated is determined. If it is less than 0.05, W is significant at the 0.05-level and the ranking agreement among the drivers is not due to chance alone. If it is greater than 0.05, W is not significant at the 0.05-level, meaning that there is no agreement in the ranking of the vehicles/equipment or the agreement is due to chance alone. In other words, the coefficient W thus indicates the level of agreement among the five drivers. A significant W means that the drivers consistently ranked the vehicles similarly for a given attribute. All the tests have been conducted at the 95% significance level.

Once it has been determined that W is significant, an estimate of the true rank order can be determined. The best estimate of the true rank is the order based on the sums of ranks.

Analysis Summary by Performance Attribute

The statistical analysis of the data recorded during the Roadeo provided evidence that supports the concerns raised by the Houston PuriNOx users regarding acceleration performance and loss of power. The tables in this section summarize whether the level of agreement among the ranking responses of the five operators of each equipment type is statistically significant and the best estimate of the true rank order.

Acceleration Performance

As can be seen from Table D.15, for **four** of the six vehicle/equipment types (i.e. the telescoping boom excavators, telescoping cranes, the loaders and the forklifts) a diesel vehicle was consistently ranked best with respect to acceleration performance and a PuriNOx-fueled vehicle worst. For these four vehicle types, the Coefficient of Concordance was statistically significant at the 95% significance level indicating significant agreement among the five drivers. The fact that one similarly fueled vehicle/equipment is ranked higher than the other provides evidence of the vehicle-to-vehicle differences between identical vehicles/equipment in terms of model, year, horsepower etc.

Acceleration performance seems to be less of a concern for the dump truck drivers since the driver responses were not consistent enough to show statistical significance. This seems to indicate that performance differences were less noticeable among the diesel and PuriNOx-fueled dump trucks.

Table D.15 Acceleration Performance

Vehicle	W	Significance	Rank Order		
			1	2	3
Telescoping Boom Excavator	1.000	Yes	B (Diesel)	C (Diesel)	A (PuriNOx)
Telescoping Cranes	0.832	Yes	B (Diesel)	C (Diesel)	A (PuriNOx)
Tandem-axle dump trucks	0.360	No	-	-	-
Single-axle dump trucks	0.211	No	-	-	-
Loaders	0.832	Yes	C (Diesel)	B (PuriNOx)	A (PuriNOx)
Forklifts	0.741	Yes	B (Diesel)	A (PuriNOx)	C (PuriNOx)

Power of Vehicle/Equipment

From Table D.16 it is evident that loss of power attributable to the use of PuriNOx was noticeable in the case of three of the equipment types. Ranking responses from telescoping boom excavator, telescoping crane and loader operators consistently ranked a diesel vehicle as the best in terms of the power of the equipment and a PuriNOx vehicle as the worst.

The fact that there is no statistically significant agreement among the respondents for the dump trucks and forklifts seems to suggest that loss of power is less noticeable for these types of equipment.

Table D.16 Power of Vehicle/Equipment

Vehicle	W	Significance	Rank Order		
			1	**2**	**3**
Telescoping Boom Excavator	0.760	Yes	B (Diesel)	C (Diesel)	A (PuriNOx)
Telescoping Cranes	0.744	Yes	B (Diesel)	C (Diesel)	A (PuriNOx)
Tandem-axle dump trucks	0.520	No	-	-	-
Single-axle dump trucks	0.284	No	-	-	-
Loaders	0.832	Yes	C (Diesel)	B (PuriNOx)	A (PuriNOx)
Forklifts	0.516	No	-	-	-

Impact on Hydraulic Movements

The performance impact on hydraulic movements could only be assessed by the telescoping boom excavator, the loader and the forklift operators during their activities, as shown in Table D.17. The ranking responses seem to indicate that only the forklifts are noticeably impacted when PuriNOx is used. The level of agreement among the ranking responses for both the telescoping boom excavators and the loaders were not statistically significant at the 95 % significance level.

Table D.17 Impact on Hydraulic Movements

Vehicle	W	Significance	Rank Order		
			1	**2**	**3**
Telescoping Boom Excavator	0.360	No	-	-	-
Loader	0.350	No	-	-	-
Forklift	0.859	Yes	B (Diesel)	A (PuriNOx)	C (PuriNOx)

Power When Digging

Only the Roadeo activities of the telescoping boom excavator and the loaders included digging. All the loader operators ranked the performance of PuriNOx-fueled vehicle A the worst when digging, as shown in Table D.18. Again the fact that there was no statistical agreement among the ranking responses of the telescoping boom excavator operators seems to indicate that a power loss when digging is less noticeable between the PuriNOx and diesel-fueled excavators.

Table D.18 Power when Digging

Vehicle	W	Significance	Rank Order		
			1	**2**	**3**
Telescoping Boom Excavator	0.650	No	-	-	-
Loader	0.832	Yes	C (Diesel)	B (PuriNOx)	A (PuriNOx)

Time to Reach and Maintain Highway Speeds

In terms of the attributes: time to reach and ability to maintain a desired/ highway speed, only the telescoping boom excavator operators consistently ranked a diesel-fueled excavator the best performer and the PuriNOx-fueled excavator the worst performer at the 95 % significance level. The statistical results are summarized in Tables D.19 and D.20.

Table D.19 Time to reach desired/highway speeds

Vehicle	W	Significance	Rank Order		
			1	**2**	**3**
Telescoping Boom Excavator	0.840	Yes	B (Diesel)	C (Diesel)	A (PuriNOx)
Telescoping Crane	0.478	No	-	-	-
Tandem-Axle Dump Truck	0.520	No	-	-	-
Single-Axle Dump Truck	0.078	No	-	-	-
Forklift	0.300	No	-	-	-

Table D.20 Ability to maintain desired/highway speeds

Vehicle	W	Significance	Rank Order		
			1	**2**	**3**
Telescoping Boom Excavator	1.000	Yes	B (Diesel)	C (Diesel)	A (PuriNOx)
Telescoping Crane	0.600	No			
Tandem-Axle Dump Truck	0.360	No	-	-	-
Single-Axle Dump Truck	0.173	No	-	-	-
Forklift	0.371	No	-	-	-

Engine Noise, Shift Points, Idling Performance

No statistical evidence, however, exists from the Roadeo data to support concerns raised by the Houston PuriNOx users regarding higher levels of engine noise, increased number of shift points required when negotiating a hill, and poorer idling performance. The ranking responses were thus very different when the operators ranked the level of engine noise, the level of vibration, the number of shift points required when negotiating a hill, the equipment's performance when lifting or operating with loads, and finally when idling. So much that there is no significant agreement among the drivers in ranking these performance attributes. This seems to suggest that the perceived effect of PuriNOx is not very different from diesel for these attributes and the tested equipment types. The statistical results for each attribute are summarized in Tables D.21 to D.26.

Table D.21 Level of Engine Noise

Vehicle	W	Significance	Rank Order		
			1	2	3
Telescoping Boom Excavator	0.360	No	-	-	-
Telescoping Crane	0.578	No	-	-	-
Tandem-Axle Dump Truck	0.160	No	-	-	-
Single-Axle Dump Truck	0.000	No	-	-	-
Loader	0.200	No	-	-	-
Forklift	0.200	No	-	-	-

Table D.22 Level of Vibration

Vehicle	W	Significance	Rank Order		
			1	2	3
Telescoping Boom Excavator	0.467	No	-	-	-
Telescoping Crane	0.120	No	-	-	-
Tandem-Axle Dump Truck	0.360	No	-	-	-
Single-Axle Dump Truck	0.067	No	-	-	-
Loader	0.253	No	-	-	-
Forklift	0.564	No	-	-	-

Table D.23 Number of Shift Points Required When Negotiating a Hill

Vehicle	W	Significance	Rank Order		
			1	2	3
Telescoping Boom Excavator	0.573	No	-	-	-
Telescoping Crane	0.478	No	-	-	-
Tandem-Axle Dump Truck	0.120	No	-	-	-
Single-Axle Dump Truck	0.278	No	-	-	-

Table D.24 Performance When Lifting Loads

Vehicle	W	Significance	Rank Order		
			1	2	3
Telescoping Boom Excavator	0.360	No	-	-	-
Loaders	0.150	No	-	-	-
Forklifts	0.411	No	-	-	-

Table D.25 Performance When Operating Under Load

Vehicle	W	Significance	Rank Order		
			1	2	3
Telescoping Boom Excavator	0.650	No	-	-	-
Tandem-Axle Dump Truck	0.350	No	-	-	-
Single-Axle Dump Truck	0.311	No	-	-	-
Loader	0.200	No	-	-	-
Forklift	0.671	No	-	-	-

Table D.26 Idling Performance

Vehicle	W	Significance	Rank Order		
			1	2	3
Telescoping Boom Excavator	0.029	No	-	-	-
Telescoping Crane	0.600	No	-	-	-
Tandem-Axle Dump Truck	0.360	No	-	-	-
Single-Axle Dump Truck	0.055	No	-	-	-
Loader	0.450	No	-	-	-
Forklift	0.200	No	-	-	-

Analysis Summary by Equipment Type

This section summarizes the driver/operator responses to the questions (attributes) pertaining to each equipment type arranged by type of equipment. Similar to the previous section, the tables summarize whether the level of agreement among the operator ranking responses is statistically significant and the best estimate of the true rank order.

Telescoping Boom Excavators

The performance of the excavators seems to be the most noticeably affected by PuriNOx. As can be seen from Table D.27, the level of agreement among the ranking responses were statistically significant for five of the thirteen attributes evaluated during the telescoping boom excavator activity: acceleration, power, time to reach the desired/highway speed from a dead stop, ability to maintain the desired/highway speed and also overall performance.

The PuriNOx-fueled excavator A was ranked the worst and the diesel-fueled excavator B the best with respect to all the five statistically significantly ranked attributes. Furthermore all the excavator operators had the same rank order in terms of acceleration, ability to maintain desired/highway speed, and overall performance: B was better than C which was better than A. The fact that excavator B was ranked higher than C is attributable to the fact that B was a 4-wheel drive and C was a 2-wheel drive excavator. It is thus worth highlighting that the respondents consistently ranked the 4-wheel drive PuriNOx-fueled excavator A to be worse than the 2-wheel drive diesel-fueled excavator in terms of acceleration, power, time it takes to reach the desired/highway speed from a dead stop, ability to maintain the desired/highway speed and also overall performance.

Table D.27 Telescoping Boom Excavators

Attribute	W	Significance	Rank Order		
			1	2	3
Acceleration Performance	1.000	Yes	B (Diesel)	C (Diesel)	A (PuriNOx)
Level of Engine Noise	0.360	No	-	-	-
Power of Vehicle	0.760	Yes	B (Diesel)	C (Diesel)	A (PuriNOx)
Level of Vibration	0.467	No	-	-	-
Number of shift points required when negotiating a hill	0.573	No	-	-	-
Performance when lifting loads	0.360	No	-	-	-
Impact on Hydraulic Movements	0.360	No	-	-	-
Power when digging	0.650	No	-	-	-
Time it takes to reach the desired/highway speed from a dead stop	0.840	Yes	B (Diesel)	C (Diesel)	A (PuriNOx)
Performance when required to operate with a load	0.650	No	-	-	-
Ability to maintain desired/highway speeds	1.000	Yes	B (Diesel)	C (Diesel)	A (PuriNOx)
Idling Performance	0.029	No	-	-	-
Overall Performance	1.000	Yes	B (Diesel)	C (Diesel)	A (PuriNOx)

The total scores for A, B and C are:
A: 174.5
B: 85
C: 130.5.
Maximum Possible Score: 195
Minimum Possible Score: 65

Also all five respondents ranked the PuriNOx-fueled excavator the worst in terms of power, time to reach the desired/highway speeds, and the ability to maintain the desired/highway speeds.

Loaders

Second to the telescoping boom excavators, the loader performance seems to be most noticeably affected when fueled with PuriNOx.

The level of agreement among the operators in their ranking responses was statistically significant for four of the ten attributes evaluated: acceleration performance, power of the vehicle, power when digging, and overall performance. In terms of acceleration performance, power of the vehicle, and power when digging, the diesel-fueled loader C was consistently ranked the best and the PuriNOx-fueled vehicle A was consistently ranked the worst. Furthermore, all five respondents ranked loader A the worst with respect to power.

An anomaly, however, exists in terms of the overall performance ranking. Given the attribute ranking it was expected that the overall performance ranking would be the same. From Table D.28, it can, however, be seen that the PuriNOx-fueled loader B was ranked best in terms of overall performance. One explanation for this anomaly is that B's overall performance was considered better in terms of other attributes not included in the questionnaire.

Table D.28. Loaders

Attribute	W	Significance	Rank Order		
			1	2	3
Acceleration Performance	0.832	Yes	C (Diesel)	B (PuriNOx)	A (PuriNOx)
Level of Engine Noise	0.200	No	-	-	-
Power of Vehicle	0.832	Yes	C (Diesel)	B (PuriNOx)	A (PuriNOx)
Level of Vibration	0.253	No	-	-	-
Performance when lifting loads	0.150	No	-	-	-
Impact on Hydraulic Movements	0.350	No	-	-	-
Power when digging	0.832	Yes	C (Diesel)	B (PuriNOx)	A (PuriNOx)
Performance when required to operate with a load	0.200	No	-	-	-
Idling Performance	0.450	No	-	-	-
Overall Performance	0.832	Yes	B (PuriNOx)	C (Diesel)	A (PuriNOx)

The total scores for A, B and C are:
A: 129
B: 80.5
C: 90.5
Maximum Possible Score: 150
Minimum Possible Score: 50

Telescoping Crane

Statistically significant agreement in the respondents' rankings of the cranes was recorded for three attributes: acceleration, power and overall performance. The operators consistently identified the PuriNOx-fueled vehicle as the worst performer in terms of these attributes, as shown in Table D.29. Diesel-fueled crane B was ranked the best in terms of acceleration, power and overall performance, while PuriNOx-fueled crane A was ranked consistently the worst. Furthermore all five crane operators ranked B as the best in terms of acceleration.

Table D.29 Telescoping Crane

Attribute	W	Significance	Rank Order		
			1	2	3
Acceleration Performance	0.832	Yes	B (Diesel)	C (Diesel)	A (PuriNOx)
Level of Engine Noise	0.578	No	-	-	-
Power of Vehicle	0.744	Yes	B (Diesel)	C (Diesel)	A (PuriNOx)
Level of Vibration	0.120	No	-	-	-
Number of shift points required when negotiating a hill	0.478	No	-	-	-
Time it takes to reach the desired / highway speed from a dead stop	0.478	No	-	-	-
Ability to maintain desired / highway speeds	0.600	No	-	-	-
Idling Performance	0.600	No	-	-	-
Overall Performance	0.640	Yes	B (Diesel)	C (Diesel)	A (PuriNOx)

The total scores for A, B and C are:
A: 120.5
B: 58
C: 91.5
Maximum Possible Score: 135
Minimum Possible Score: 45

There was, however, no statistically significant agreement in the ranking of the remaining six attributes, including: time to reach the desired/highway speed from a dead stop, and ability to maintain desired/highway speed. This seems to suggest that the performance impacts on the telescoping crane performance might be limited, although noticeable.

Forklift

Statistically significant agreement in the respondents' rankings of the forklifts was recorded for only two attributes: acceleration and impact on hydraulic movements. As can be seen from Table D.30, the diesel-fueled forklift B was ranked the best in terms of both these attributes and the PuriNOx-fueled forklift C was ranked the worst.

Table D.30 Forklift

Attribute	W	Significance	Rank Order		
			1	**2**	**3**
Acceleration Performance	0.741	Yes	B Diesel	A PuriNOx	C PuriNOx
Level of Engine Noise	0.200	No	-	-	-
Power of Vehicle	0.516	No	-	-	-
Level of Vibration	0.564	No	-	-	-
Performance when lifting loads	0.411	No	-	-	-
Impact on Hydraulic Movements	0.859	Yes	B Diesel	A PuriNOx	C PuriNOx
Time it takes to reach the desired / highway speed from a dead stop	0.300	No	-	-	-
Performance when required to operate with a load	0.671	No	-	-	-
Ability to maintain desired / highway speeds	0.371	No	-	-	-
Idling Performance	0.200	No	-	-	-
Overall Performance	0.576	No	-	-	-

The total scores for A, B and C are:
A: 111
B: 88
C: 131
Maximum Possible Score: 165
Minimum Possible Score: 55

No statistically significant agreement in the ranking of the remaining attributes, including power of the vehicle and performance when lifting loads, seems to suggest that the performance impacts on the forklifts might be limited.

Dump Trucks

In the case of the dump trucks, the drivers ranked the differently fueled vehicles very differently in terms of each of the attributes so that no statistically significant ranking agreement was observed. Hence there was no statistical evidence that the respondents perceived one vehicle to perform better or worse than another, which seems to indicate that PuriNOx does not significantly affect the performance of either the single-axle or tandem-axle dump trucks. The results are provided in Tables D.31 and D.32.

Table D.31 Tandem-Axle Dump Truck

Attribute	W	Significance	Rank Order		
			1	2	3
Acceleration Performance	0.360	No	-	-	-
Level of Engine Noise	0.160	No	-	-	-
Power of Vehicle	0.520	No	-	-	-
Level of Vibration	0.360	No	-	-	-
Number of shift points required when negotiating a hill	0.120	No	-	-	-
Time it takes to reach the desired / highway speed from a dead stop	0.520	No	-	-	-
Performance when required to operate with a load	0.350	No	-	-	-
Ability to maintain desired / highway speeds	0.360	No	-	-	-
Idling Performance	0.360	No	-	-	-
Overall Performance	0.360	No	-	-	-

The total scores for A, B and C are:
A: 74
B: 130
C: 96
Maximum Possible Score: 150
Minimum Possible Score: 50

Table D.32 Single-Axle Dump Truck

Attribute	W	Significance	Rank Order		
			1	2	3
Acceleration Performance	0.211	No	-	-	-
Level of Engine Noise	0.000	No	-	-	-
Power of Vehicle	0.284	No	-	-	-
Level of Vibration	0.067	No	-	-	-
Number of shift points required when negotiating a hill	0.278	No	-	-	-
Time it takes to reach the desired / highway speed from a dead stop	0.078	No	-	-	-
Performance when required to operate with a load	0.311	No	-	-	-
Ability to maintain desired / highway speeds	0.173	No	-	-	-
Idling Performance	0.055	No	-	-	-
Overall Performance	0.284	No	-	-	-

The total scores for A, B and C are:
A: 106.5
B: 83.5
C: 110
Maximum Possible Score: 150
Minimum Possible Score: 50

Concluding Remarks

To conclude, the performance impacts of PuriNOx on certain attributes are more evident than on others. PuriNOx-fueled vehicles/equipment were consistently ranked worse with respect to acceleration in four of the six equipment types. Hence the statistical evidence supports the Houston users' claims that acceleration is impacted by PuriNOx. Also, the power of certain equipment types is influenced by PuriNOx. It was found that PuriNOx-fueled vehicles were not as powerful as diesel-fueled ones in three of the six equipment types. In the cases where there was a statistical significant level of agreement between the ranking responses of the performance attributes, including impacts on hydraulic movements, power when digging, time taken to reach the desired/highway speed, and ability to maintain desired speeds a diesel-fueled vehicle was rated better than the PuriNOx-fueled vehicle. The rankings of attributes like engine noise, vibration, number of shift points required when negotiating a hill, performance when lifting loads, performance when operating under load and during idling were very different among the operators (for all equipment types) providing no evidence that the PuriNOx-fueled vehicles performed better/worse than the diesel vehicles in terms of these attributes.

The perceived performance impacts of PuriNOx on specific types of equipment varied significantly. The data seems to suggest that the excavator performance was impacted most noticeably when fueled with PuriNOx. The PuriNOx-fueled excavator was consistently ranked worse compared to the two diesel-fueled excavators with respect to five of the thirteen attributes that were considered. Also, the PuriNOx-fueled crane was ranked the worst performer with respect to three of the nine attributes that were tested. On the other hand, the performance of the dump trucks was ranked very differently with respect to all the attributes. Hence there was no evidence that the PuriNOx dump trucks performed better or worse than the diesel dump trucks in terms of the tested criteria. Loaders presented an interesting scenario. The level of agreement among the operators in their ranking responses was statistically significant for four of the ten attributes evaluated: acceleration performance, power of the vehicle, power when digging, and overall performance. In terms of acceleration performance, power of the vehicle, and power when digging, the diesel-fueled loader C was consistently ranked the best and the PuriNOx-fueled vehicle A was consistently ranked the worst. The PuriNOx-fueled loader (B) was, however, ranked best in terms of overall performance. One explanation for this anomaly is that B's overall performance was considered better in terms of other attributes not included in the questionnaire.

<u>D.2.C. Quantitative Results from the Roadeo</u> - In this section, the data from the dataloggers on each of the vehicles are analyzed to determine the size of performance differences attributed to fuel differences. For all of the vehicle types the staff analyzing the Roadeo performance data did not know which fuels the vehicles had used. Analysts knew only that two fuels had been used for every vehicle type. Once the analysis was completed, the project management revealed to the analysts which vehicles had used PuriNOx. Accordingly, the discussion of analysis for each vehicle type is presented as if the analysts did not know the PuriNOx-fueled vehicles. Then, in the last paragraph of each discussion, the fuel identities are revealed.

In the subsections that follow this introduction, an analysis of each of the datalogger datasets from each of the six vehicle types that were tested is presented. Table D.33 shows the six vehicle types and the corresponding regimes of operation that are used to make the analyses. The first four vehicle types were all driven on the road on defined routes. The performance of these four vehicle types during driving will be evaluated for speed and/or acceleration performance. In addition, the bucket trucks and telescoping boom excavators stopped during their route to perform a special work activity test. For those two vehicle types, the work activity test is evaluated separately. The wheeled loaders and the forklifts were not driven on the road and, accordingly, are evaluated below using only work activity tests that were designed for them.

Table D.33 Activities for Vehicle Evaluation

Vehicle Type	Driving Route	Work Activity
Single-axle dump trucks	A	None
Tandem-axle dump trucks	-A	None
Bucket Trucks	B	Operating Bucket
Telescoping Boom Excavators	B	Digging and Loading Dump Trucks
Wheeled Loaders	None	Loading Dump Trucks
Forklifts	None	Lifting and Transferring Pallets

As described in Section D.2.A., two driving routes were used to test the dump trucks, bucket trucks, and telescoping boom excavators. Single-axle dump trucks used Route A, which was 18.5 miles long, in the counterclockwise direction. The tandem-axle dump trucks followed the same route except that they used the route in the opposite, clockwise, direction. The bucket trucks and the telescoping boom excavators followed a different route that was 34.3 miles long, which is designated B in Table D.33, and they all used the route in the same direction.

For single-axle dump trucks, tandem-axle dump trucks, and bucket trucks, the speed versus time profiles for each of the fifteen runs during an acceleration were compared on a second-by-second basis to determine which of the vehicles had better acceleration performance. For the comparison to be valid, the road conditions, accelerator position, and transmission gear had to be the same among the fifteen runs.

Comparison at the same road conditions was achieved by using data from the same location in the route. Within each vehicle type, the driving characteristics of the vehicles for different drivers and different fuels can be compared at the same location on the route because the vehicle drivers were instructed to follow exactly the same route. However, since individual vehicles drove different speeds, the observations in each vehicle's dataset that corresponded to operation at a given location could not be easily determined based on time. Instead, the speed versus time data for each of the fifteen runs for each vehicle type were converted to speed versus distance. When the traces for individual vehicles were overlaid, the corresponding points of operation for the different vehicles were easily found. This type of plot was used to select specific locations where the performance of the vehicles at exactly the same location could be compared in the analysis.

During accelerations the transmission gear is important since higher accelerations will be produced by lower gears. The gear in which the vehicle was being operated was determined by comparing vehicle speed with engine RPM for the entire dataset. For the observations where the ratio of speed to RPM is independent of vehicle speed, the transmission is in the same gear as in the example shown in Figure D.2.5. When the ratio of speed to RPM does not match any of the frequently occurring ratios of speed to RPM in the dataset, the transmission can be assumed to be out of gear, between gears, or with the clutch disengaged. Using this technique, we were able to assign gears to all of the observations in the dump truck and bucket truck datasets.

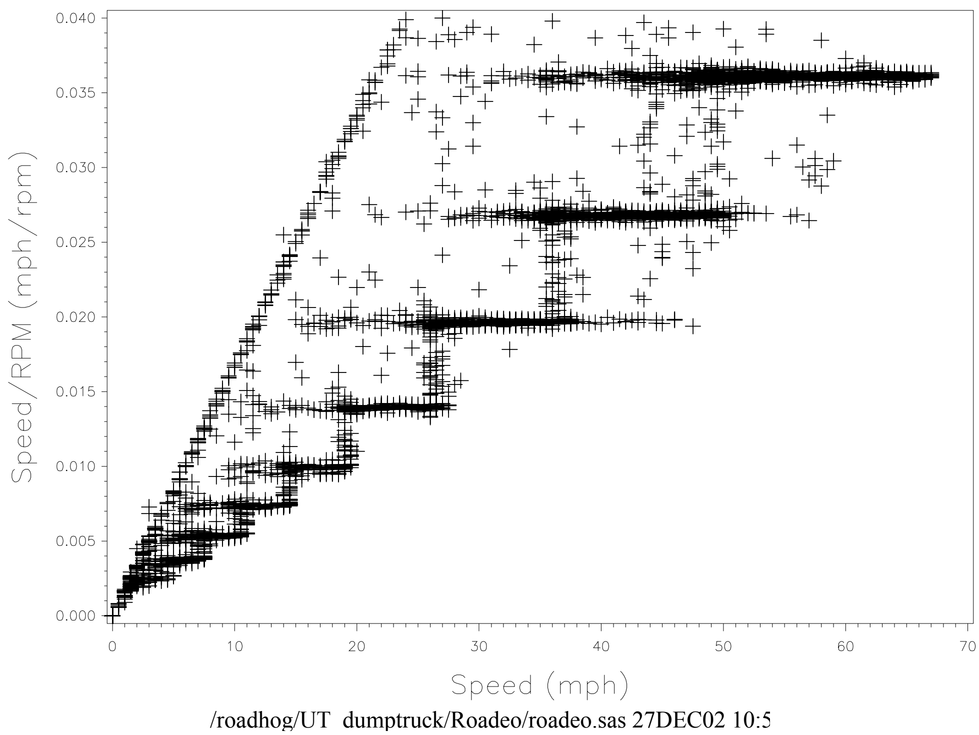


Figure D.2.5 Ratio of vehicle speed to engine speed for tandem-axle dump truck C

Since run-to-run acceleration differences can be produced by accelerator pedal position differences, such as when the driver must reduce acceleration when approaching another vehicle from the rear, we chose to accept acceleration run observations for analysis only if the accelerator position was greater than 95%. Observations with any accelerator position were allowed during transmission shifting.

For each of the locations selected for acceleration analysis, once the constraints for location, transmission gear, and accelerator pedal position were imposed, the remaining vehicle speed observations from the fifteen vehicle runs were time-aligned so that the initial observation of each run had as close to the same speed as possible. When the fifteen time-aligned runs were considered together on a single overlaid plot, each speed versus time trace could be compared at the same location and for essentially full accelerator position. The transmission gear for different runs was usually the same from run to run, but occasionally drivers were in different gears. In these instances, the analysis took gear differences into account.

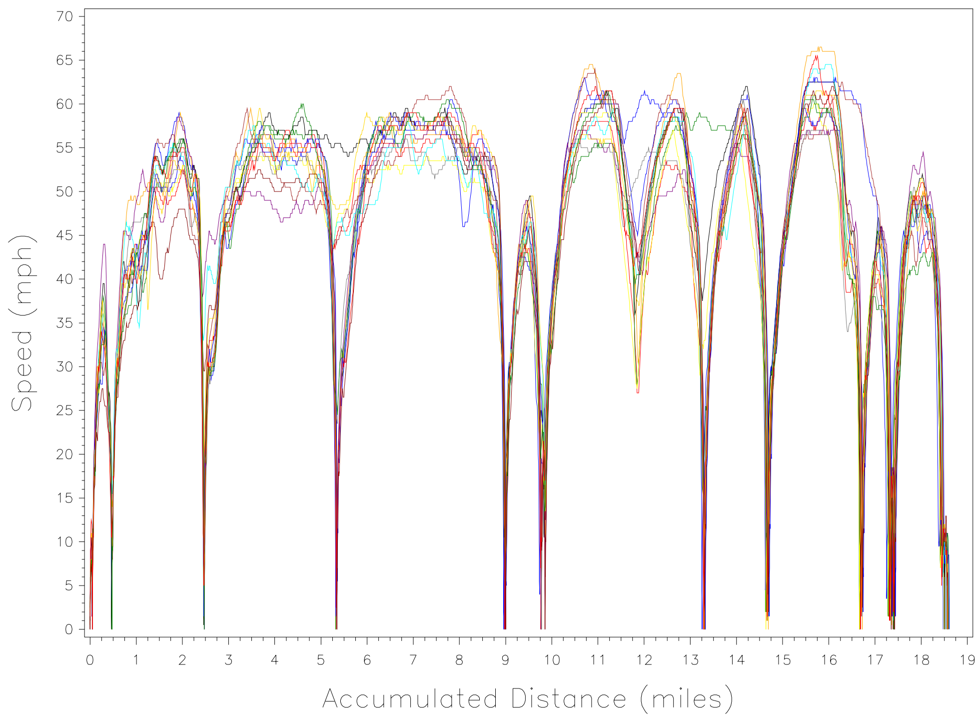
To provide a more quantitative measure of the different acceleration performances of the test vehicles, we used the same acceleration curves to pick off speeds at the beginning and end of each acceleration in those places that the transmission was in each gear. The initial and final speeds of each gear were selected such that the accelerator pedal position was greater than 95% and the load on the engine was 100%. From the initial and final speeds in each gear, we calculated the average acceleration in the gear. This produced average accelerations for each combination of vehicle type (single-axle dump truck, tandem-axle dump truck, bucket truck), acceleration run (1, 2, 3), driver, and vehicle (A, B, C).

In general, there was no effect of driver on the calculated accelerations. This is the expected result since all the accelerations were calculated only for conditions with full accelerator pedal and full engine load. However, important differences were observed for acceleration run, transmission gear, test vehicle, and vehicle type. For each of the three vehicle types we produced a table that averages the measured accelerations to determine the size of the loss of performance that is produced by vehicles using PuriNOx.

For the single-axle dump trucks, the tandem-axle dump trucks, and the bucket trucks, the analyses presented below consider the acceleration performance of the vehicles as they were driven by their drivers at selected locations on the routes where vehicles are accelerating away from stoplights or stop signs. The analysis for the driving performance of the telescoping boom excavators is somewhat different since the engine computer of the telescoping boom excavator did not provide vehicle speed to the data bus for the QuickCheck datalogger to pick up. Accordingly, in the case of the telescoping boom excavator, the analysis considers the acceleration and speed performance based on the engine RPM since, in a given gear, the vehicle speed is proportional to engine RPM. The telescoping boom excavator performance analysis based on engine RPM also takes into account engine load and accelerator pedal position.

Quantitative Results for Single-Axle Dump Trucks - Three 1999 GMC Model C7500 single-axle dump trucks were used to test fuel performance in the Roadeo. The vehicles are described in detail in Section D.2.A. Each single-axle dump truck was instrumented with a QuickCheck datalogger to record second-by-second speed, engine RPM, engine percent load, and accelerator pedal position. For the Roadeo testing, the single-axle, 6 yard, dump trucks were loaded with recycled asphalt product to a loaded vehicle weight of approximately 29,400 pounds.

The speed versus time data for each of the fifteen single-axle dump truck runs were converted to speed versus distance traces and overlaid as shown in the plot in Figure D.2.6. The figure shows that the single-axle dump trucks followed the same route for all fifteen runs. The plot indicates where vehicles sometimes stopped and sometimes did not stop depending on traffic signals. Two accelerations were selected for analysis for the single-axle dump trucks. Acceleration 1 occurred at 9.8 miles in the route where the vehicles turned left from FM 362 onto Highway 290 going west and accelerated. Acceleration 2 occurred at 14.7 miles in the route.



/roadhog/UT dumptruck/Roadeo/single.sas 26DEC02 14:3

Figure D.2.6 Vehicle speed vs. distance for single-axle dump truck runs

The results of the comparison of observations for Acceleration 1 are shown in Figure D.2.7. In the case of this acceleration, 9 of the 15 runs met the requirement that the accelerator position was greater than 95% during a substantial portion of the acceleration. Our analysis of the Acceleration 1 data indicated that the two runs for Single B produced higher accelerations than the runs for Singles A and C. In addition, the acceleration data for Single A and C look similar to each other. Consequently, we used dashed lines to connect the data points for Single B. All observations in the figure for Driver S3 in Single A were made with the transmission in sixth gear. All other observations for other runs in the figure were made with the transmission in fifth gear and then shifting to sixth gear.

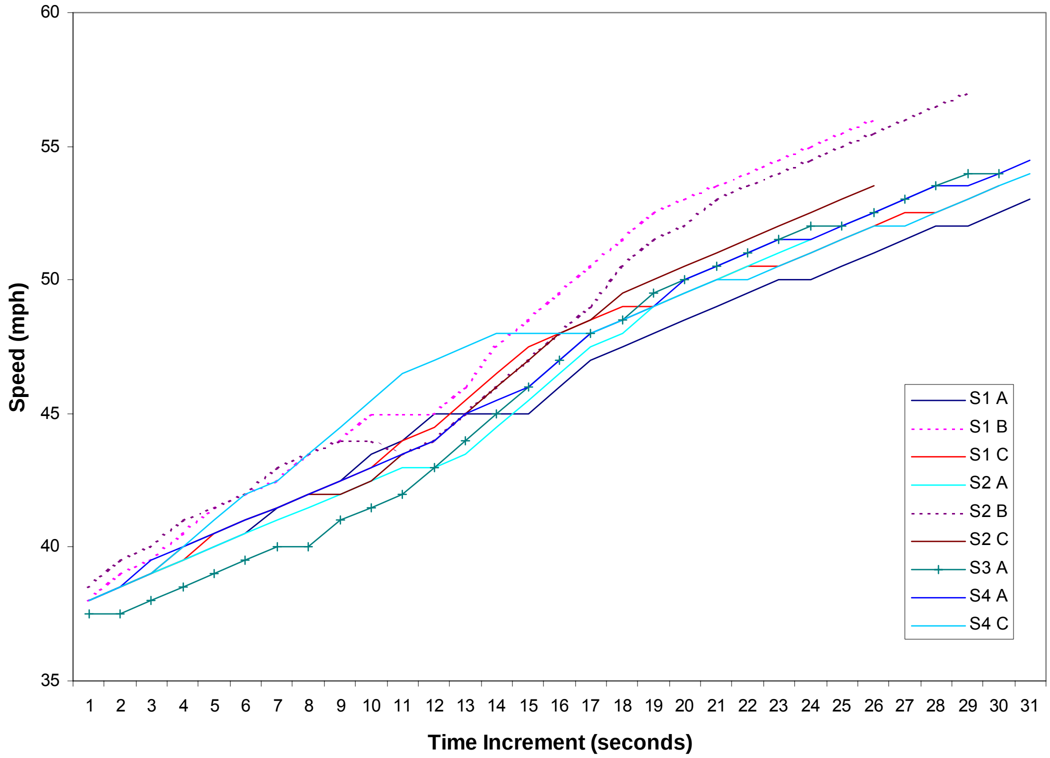


Figure D.2.7 Single-axle dump truck acceleration 1

The performance of the vehicles at Acceleration 2 for the single-axle dump trucks are shown in Figure D.2.8. In this figure, all observations were made with the vehicle in fourth gear shifting to fifth and then to sixth. Again, our analysis of the acceleration curves indicated that the two curves for Single B in this figure (the two upper curves) showed higher rates of acceleration in all three gears than for the curves for Single A and C. In addition, the curves for Singles A and C were very similar to each other. Accordingly, the curves for Single B are shown with dashed lines.

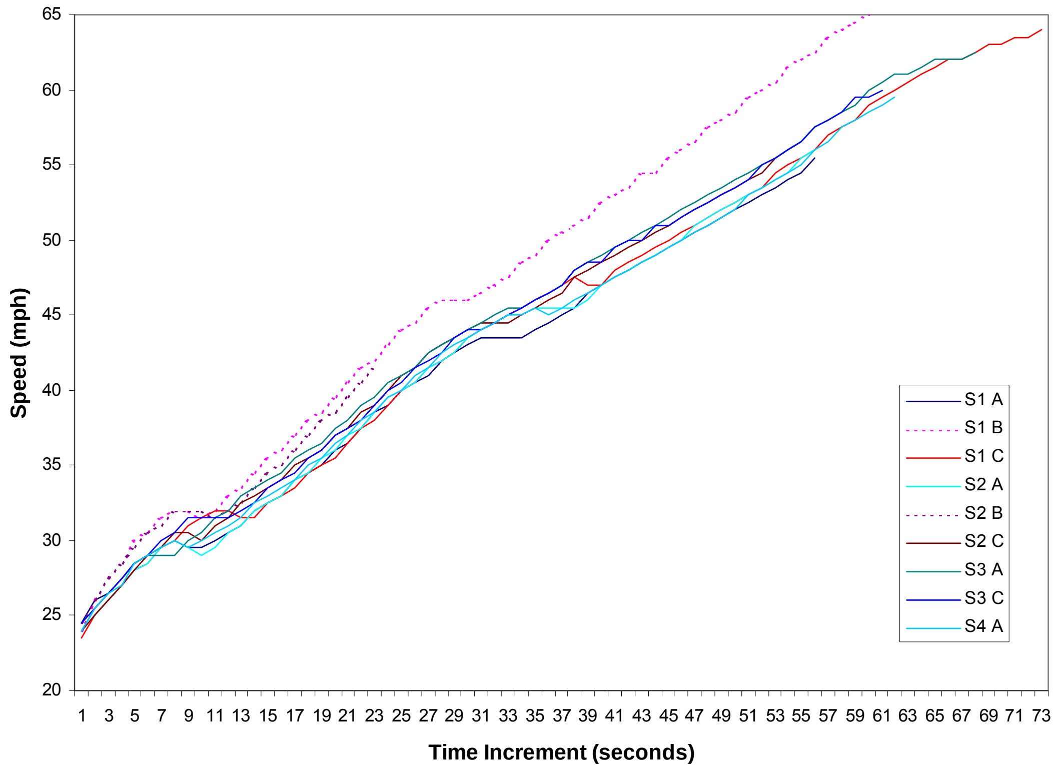


Figure D.2.8 Single-axle dump truck acceleration 2

The previous two figures show the relative acceleration performance of single-axle dump trucks in the Roadeo on selected accelerations by displaying their acceleration curves. Those curves provide a visual demonstration of the relative acceleration performance of the vehicles with the different fuels.

Table D.34 shows the results of the quantitative in-gear acceleration analysis for single-axle dump trucks. Accelerations were determined for the top three gears. The average acceleration of all acceleration runs was averaged for each gear, acceleration run, and test vehicle. These averages are shown for Vehicles A, B, and C in the third, fourth, and fifth columns of the table. Examination of the acceleration values in these cells shows that for each combination of gear and acceleration run, the average acceleration for Vehicle B is always higher than for Vehicles A and C, and the average accelerations of A and C are similar to each other. This is the same result that was seen in the previous plots of acceleration. The acceleration values that tend to be lower are shown in bold in the table. In columns 6, 7, and 8 of the table, we show the average values for each gear obtained by averaging the accelerations for each run for each gear. Again, these averages show that Vehicle B had higher accelerations in all the gears, and Vehicles A and C had lower accelerations in all the gears. In addition, these values also show that the acceleration of the vehicle is higher in lower gears as we would expect. In the next two columns, we average the acceleration values for each gear for those vehicles that have high acceleration performance; we do the same for those vehicles that have low acceleration performance.

Table D.34 Quantitative Analysis of In-Gear Acceleration Performance for Single-Axle Dump Trucks

Gear	Run	Acceleration (mph/s)								Performance Change for High to Low
		Run Average			Gear Average			Average for Vehicles with Similar Performance		
		A	B	C	A	B	C	High (B)	Low (A,C)	(%)
4	Acceleration 2	**0.93**	1.11	**0.85**	**0.93**	1.11	**0.85**	1.11	**0.89**	-20%
5	Acceleration 1	**0.56**	0.74	**0.68**						
	Acceleration 2	**0.66**	0.85	**0.68**	**0.61**	0.80	**0.68**	0.80	**0.65**	-19%
6	Acceleration 1	**0.57**	0.75	**0.51**						
	Acceleration 2	**0.55**	0.65	**0.55**	**0.56**	0.70	**0.53**	0.70	**0.55**	-22%

Finally, we use the two values in those columns to determine the difference in acceleration performance when the high performing vehicles are compared to the low performing vehicles. Subsequent to this analysis of the data, we learned that single-axle dump trucks A and C were fueled with PuriNOx. Therefore, in the case of the single-axle dump trucks, the average performance loss for acceleration for PuriNOx is observed to be 20%.

Quantitative Results for Tandem-Axle Dump Trucks - Three International Model 2574 tandem-axle dump trucks were used to test the fuel performance in the Roadeo. The vehicles are described in detail in Section D.2.A. Each tandem-axle dump truck was instrumented with the QuickCheck datalogger to record second-by-second speed, engine RPM, engine percent load, and accelerator pedal position. For the Roadeo testing, the tandem-axle, 10-yard dump trucks were filled with recycled asphalt product to a loaded vehicle weight of approximately 43,500 pounds.

All of the data designated as Tandem A were taken using the TxDOT #12-4456-G vehicle. All of the data designated as Tandem B were taken on the TxDOT #12-4457-G vehicle. Data designated as Tandem C for Drivers T1, T2, and T4 were taken on the TxDOT #12-4521-G vehicle. During the fourth run on this vehicle, the engine experienced fuel injector problems, which caused additional data collection on this vehicle to be impossible. The remaining two runs for Tandem C for Drivers T3 and T5 were taken on the TxDOT #12-4457-G vehicle.

The speed versus time data for each of the fifteen tandem-axle dump truck runs were converted to speed versus distance traces and overlaid in the plot shown in Figure D.2.9. The speed versus distance trace for Tandem C when it was driven by Driver T2 was left off the figure because the total distance for that run was about two miles longer than the other fifteen traces. We attempted to match up portions of that trace with the traces shown in the figure but were unsuccessful. Our conclusion is that the route driven for that run was at least somewhat different. The figure shows that for the remaining fourteen runs, the tandem-axle dump trucks followed the same route.

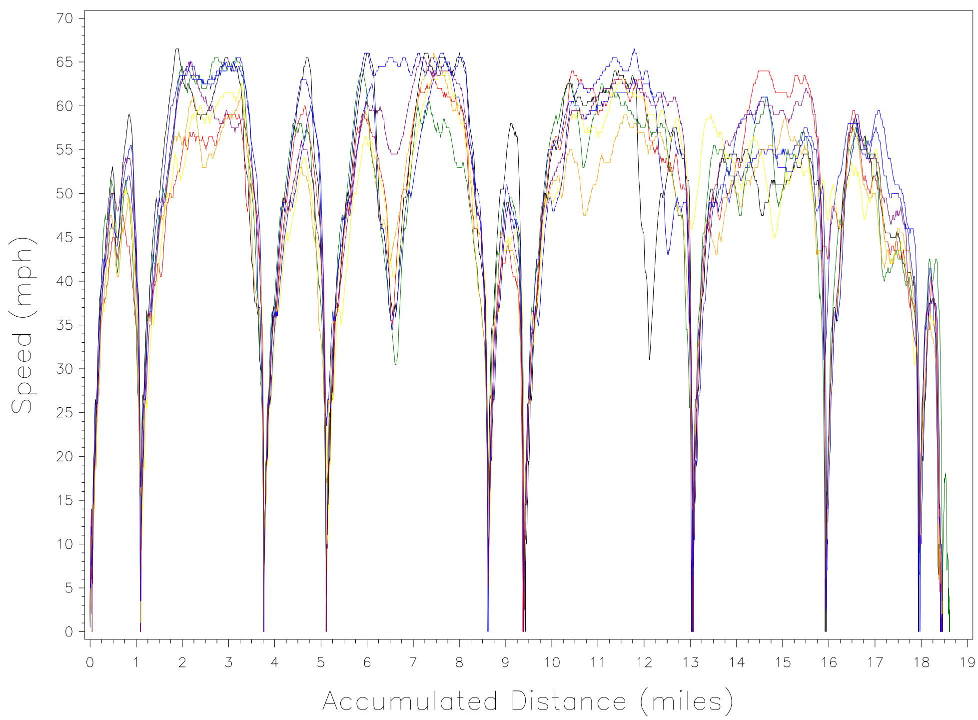


Figure D.2.9 Vehicle speed vs. distance for tandem-axle dump truck runs

Accelerations were selected for analysis for the tandem-axle dump trucks. Acceleration 1 occurred at 3.8 miles in the route. Acceleration 2 occurred at 9.4 miles in the route where the vehicle turned off from FM 362 onto Business Route 290 going west. Acceleration 3 occurred at 13.1 miles in the route which is the acceleration going west on Business Route 290 from the intersection with FM 1098.

The results of the comparison of observations for Acceleration 1 are shown in Figure D.2.10. For this acceleration all fifteen runs met the requirement that the accelerator position was greater than 95% during a substantial portion of the acceleration. The acceleration curves in the figure were obtained when the tandem-axle dump truck accelerated through about seven gears. Our analysis of Acceleration 1 curves in the figure indicate that overall all five runs for Tandem A produced higher accelerations than the runs for Tandems B and C. In addition, the accelerations for Tandems B and C looked similar to each other. Consequently, we used dashed lines to connect the data points for Tandem A in the figure. Close up examination of the dashed lines in the figure shows that accelerations of Tandem A are higher than the accelerations of the other vehicles when they are in the same gear. Examination of the overall acceleration curve in the figure shows that there is a consistent tendency for Tandem A to accelerate faster than Tandems B and C.

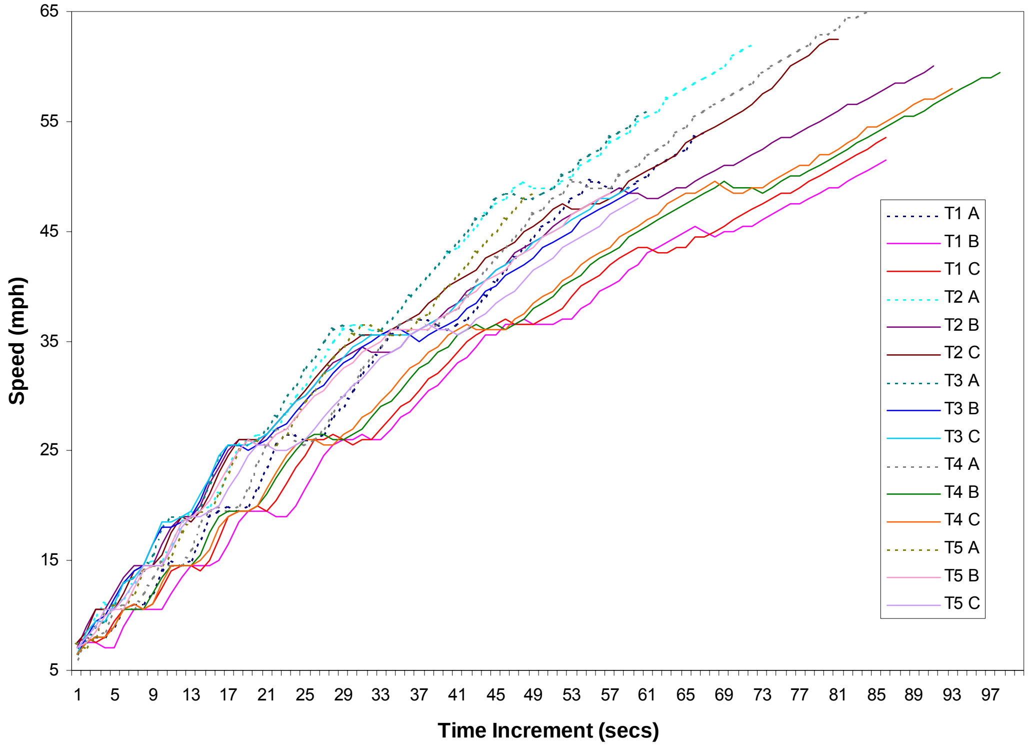


Figure D.2.10 Tandem-axle dump truck acceleration 1

The performance of the vehicles at Acceleration 2 for the tandem-axle dump trucks is shown in Figure D.2.11. The results of this acceleration set also indicates that Tandem A has better acceleration performance in each gear in comparison with Tandems B and C, and Tandems B and C have approximately the same acceleration performance. For Acceleration 2, these conclusions are based primarily on a comparison of acceleration rates when the competing vehicles were in the same gear. When examining the overall acceleration curves for the entire run, the figure shows that the amount of time that the driver takes to shift gears has a large effect on the overall time required to accelerate up to cruising speed. As a consequence of these different shifting times, the overall acceleration curves look similar among the three test vehicles. Just as in the figure for Acceleration 1, the acceleration curves for Tandem A have been designated with a dashed line.

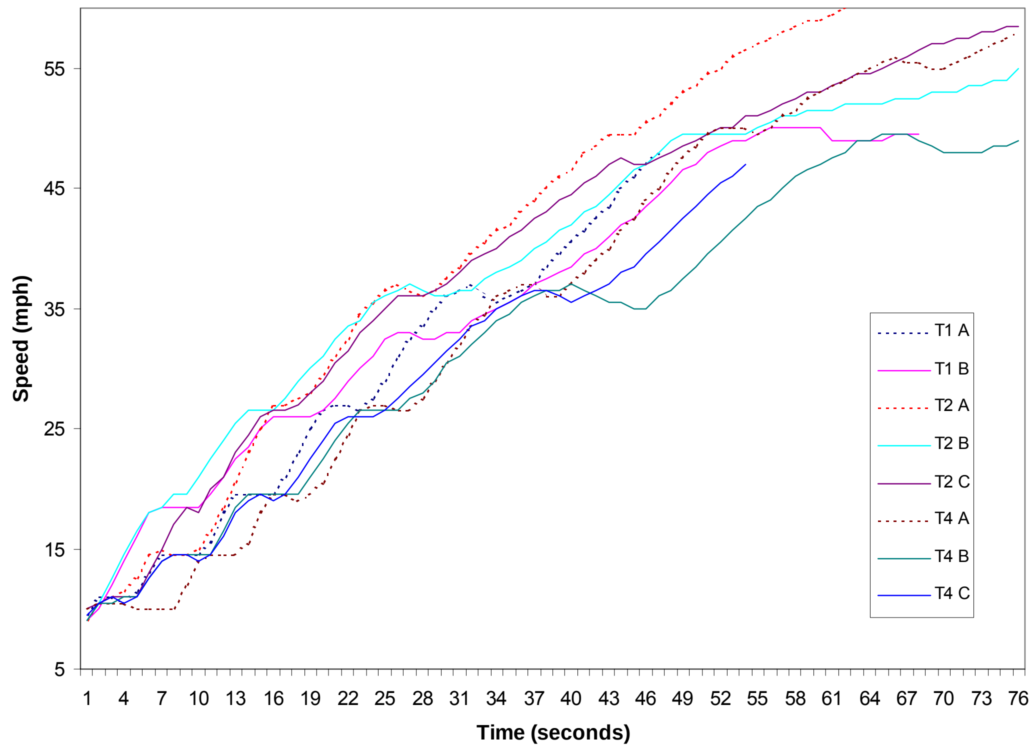


Figure D.2.11 Tandem-axle dump truck acceleration 2

A comparison of the speed curves for Acceleration 3 is shown in Figure D.2.12. Again, the acceleration performance of Tandem A appears to be somewhat better than Tandems B and C. This can be most easily seen in the higher gears above about 25 miles an hour where the slopes of the speed traces are steeper for Tandem A compared to the competing vehicles.

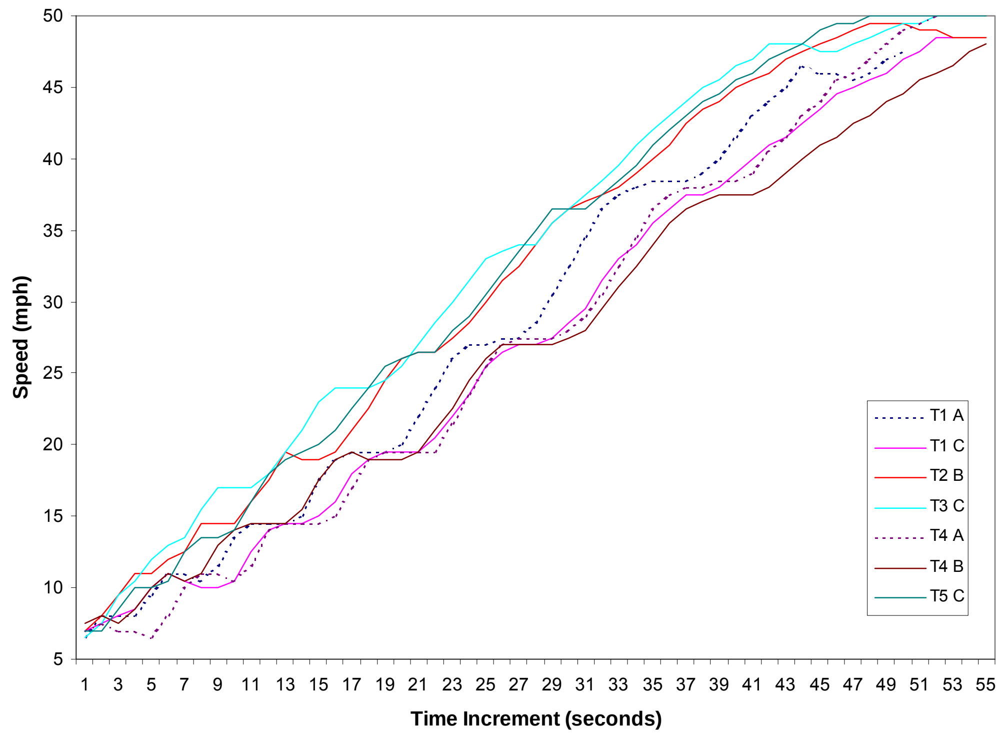


Figure D.2.12 Tandem-axle dump truck acceleration 3

Table D.35 shows the results of the quantitative in-gear acceleration analysis for tandem-axle dump trucks. Accelerations were determined for the top four gears. The average acceleration of all acceleration runs was averaged for each gear, acceleration run, and test vehicle. These averages are shown for Tandems A, B, and C in the third, fourth, and fifth columns of the table. Examination of the acceleration values in these cells shows that for each combination of gear and acceleration run, the average acceleration for Tandem A is always higher than for Tandems B and C and the average accelerations of B and C are similar to each other. This is the same result that was seen in the previous plots of acceleration. The acceleration values that tend to be lower and that we suspect are in vehicles fueled by PuriNOx are shown in bold in the table. In columns 6, 7, and 8 of the table, we show the average values for each gear obtained by averaging the accelerations for each run for each gear. Again, these averages show that Tandem A had higher accelerations in all the gears and Tandems B and C had lower accelerations in all the gears. In addition, these values also show that the acceleration of the vehicles is higher in lower gears as we would expect. In the next two columns, we average the acceleration values for each gear for those vehicles that have high acceleration performance; we do the same for those vehicles that have low acceleration performance.

Table D.35 Quantitative Analysis at In-Gear Acceleration Performance for Tandem-Axle Dump Trucks

		Acceleration (mph/s)								
		Run Average			Gear Average			Average for Vehicles with Similar Performance		Performance Change for High to Low
Gear	Run	A	B	C	A	B	C	High (A)	Low (B,C)	(%)
6	Acceleration 1	1.88	**1.36**	**1.35**						
	Acceleration 2	2.00	**1.44**	**1.50**						
	Acceleration 3	1.70	**1.67**	**1.44**	1.86	**1.49**	**1.43**	1.86	**1.46**	-22%
7	Acceleration 1	1.18	**0.78**	**0.81**						
	Acceleration 2	1.33	**0.88**	**0.95**						
	Acceleration 3	1.46	**1.35**	**1.39**	1.32	**1.00**	**1.05**	1.32	**1.03**	-22%
8	Acceleration 1	0.93	**0.62**	**0.62**						
	Acceleration 2	1.01	**0.66**	**0.81**						
	Acceleration 3	1.17	**0.79**	**0.79**	1.04	**0.69**	**0.74**	1.04	**0.72**	-31%
9	Acceleration 1	0.64	**0.35**	**0.51**						
	Acceleration 2	0.46	**0.22**	**0.38**	0.55	**0.29**	**0.45**	0.55	**0.37**	-34%

Finally, we use the two values in those columns to determine the performance change in acceleration when the high performing vehicles are compared to the low performing vehicles. Subsequent to this analysis of the data, we learned that Tandem-Axle Dump Trucks B and C were fueled with PuriNOx. In the case of the tandem-axle dump trucks, the average performance loss for acceleration for PuriNOx is observed to be 27%.

Quantitative Results for Bucket Trucks - Three bucket trucks were used to test fuel performance in the Roadeo. The vehicles are described in detail in Section D.2.A. Each bucket truck was instrumented with a QuickCheck datalogger to record second-by-second vehicle speed, engine RPM, engine percent load, and accelerator pedal position. For an unknown reason, the datalogger on Bucket Truck B stopped recording data for the last half of the run made by Driver B5 and for all of the runs made by Driver B4.

The speed versus time data for each of the bucket truck runs were converted to speed versus distance traces. Runs for Drivers B4 and B5 on Vehicle B were incomplete because of datalogger failures. Of the remaining thirteen runs, the nine runs for Drivers B1, B2, and B3 indicated that they followed almost exactly the same route. Accordingly, the speed versus distance traces for these nine runs are overlaid in Figure D.2.13. The remaining runs for Drivers B4 and B5 had slight differences in the cumulated distance that seemed to arise from slightly different paths at 10.5 miles and 25.5 miles in the route. These deviations amounted to a total difference in the distance of 0.6 miles. These slight differences in route did not prevent us from easily selecting acceleration locations for us to compare for the thirteen complete data runs.

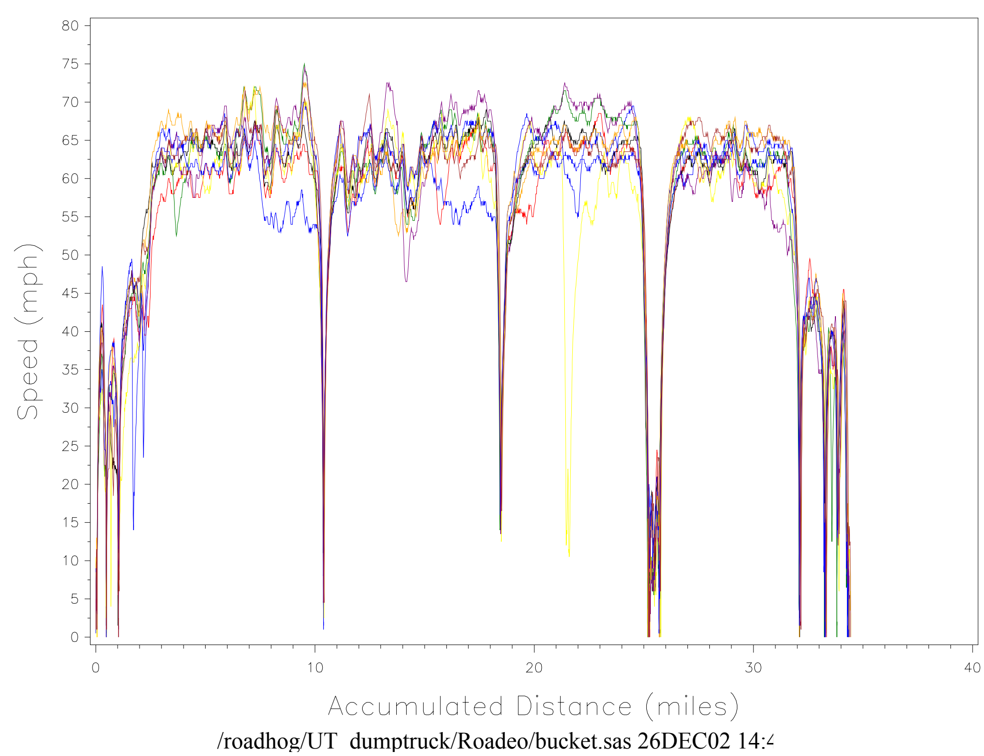


Figure D.2.13 Vehicle speed vs. distance for bucket truck runs

Three accelerations were selected for analysis of the bucket truck driving performance. Acceleration 1 occurred at 10.5 miles in the route where each vehicle accelerated after performing a U-turn on Highway 6 and going south. Acceleration 2 occurred at 18.5 miles in the route where vehicles turned west from Highway 6 and accelerated onto Highway 290. Acceleration 3 occurred at 25.7 miles in the route where vehicles accelerated onto Highway 290 going east after performing their work activity test.

The results of the analysis of the acceleration curves for the bucket trucks are less clear than for the single-axle and tandem-axle dump trucks. This may be partly a result of the different type of transmission used in the bucket trucks. The single- and tandem-axle dump trucks clearly had a manual transmission and the acceleration curves clearly demonstrated when the vehicles transmissions were being shifted. In the case of the bucket trucks, the acceleration curves alone do not show clear drops in acceleration when the transmission is being shifted. In spite of these transmission differences, we believe that the acceleration curves still demonstrate differences in acceleration performance for the bucket trucks.

The results of the comparison of observations for Acceleration 1 are shown in Figure D.2.14. Eight of the thirteen acceleration runs met the requirement that the accelerator position was greater than 95% during a substantial portion of the acceleration. The curves in the figure at first did not tell a consistent story to us about the grouping of vehicles with respect to their acceleration performance until we took into account the earlier observation that Drivers B4 and B5 seemed to be taking a slightly different route for the U-turn that was needed just before this acceleration on Highway 6. When we remove the curves in the figure for Drivers B4 and B5, which are the curves shown with symbols, then the remaining five curves tell a consistent story. The top two curves are for Buckets B and C and the bottom three curves with dashes are for Bucket A. Thus, based on Acceleration 1, it appears that Buckets B and C have very similar acceleration performance which is superior to the consistent acceleration performance for Bucket A in three separate runs.

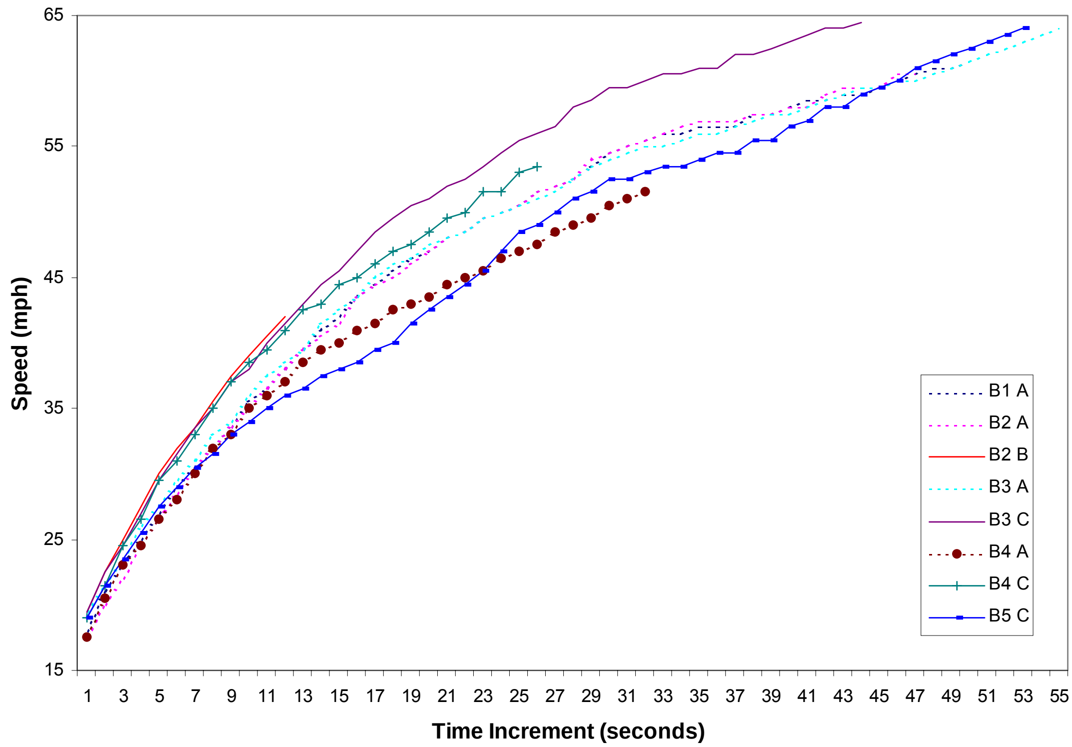


Figure D.2.14 Bucket truck acceleration 1

The Acceleration 2 curves that meet the data requirements are shown overlaid in Figure D.2.15. The upper two curves with the solid lines that are closely overlaid are for Bucket B. The bottom four curves with the dashed lines are for Bucket A; these curves are also closely overlaid. The remaining curve with the symbols is for Bucket C. This curve shows stronger accelerations than were demonstrated by the Bucket A curves but the strength of the acceleration at speeds below 40 miles an hour is not as strong as the accelerations for the upper curves that belong to Vehicle B. So as a result of the analysis of Acceleration 2, we can say that Bucket B runs are noticeably stronger in acceleration than Bucket A runs, however, the single Bucket C curve has properties which are in some ways similar to A and in some ways similar to B.

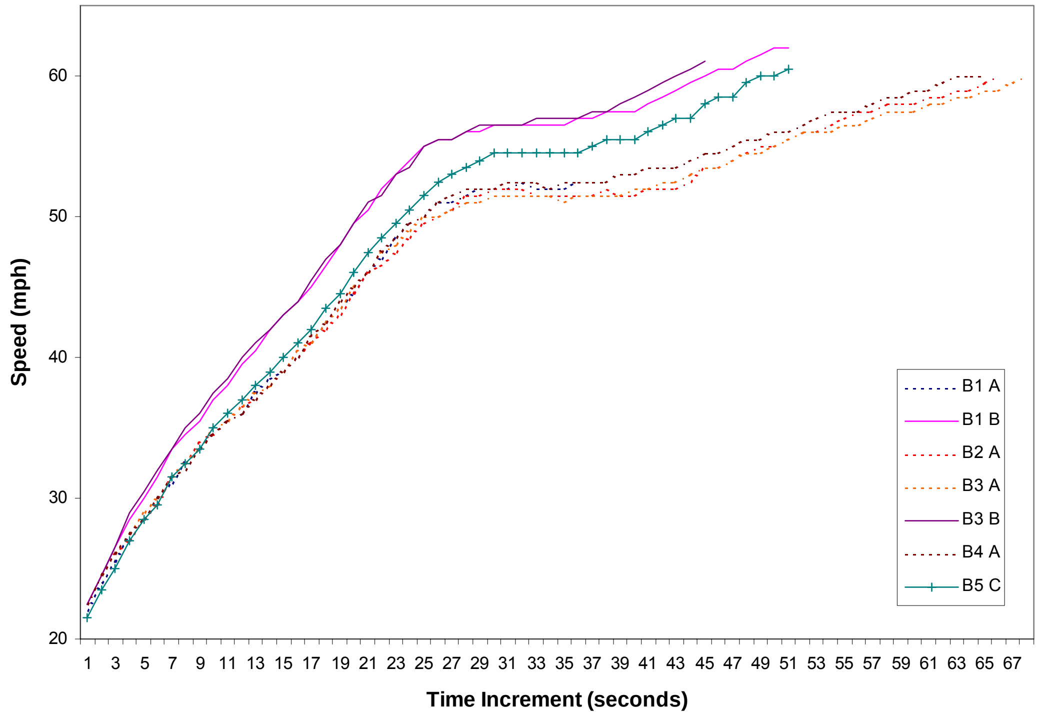


Figure D.2.15 Bucket truck acceleration 2

The overlaid acceleration curves for the bucket trucks in Acceleration 3 are shown in Figure D.2.16. These acceleration curves clearly distinguish two groups of vehicles. The top group of solid lines is for Buckets B and C with Bucket B having the symbols. The bottom five acceleration curves are for Bucket A.

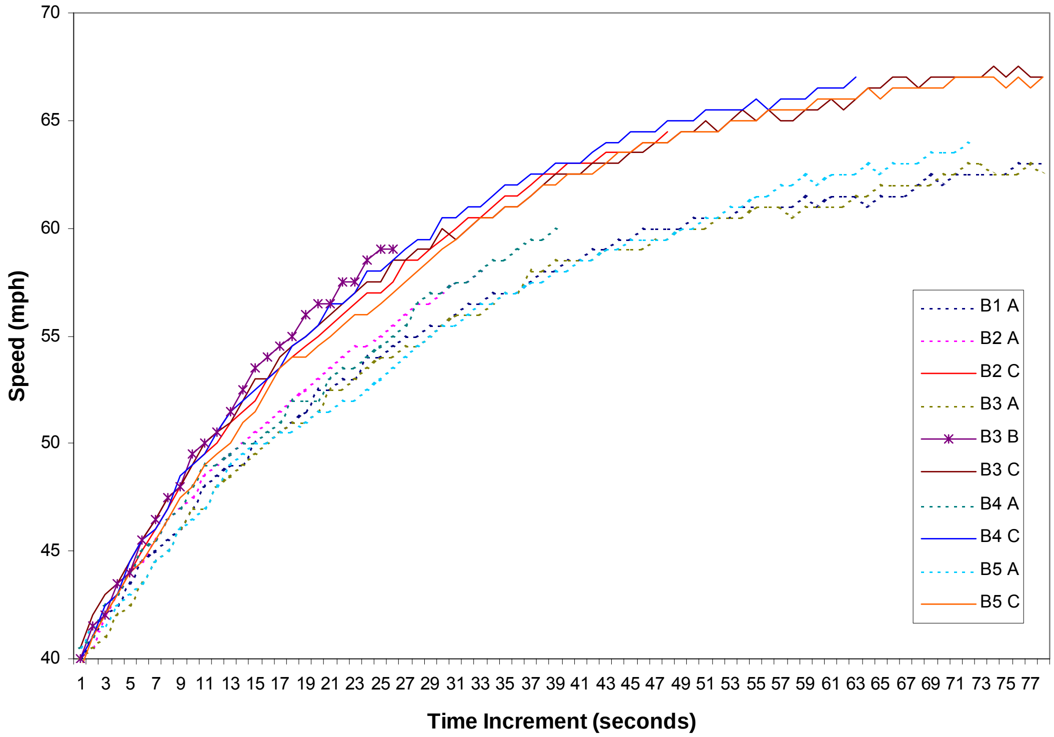


Figure D.2.16 Bucket truck acceleration 3

Table D.36 shows the results of the quantitative in-gear acceleration analysis for bucket trucks. Accelerations were determined for the top five gears. The average acceleration of all acceleration runs was averaged for each gear, acceleration run, and test vehicle. These averages are shown for Buckets A, B, and C in the third, fourth, and fifth columns of the table. Examination of the acceleration values in these cells shows that for each combination of gear and acceleration run, the average acceleration for Buckets B and C are always higher than for Bucket A, and the average accelerations of B and C are similar to each other. This is the same result that was seen in the previous plots of acceleration. The acceleration values that tend to be lower are shown in bold in the table. In columns 6, 7, and 8 of the table, we show the average values for each gear obtained by averaging the accelerations for each run for each gear. Again, these averages show that Buckets B and C had higher accelerations in all the gears and Bucket A had lower accelerations in all the gears. In addition, these values also show that the acceleration of the vehicle is higher in lower gears as we would expect. In the next two columns, we average the acceleration values for each gear for those vehicles that have high acceleration performance; we do the same for those vehicles that have low acceleration performance.

Table D.36 Quantitative Analysis of In-Gear Acceleration Performance for Bucket Trucks

		Acceleration (mph/s)								
		Run Average			Gear Average			Average for Vehicles with Similar Performance		Performance Change for High to Low
Gear	Run	A	B	C	A	B	C	High (B,C)	Low (A)	(%)
2	Acceleration 1	**2.28**	2.75	2.50						
	Acceleration 2	**2.00**	2.00	NM	**2.14**	2.38	2.50	2.44	**2.14**	-12%
3	Acceleration 1	**1.64**	2.00	1.83						
	Acceleration 2	**1.25**	1.71	1.71	**1.45**	1.86	1.77	1.81	**1.45**	-20%
4	Acceleration 1	**1.16**	1.63	1.43						
	Acceleration 2	**1.05**	1.22	1.14						
	Acceleration 3	**0.75**	1.07	1.00	**0.99**	1.31	1.19	1.25	**0.99**	-21%
5	Acceleration 1	**0.52**	NM	0.60						
	Acceleration 2	**0.25**	0.44	0.39						
	Acceleration 3	**0.29**	0.65	0.45	**0.35**	0.55	0.48	0.51	**0.35**	-31%
6	Acceleration 3	**0.17**	NM	0.15	**0.17**	NM	0.15	0.15	**0.17**	13%

Finally, we use the two values in those columns to determine the performance change in acceleration when the high performing vehicles are compared to the low performing vehicles. Therefore, in the case of the bucket trucks, the average performance loss for acceleration for bucket trucks is observed to be 21%.

While the bucket trucks were driving on their route, they stopped and performed a work activity test. This test involved putting out the stabilizing feet on the truck and raising the bucket on its arm and moving it around in a circle. Examination of the datalogger data clearly revealed the periods during which this work activity test was made. We examined the engine RPM and engine load for the tests during all of the bucket truck tests. As an example, Figures D.2.17 and D.2.18 show engine load and engine RPM for Bucket A while it was being tested by Driver B2. Engine loads moved between 15 and 40% and engine RPM moved from idle to about 2300 rpm. Figure D.2.19 shows a plot of engine load versus engine RPM for all of the bucket truck runs recorded by the datalogger. This figure shows that engine RPM did not exceed 2700 rpm and engine load during the tests rarely exceeded 50%. Since the engine load was low to moderate during these work activity tests, we expect that PuriNOx would be able to operate the bucket of the bucket truck with no problem.

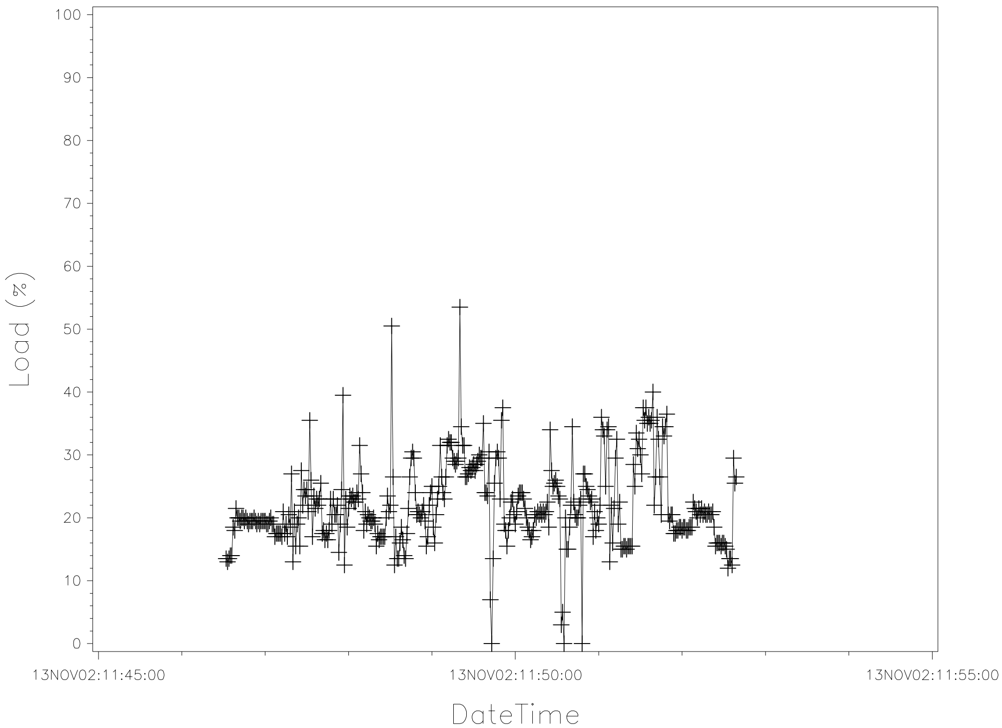


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Figure D.2.17 Sample engine load during bucket truck work activity

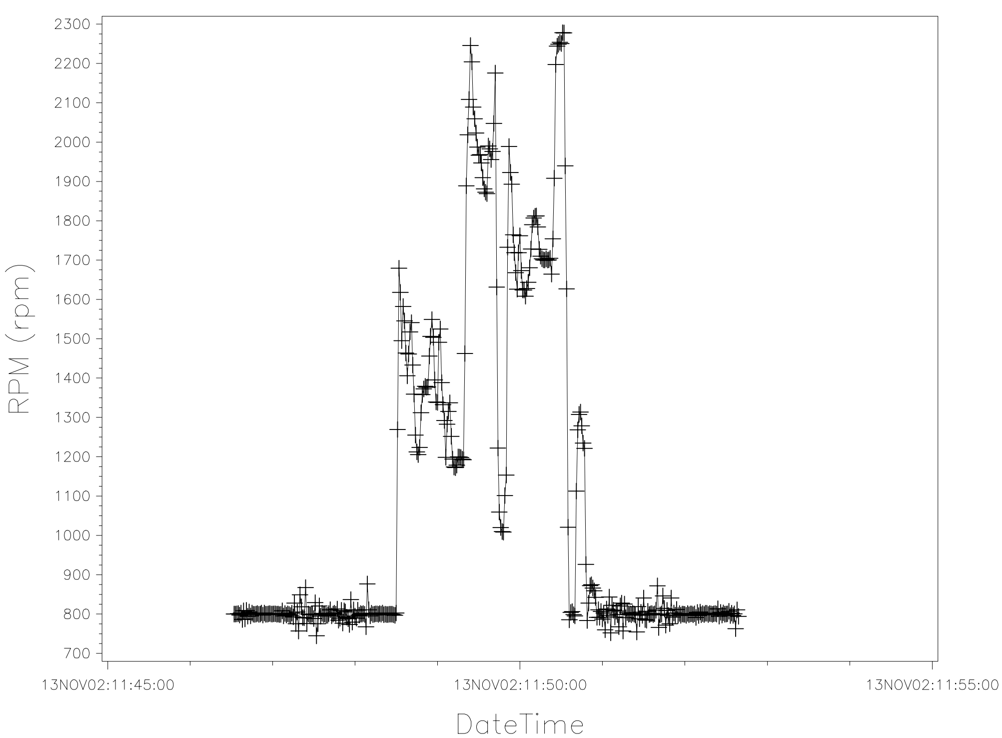

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Figure D.2.18 Sample engine speed during bucket truck work activity

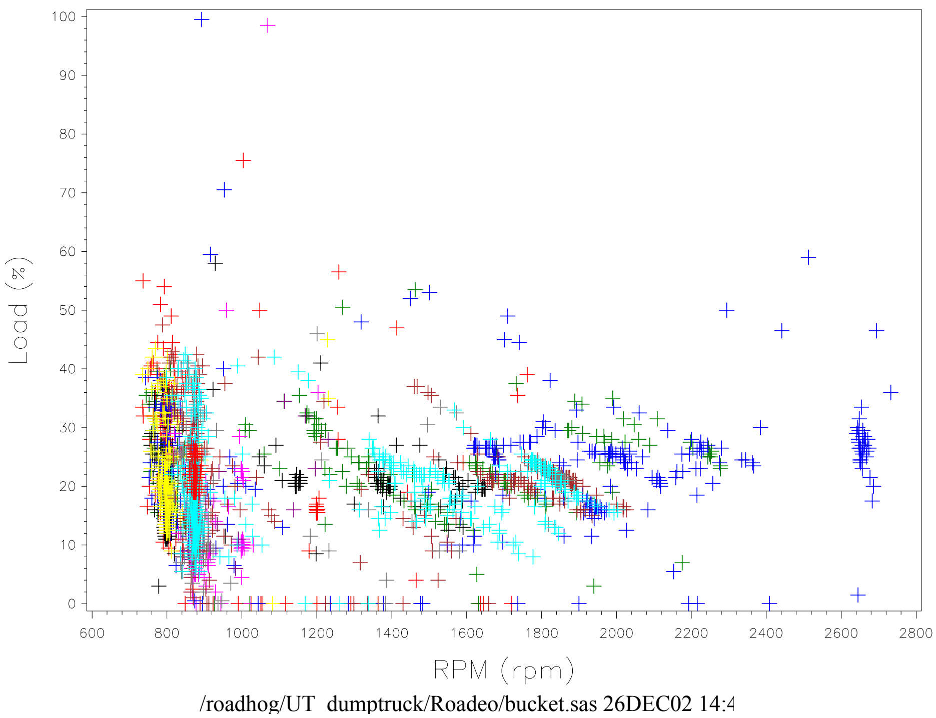

Figure D.2.19 Engine operating regime for all bucket truck work activity tests

Quantitative Results for Telescoping Boom Excavators - The telescoping boom excavators were driven on the same route as the bucket trucks. The vehicles are described in Section D.2.A. The analysis of the speed and acceleration performance of the three Gradalls must be somewhat different from the analysis of the speed and acceleration of the vehicles discussed so far because the Gradall engine computer did not provide data for vehicle speed. Because vehicle speed was not available for our analysis, we needed to adapt the RPM information for use as a surrogate for vehicle speed. The top speed of the Gradall XL3100 in each of its gears is given in Table D.37. From an analysis of the bucket truck distances and the Gradall RPMs, we determined that these gear top speeds correspond to an engine speed of 2,200 rpm using the standard size tires for the vehicle. In many cases, it is possible to observe places in the RPM data where the Gradall was being shifted. Since we surmised that the Gradall would be in eighth gear during the high speed cruises on Highway 6 and Highway 290, it is conceivable that the gears for all of the driving in each of the fifteen Gradall test runs could be determined. However, for the purposes of this analysis, we chose to assign gears only to those portions of the runs that we chose to analyze.

Table D.37 Top Speeds of Forward Gears for Gradall XL3100

Gear	Top Speed (mph)
Lo	3.1
1	5.2
2	7.4
3	10.2
4	14.0
5	20.0
6	28.3
7	39.0
8	53.4

Our initial examination of the Gradall data indicated that in most cases, the Gradall was driven during cruises with the accelerator pedal position at 100%. This presented an opportunity for us to examine the different performance of the three vehicles under the same operating conditions, that is, with the accelerator position all the way down and on the same portion of the route. To determine where the vehicles were in the same location, we calculated traces of speed versus distance for the first cruise for each of the fifteen runs. This was the cruise that extended from the town of Hempstead north on Highway 6.

Figures D.2.20, D.2.21, and D.2.22 show these speed traces for Gradalls A, B, and C. On each figure are the five traces for the five drivers operating the vehicle. Each of the five traces on each plot has been aligned so that the features of the traces line up with each other. The trace features correspond to road grade changes. In almost all cases for these fifteen runs, the drivers used 100% accelerator pedal positions. Consequently, when we see a large downward excursion in speed, it means the vehicle is going up a grade and slowing down. When we see large upward excursions of the speed traces, it means the vehicle is going down a grade and speeding up. In some of these down hill events, the percent load on the engine drops from 100% since gravity is reducing the load on the engine.

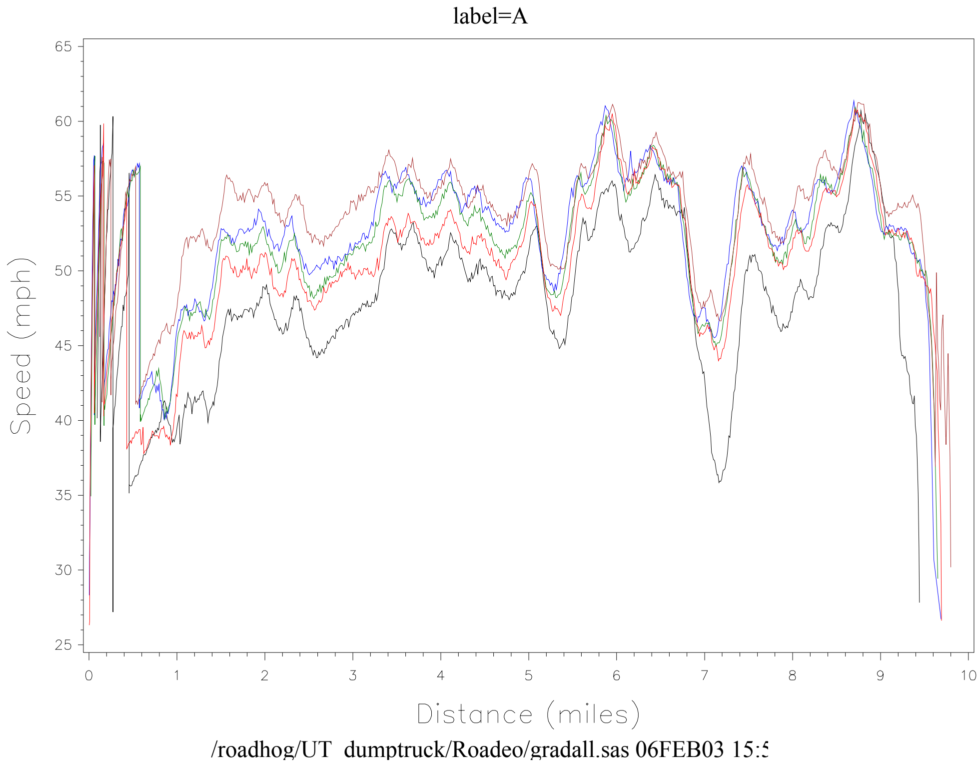

Figure D.2.20 Vehicle speed trace for Cruise 1 of Gradall A

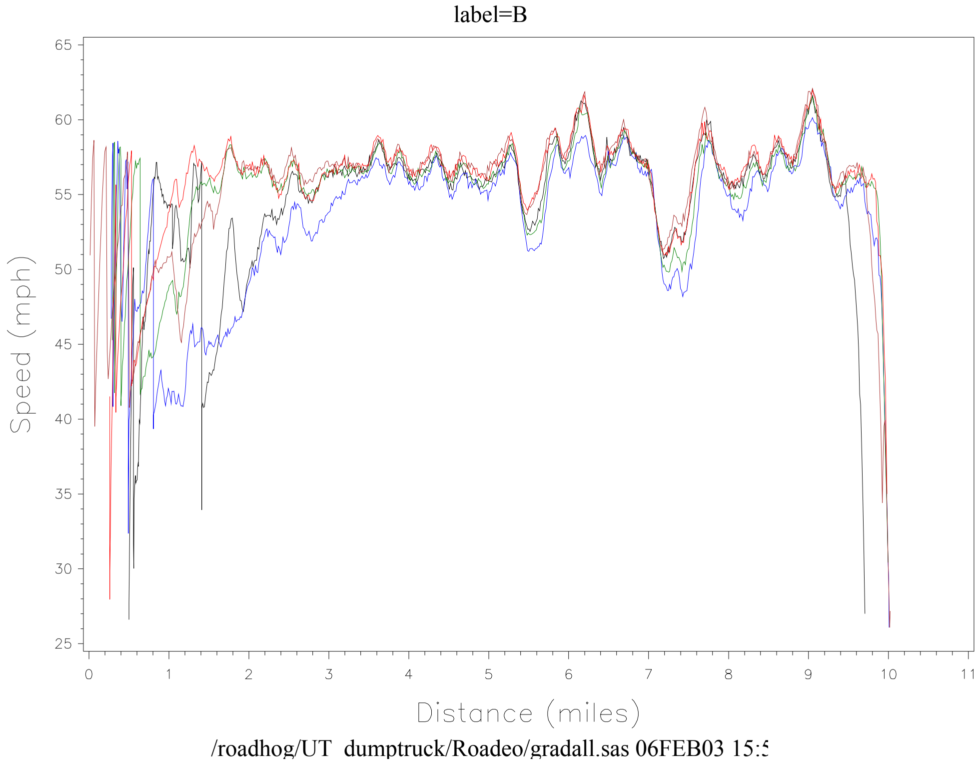

Figure D.2.21 Vehicle speed trace for Cruise 1 of Gradall B

A comparison of the three figures shows that the five traces for Gradall B and the five traces for Gradall C are much closer to each other than are the five traces for Gradall A. In addition, the traces for Gradall A seem to be somewhat lower in speed than the traces for Gradalls B and C, which seem to have approximately the same speed. This is seen more clearly by averaging each of the five traces for each of the three Gradalls. An overlay of the three average traces is shown in Figure D.2.23. This figure clearly shows that the top two curves which are for Gradalls B and C are close to each other and somewhat higher than the curve for Gradall A. When the three Gradalls go down hills, as they do at 6.2 and 9.1 miles, the difference in the speeds of the three Gradalls is small since the engine loads are all significantly less than 100%. However, at other times when the Gradalls are cruising on relatively level roads or going up hills, the Gradalls B and C go approximately 8% faster than Gradall A.

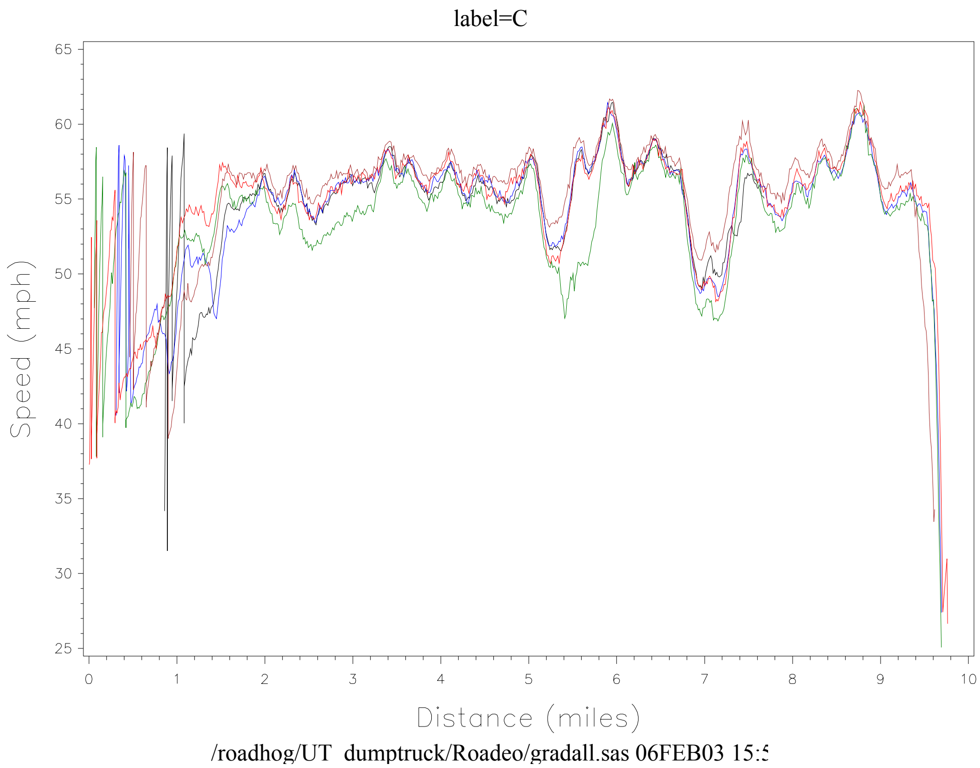

Figure D.2.22 Vehicle speed trace for Cruise 1 of Gradall C

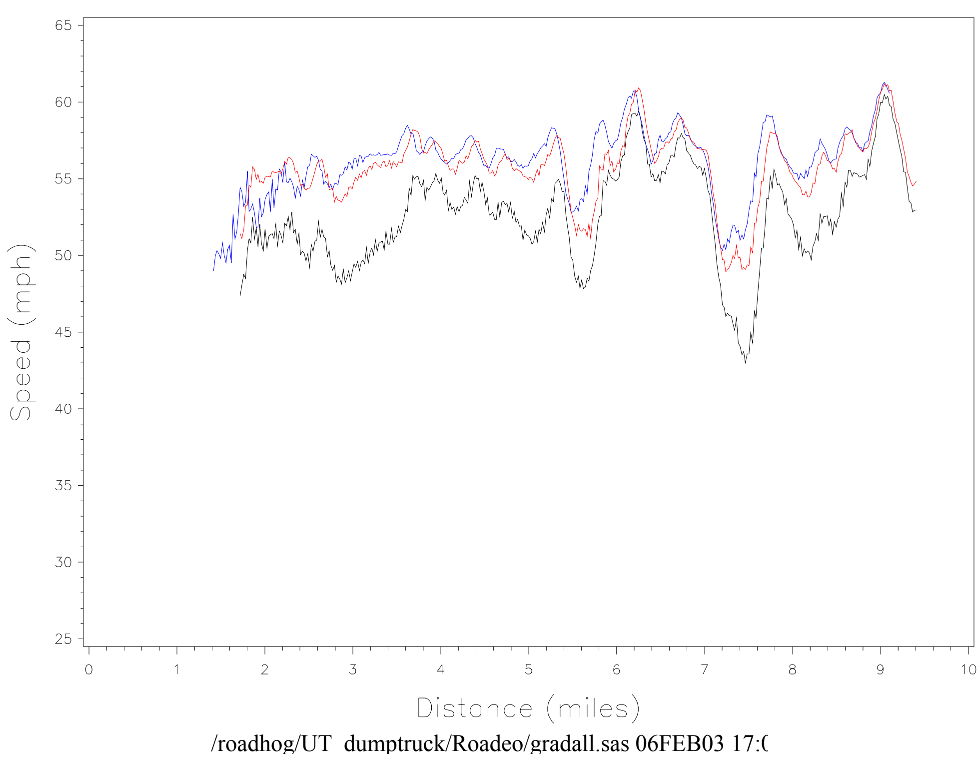

Figure D.2.23 Average speed traces for Cruise 1 for Gradalls A, B, and C

Because the Gradall XL3100 may be the most underpowered TxDOT vehicle that drives on the road and because it is a major user of diesel fuel in TxDOT, evaluation of its acceleration performance for the different fuels is important. Since the Gradall engine computer did not provide vehicle speed, we again had to use the logged RPM values to calculate relative vehicle speed. Examination of the datasets of the bucket trucks, which followed the same route as the Gradalls, indicated that the acceleration immediately following the Gradall's work activity tests would be a clean acceleration that could be used to evaluate fuel differences. This acceleration began where the Gradall accelerates from the crossover onto Highway 290 going east. Following the acceleration, the Gradalls cruises for several minutes at highway speed.

Examination of the Gradall data during this acceleration revealed that with the help of the RPM, accelerator pedal position, and engine load variables, it was easy to distinguish the shift points for the Gradall gears 5, 6, 7, and 8, the top four gears of the Gradall. We assumed that the cruise at top speed on Highway 290 going east would be made in eighth gear. With this assumption about Gear 8 and knowledge of the preceding shifts, we could easily determine the RPMs during the acceleration for Gears, 5, 6, 7, and 8. By using the top speeds of Table D.37 at 2200 rpm, the vehicle speeds during the acceleration runs were calculated.

Except during the brief periods of transmission shifting, the entire cruise going east on Highway 290 including the initial acceleration was made with the transmission in gear. Therefore, during the cruise the cumulative engine revolutions are proportional to the distance that the Gradall traveled down Highway 290 as long as all revolutions are expressed on a Gear 8 basis. Just as we did for the speed traces for Cruise 1 in Figures D.2.20, 21, and 22, we aligned the speed versus distance traces for the fifteen different Gradall test runs in Cruise 4 on the basis of the shape of the trace, which is an indication of road grade.

Finally, we examined the acceleration portion of the trace near its beginning where the Gradalls are all accelerating onto Highway 290. These overlaying traces are shown in Figure D.2.24. Eleven of the fifteen runs are shown on the figure. The runs for Drivers G1 and G4 on Gradall A were eliminated because the drivers down shifted from eighth into seventh gear in the vicinity of 0.75 miles. The runs for Driver G4 on Gradalls B and C were eliminated because the Gradall had considerable periods of part throttle in seventh and eighth gear. All of the eleven runs shown in the figure were operated with 100% accelerator pedal position and 100% engine load during the periods shown except while shifting.

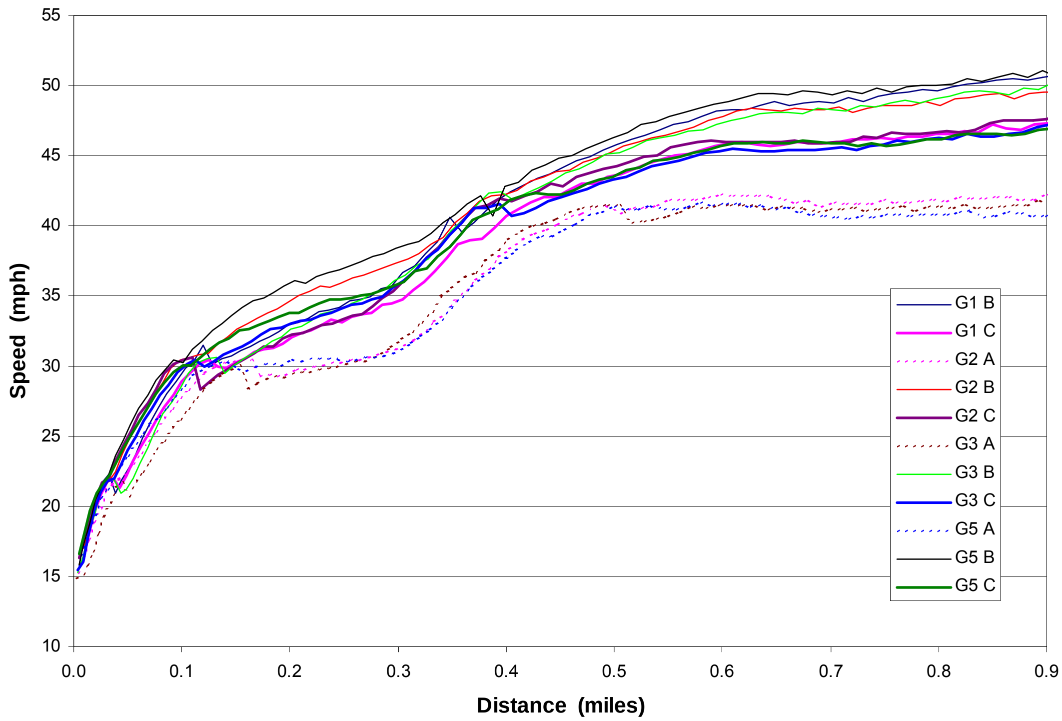

Figure D.2.24 Gradall Acceleration 4

The figure shows data only for acceleration while the Gradall was in Gears 5, 6, 7, and 8. Assignment of lower gears was not always possible for all runs and so lower gears were eliminated from consideration. The figure shows that for all of the eleven runs, the Gear 5 to Gear 6 shift point, the Gear 6 to Gear 7 shift point, and the Gear 7 to Gear 8 shift point occurred at approximately 22, 30, and 41 mph, respectively.

The figure shows that the runs made by different drivers on the same vehicle produced acceleration curves that were quite repeatable. The bottom curves are shown with dashed lines and are for Gradall A. The top curves with thin solid lines are for Gradall B, and the middle curves with solid thicker lines are for Gradall C. In general, the entire acceleration curve for the three vehicles indicates that Gradalls B and C are somewhat similar with Gradall B having better acceleration performance. Far below B and C in performance is Gradall A. The figure shows that after Gradalls B and C shift to eighth gear at 41 mph, they accelerate and continue accelerating all the way to the right edge of the plot. On the other hand, when Gradall A shifts from Gear 7 at 41 mph it does not accelerate in spite of the fact that the accelerator pedal position is at 100% and the engine is at full load. Keep in mind that all of these runs are on the same stretch of highway since the traces have been aligned for plotting purposes. It was during the Gear 8 portion of Gradall A driving that Drivers G1 and G4 down-shifted from Gear 8 back into Gear 7. We presume this was because the drivers perceived that the engine was not providing enough power to accelerate the vehicle to their satisfaction.

We used these speed traces as a function of time to calculate the relative accelerations of the Gradalls in Gears 5, 6, 7, and 8. Table D.38 provides the results of that analysis. Just as we have seen in the previous figure, the table indicates that the accelerations for B and C are similar and substantially larger than the accelerations for Gradall A. The table indicates that for this single acceleration run at this particular location on Highway 290, Vehicle A accelerated between 22% and 32% slower than Vehicles B and C. The acceleration in Gear 8 shows an even larger loss, but we expect that this operation was on a slight uphill portion of the highway.

Table D.38 Quantitative Analysis of In-Gear Acceleration Performance of Gradalls

		Relative Acceleration (mph/s)					
		Run Average			Average for Vehicles with Similar Performance		Performance Change for High to Low
Gear	**Run**	**A**	**B**	**C**	**High (B,C)**	**Low (A)**	**(%)**
5	Acceleration 4	**0.99**	1.26	1.25	1.25	**.99**	-23%
6	Acceleration 4	**0.60**	0.92	0.85	0.88	**.60**	-32%
7	Acceleration 4	**0.34**	0.45	0.41	0.43	**.34**	-22%
8	Acceleration 4	**0.02**	0.24	0.15	0.20	**.02**	-88%

The speed versus distance traces for the cruise portion of Cruise 4 is shown in Figure D.2.25. The figure shows that Gradall B was able to consistently maintain cruise speeds from 10 to 15% faster than Gradall A. In addition, Gradall A was not always able to maintain a minimum speed of 45 mph.

Subsequent to this analysis, we learned that Gradall A was fueled with PuriNOx. Therefore, the performance losses for acceleration for Gradalls shown in Table D.38 are representative of PuriNOx effects.

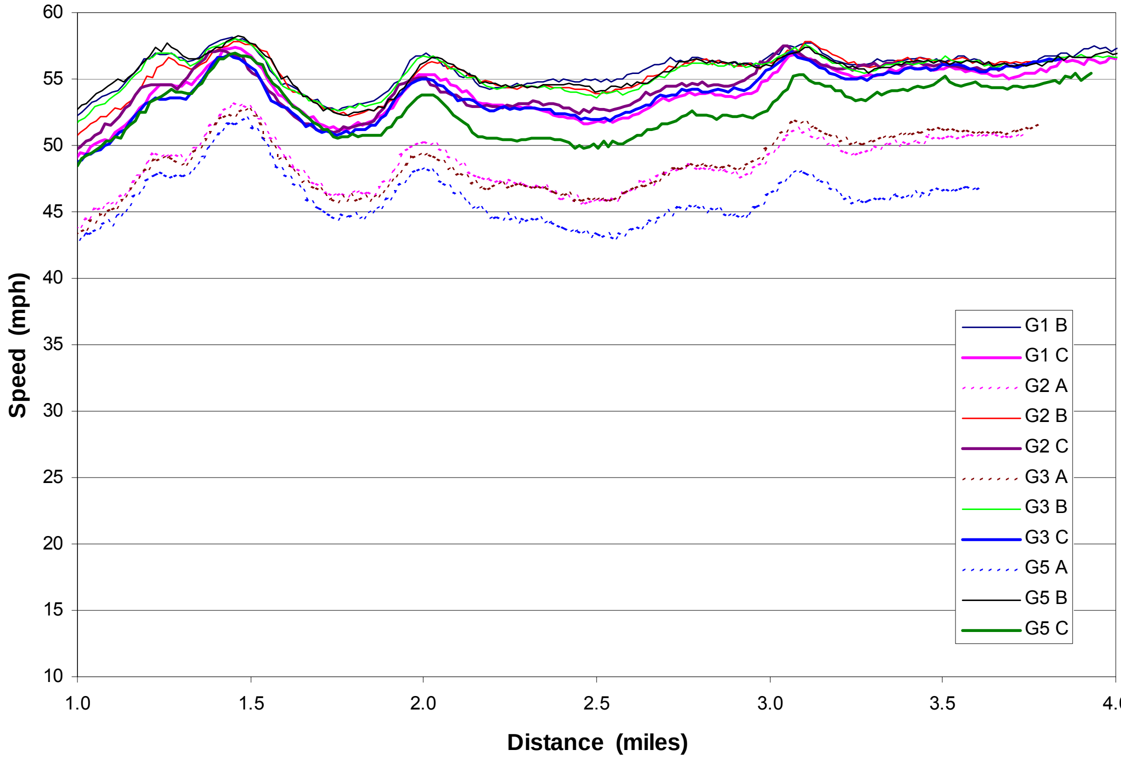

Figure D.2.25 Gradall speed during Cruise 4

Just as for bucket trucks, Gradalls also performed a work activity test while on their route. The test involved excavating soil from the roadside and filling a dump truck. The period in the datalogger dataset for each test run that this work activity took place was clearly observable. The work activity was characterized by an engine RPM between 1700 and 1900 RPM and an engine load that fluctuated rapidly from about 10% to approximately 90% load.

In our analysis of the data, we found no consistent relationship between the average engine RPM during the work activity test and the identity of the Gradall. The engine RPM seemed to be more closely associated with the vehicle driver. When we examined the engine load, as a function of the identity of the Gradall, we found that Gradall A tended to have a higher average load and higher peak loads than Gradall B. The engine of Gradall B also tended to have higher loads than Gradall C. This trend is demonstrated by the sample comparison for Driver G3 on the three Gradalls as shown in Figure D.2.26.

When we use the data such as that in Figure D.2.26 to consider how the Gradall will respond to the PuriNOx fuel, we need to remember that the load as measured by the engine computer and recorded by the datalogger is an inferred load and not a measured load. The engine computer does not know that the fuel being used contains 20% water. It infers the percent load based on sensors on the engine such as rack position and engine RPM. We would expect that PuriNOx would produce higher inferred engine load values since rack position, for example, would be operating at higher fuel injection rate positions. Accordingly, the higher logged engine loads on Gradall A in comparison with those of Gradalls B and C are consistent with PuriNOx being used in A but not B or C.

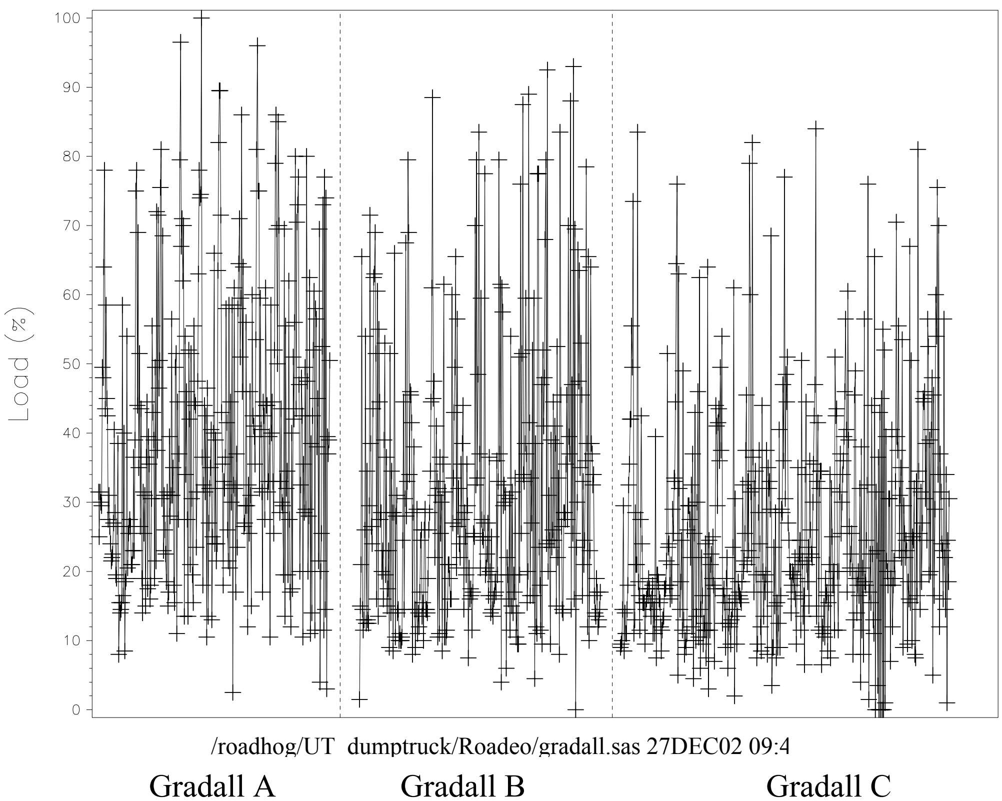

Figure D.2.26 Sample comparison of engine load during Gradall work activity for Driver G3

Our statistical analysis of the Gradall work activity test data indicated that there were significant differences in the loads that the different vehicles were subjected to during the fifteen test runs. We calculated the inferred torque by multiplying the percent load recorded by the datalogger with the torque curve of the engine when using No. 2 diesel fuel (see Figure C.2.1). We performed regression analyses on the individual one-second values of the inferred torque, on the average inferred torque for each of the fifteen work activity test runs, and on the 95th percentile value of the inferred torque for each of the fifteen work activity test runs. The results for each of these regressions were consistent. Gradall A tended to have the highest values of inferred torque and Gradall C tended to have the lowest values of inferred torque. The difference between the inferred torques of A and C was statistically significant. However, the differences between A and B or between B and C were not sufficiently different to be statistically significant. In addition, the statistical analysis found that there were statistically significant differences among the aggressiveness of the drivers when they were performing the work activity test. Driver G4 produced the highest average inferred torques and Driver G2 produced the lowest average inferred torques. The results of the statistical analyses on the 95th percentile of the inferred torque are demonstrated graphically in Figure D.2.27.

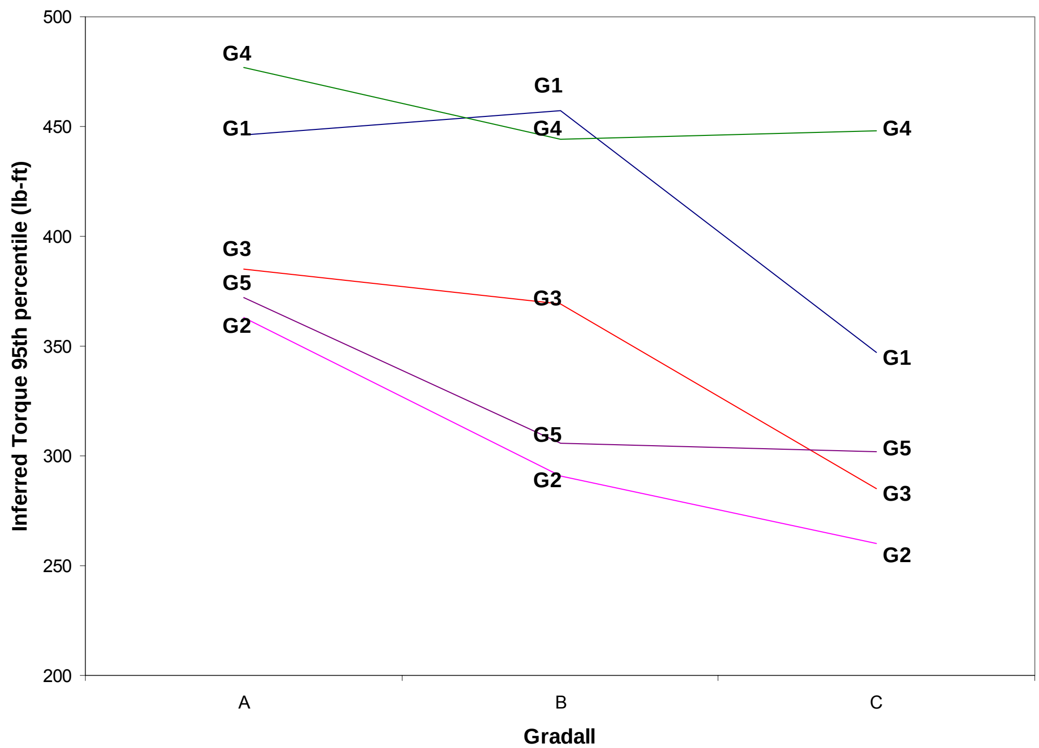

Figure D.2.27 95 percentile inferred torque for the work activity tests

Occasionally, drivers would challenge the vehicle so heavily during the work activity test that the datalogger would record 100% engine load for an observation. On Gradall A, this occurred during 8 seconds of G4's operation and during 1 second of G3's operation. It occurred on Gradall B for 3 seconds of G1's operation and for 3 seconds of G4's operation. It occurred for only 1 second of G4's operation on Gradall C. Each of the work activity tests lasted approximately 300 seconds.

These work activity test results indicate that overall the Gradalls can perform their work activities for almost all work conditions even when using PuriNOx. Only occasionally, for a second here and there, will the torque available from the engine be insufficient to meet the demands of the operator.

Quantitative Results for Wheeled Loaders - Three wheeled loaders were used to test fuel performance in the Roadeo. The vehicles are described in detail in Section D.2.A. Each loader was instrumented with a datalogger to record second-by-second speed and a separate datalogger to record second-by-second engine RPM. A magnetic induction pickup coil sensed the speed. Magnets were evenly spaced around the drive shaft to the drive wheels and fastened with a nylon tie wrap. The engine speed was sensed in a similar manner by a single magnet epoxied to the idler pulley of the engine. The speed datalogger was calibrated by driving the loader over a measured distance while the datalogger counted pulses from the magnets. The RPM datalogger was calibrated by counting magnet pulses for one minute with the engine operating at idle. A photo-tachometer was used to measure the idle speed of the engine for the calibration.

The test activity required operators to load dump trucks with material from a single large pile. The dump truck capacity was 6 yards and the loader bucket capacity was 1.5 yards. Typically, four buckets were used to fill a dump truck. The dump trucks were filled for approximately 30 minutes for each loader/driver combination. Project staff observers watched each driver perform the tests and counted the number of dump trucks that were filled during the 30 minute test period.

There were several problems that arose in testing the loaders. First, the magnet used for the RPM datalogger fell off of Loaders B and C before testing began so that no RPM data was recorded for these vehicles. Second, Driver L4's test of Loader B was interrupted for refueling.

The analysis of the loader datalogger data focused on the speed data and the number of loaded dump trucks recorded by the observers. Table D.39 shows the number of dump trucks loaded for each of the loader and driver combinations as well as averages by driver and by loader. The small number 1, 2, or 3 in the upper right corner of each cell in the table gives the order that the driver drove the three loaders. For example, Driver L3 drove Loader C, A, and then B.

Table D.39 Number of Loaded Dump Trucks for Combinations of Loaders and Drivers

		Loader			
		A	**B**	**C**	**Average**
Driver	**L1**	3.5 [1]	4.5 [2]	5 [3]	4.3
	L2	3.8 [3]	4.8 [1]	5 [2]	4.2
	L3	6 [2]	6.5 [3]	6 [1]	6.2
	L4	3 [1]	4 [3]	5 [2]	4
	L5	3.5 [2]	3 [1]	4 [3]	3.5
	Average	4.0	4.6	5	

In an attempt to distinguish the different abilities of the loader test vehicles to load dump trucks, we performed a statistical analysis of the number of dump trucks loaded in 30 minutes. An analysis of variance for the fifteen values in the table were described in terms of test vehicle, operator, and the order in which operators tested the vehicles. The analysis found that the order of vehicle testing did not have a significant effect on the number of dump trucks loaded. The analysis found that there was a significant difference among the operators at loading dump trucks. In particular, Driver L3 was noticeably faster than the other drivers. With respect to the loaders themselves, the analysis indicated that on the average, Loader B loaded was about 0.8 of a load slower than Loader C and that Loader A loaded about 1.5 loads slower than Loader C. The statistical difference between the number of dump trucks loaded between A and C was large, but the differences between A and B and between B and C were just barely statistically significant.

Subsequent to this analysis of the data, we found out that Loaders A and B were fueled with PuriNOx. Based on our statistical analysis of the number of dump trucks loaded in 30 minutes and after correcting for driver and order effects, the performance loss for the PuriNOx fuel is about 20%.

Most of the speed data from the loaders was too random to determine how much time a driver spent completely filling a dump truck or filling and emptying a bucket. Figure D.2.28 plots speed versus time for Driver L2 on Loader A and illustrates the difficulty of determining the driver's loading pattern. Unlike the other drivers, Driver L3 appears to always have idled between each full dump truck, as shown in Figure D.2.29 for Loader C. Possibly, the other drivers were tidying the pile of material between dump trucks rather than idling.

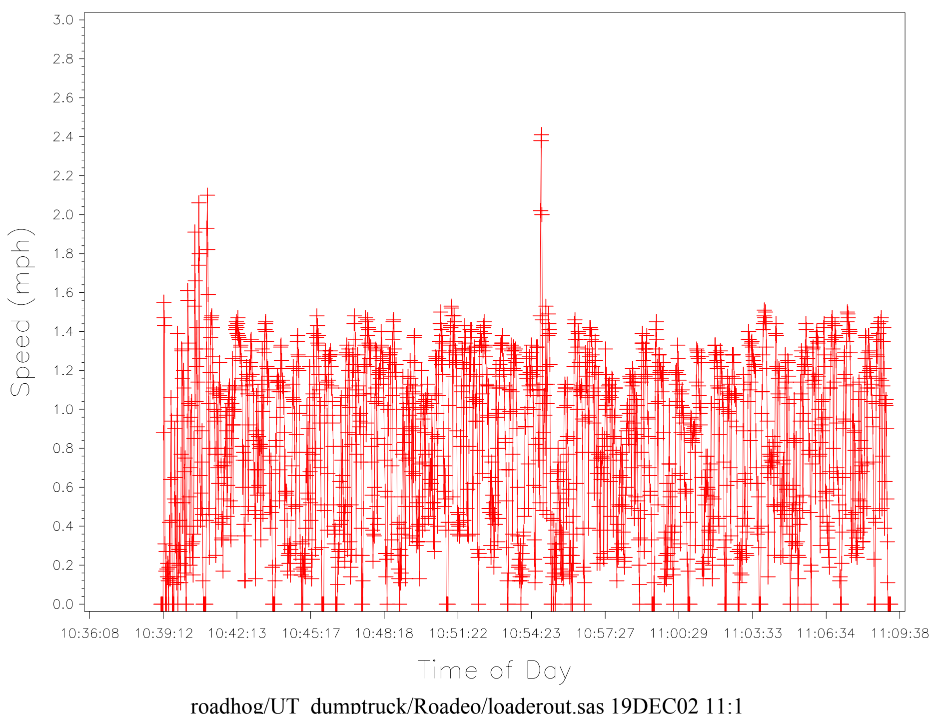

Figure D.2.28 Vehicle speed trace for Driver L2 on Loader A

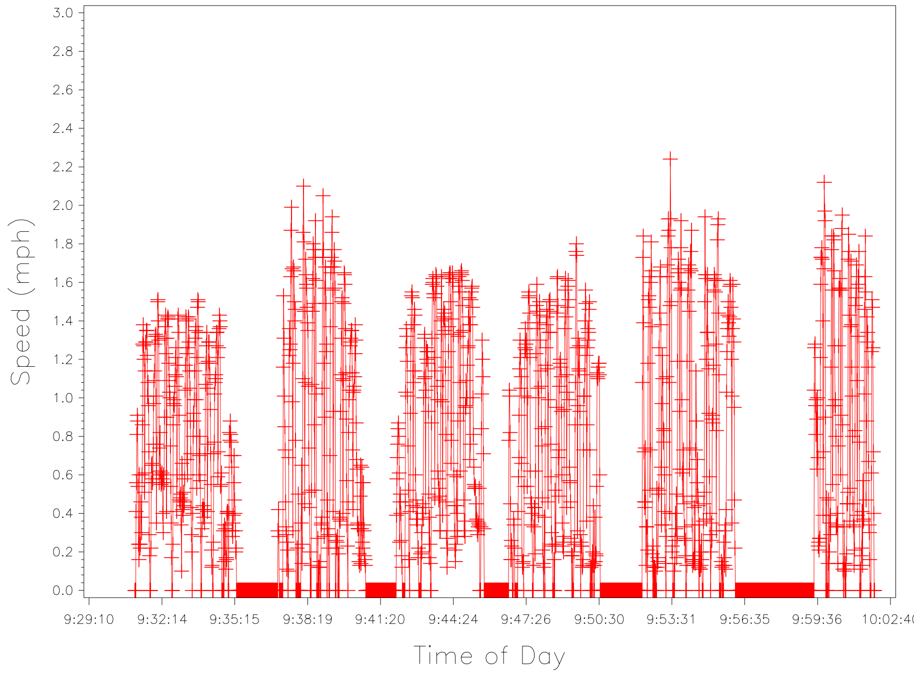

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Figure D.2.29 Vehicle speed trace for Driver L3 on Loader C

In the tests with Driver L3, we were able to determine the length of time spent to fill each dump truck. An analysis of variance on these times shows that the difference between loaders is statistically insignificant. The observer for Driver L3 recorded that in all cases except one, four buckets filled a dump truck, but the data does not reveal start and end times for loading and emptying a bucket. For the other loaders we can only estimate the average time each driver spent loading a dump truck by dividing the total test duration by the number of full dump trucks recorded. Table D.40 shows these averages. Table D.41 gives the total distance traveled by each driver on a particular loader to give an idea of how much work the loader and driver could do in 30 minutes.

Table D.40 Average Time (seconds) to Load a Dump Truck for Combinations of Loaders and Drivers

		Loader			
		A	**B**	**C**	**Average**
Driver	**L1**	533	418	377	442
	L2	302	378	491	390
	L3	294	269	309	291
	L4	597	950	355	634
	L5	438	603	498	513
	Average	433	524	406	

Table D.41 Total Distance Traveled (miles) for Combinations of Loaders and Drivers

		Loader			
		A	**B**	**C**	**Average**
Driver	**L1**	0.34 [1]	0.38 [2]	0.31 [3]	0.34
	L2	0.41 [3]	0.40 [1]	0.42 [2]	0.41
	L3	0.37 [2]	0.46 [3]	0.28 [1]	0.37
	L4	0.47 [1]	0.84 [3]	0.54 [2]	0.62
	L5	0.35 [2]	0.43 [1]	0.32 [3]	0.37
	Average	0.39	0.50	0.37	

Quantitative Results for Forklifts - Three Caterpillar forklifts were used to test fuel performance in the Roadeo. The vehicles are described in detail in Section D.2.A. Each forklift was instrumented with a datalogger to record second-by-second speed and a separate datalogger to record second-by-second engine RPM. A magnetic induction pickup coil mounted about 1 cm from the left front wheel rim sensed the speed. Six magnets were evenly spaced around the rim and were epoxied to it. The speed was sensed in a similar manner by a single magnet epoxied to the idler pulley of the engine. The speed datalogger was calibrated by driving the forklift over a measured distance while the datalogger counted pulses from the magnets. The RPM datalogger was calibrated by counting magnet pulses for one minute with the engine operating at idle. A photo-tachometer was used to measure the idle speed of the engine for the calibration.

The test activity required operators to move pallets back and forth a distance of 50 yards across a paved parking lot. Each pallet was loaded with 42 80-pound bags of concrete mix. Thus, each pallet weighed about 3400 pounds. During each leg of the test, a forklift performed the following maneuvers, assuming the forklift starts with a pallet already loaded:

- Set down the pallet in the designated area on the pavement,
- Back up to get ready to approach the adjacent pallet,
- Move forward and pick up pallet,
- Back up and turn to face down-field, and
- Drive the 50 yards to the other end of the field.

The analysis of the forklift datalogger data focused on the speed data. The duration of each leg of the test was calculated from the second-by-second speed data. The average duration for all of the legs (about 20 legs) in each combination of forklift and operator was calculated. Table D.42 shows the average duration for each of the forklift and driver combinations. The table also shows the average duration for all legs by each driver in the right column and the average duration for all legs driven on each forklift in the bottom row. The small number 1, 2, or 3 in the upper right corner of each cell in the table gives the order that the driver drove the three forklifts. For example, Driver F3 drove forklift C, A, and then B.

Table D.42 Average Leg Duration (seconds) for Combinations of Forklifts and Drivers

		Forklift			
		A	**B**	**C**	**Average**
Driver	**F1**	38 [1]	31 [2]	30 [3]	33
	F2	41 [1]	41 [2]	39 [3]	40
	F3	34 [2]	31 [3]	39 [1]	34
	F4	38 [1]	37 [2]	37 [3]	38
	F5	42 [1]	37 [2]	38 [3]	39
	Average	38	35	36	

The uncertainty in the mean value in each cell is about ± 1 second (± 2 standard deviations of the mean). Accordingly, differences larger than 1 second between cell values are statistically significant at the 95% confidence level. Examination of the cell averages shows that many pairs of averages are statistically different. An analysis of variance of the duration of the legs showed that the effects of forklift, driver, and the forklift*driver interaction were all statistically different.

An examination of the table and a statistical analysis for the effect of the order in which each driver tested the forklift indicates that the first forklift tested tended to have a longer average duration than the last two tested. For example, for Driver F3 the average leg durations in the CAB order were 39, 34, and 31 seconds. This may be a consequence of each driver becoming acquainted with the forklift exercise as testing proceeded. Perhaps, by the time the driver got to the third forklift being tested, he had learned how to do the exercise more efficiently.

Because four of the five drivers tested the forklifts in the same order, that is, ABC, the average duration of forklift A tends to be higher than the average for forklifts B and C. The table shows that the average leg durations for Forklifts A, B, and C were 38, 35, and 36 seconds, respectively. The analysis of forklift results with test order included indicates that after correcting for the effects of test order the average leg durations for Forklifts A, B, and C are 33, 33, and 35 seconds, respectively.

Subsequent to this analysis of the data, we learned that Forklifts A and C were fueled with PuriNOx. After corrections for driver and order, the PuriNOx-fueled forklifts averaged 34 seconds per leg while the regular diesel fueled forklift averaged 33 seconds. These values are so close to each other that the effects of PuriNOx on leg duration is non-detectable as measured by the average duration of each leg of this forklift activity.

D.3. Estimated Effects of PuriNOx on Loss of Productivity

Because PuriNOx fuel contains 20% water, users can expect a loss in engine performance. In this section, we estimate how much this loss in engine performance might affect productivity. In Appendix C, the torque curves for several engines fueled with PuriNOx and fueled with regular diesel fuel were used to estimate the torque loss attributed to the use of PuriNOx. Figure C.4.1 shows that torque losses ranged from 8 to 38%, depending on the engine and the RPM. For the purposes of estimating the effect of torque loss on productivity, in this section we used a torque loss value of 20% for all engine speeds. A torque loss of 20% does not necessarily mean that there is an associated loss in job productivity of 20%. For example, if in the course of its normal operation with regular diesel fuel, an engine was never required to produce 80% of the maximum torque at a given RPM, the use of PuriNOx would be expected to be transparent from a productivity point-of-view.

Accordingly, in this section, we will estimate the size of the expected productivity loss when switching from regular diesel fuel to PuriNOx. In the subsections that follow, we estimate the size of the productivity loss for single-axle dump trucks, tandem-axle dump trucks, telescoping boom excavators, and wheeled loaders. Two factors affect the size of the productivity loss: the distribution of engine loads during normal vehicle operation and the size of the productivity loss as a function of engine loads. This first factor is obtained from analysis of the field data that was used to generate the dynamometer cycles. This second-by-second data was collected during 1 to 4 weeks of field operation. The second factor is estimated from the analysis of the Roadeo speed and acceleration data comparisons between regular diesel fuel and PuriNOx.

As it turns out, the Roadeo data can be used to estimate the effect of PuriNOx on speeds and accelerations for only those conditions when the engine load is at 100% and the accelerator pedal position is at 100% for regular diesel fuel. We assume that, for all operating conditions with engine loads less than or equal to 80%, productivity losses are zero. For the purpose of this analysis, we further assume that the productivity loss between 80% and 100% engine load is linear with engine load. In the next subsection we use the telescoping boom excavator data to demonstrate how the productivity loss is calculated. In the later subsections, losses for the other vehicles are calculated in a similar way.

D.3.A. Telescoping Boom Excavators

A datalogger was installed on a TxDOT telescoping boom excavator during normal operation for 2 weeks. The dataset contains 61,215 seconds of operating data. Overall, only 14 percent of the operating time had engine loads greater than 80%. As shown in Table D.43, the 3 classes of operation (idling, excavating, and moving) occurred almost equally. However, almost all of the periods of engine loads greater than 80% occurred during excavation. Figures D.3.1 through D.3.3 show the frequency distribution of seconds of operation categorized by RPM and engine load. Figures D.3.1 and D.3.2 show that while idling or excavating, the vehicle hardly ever uses greater than 80% engine load. On the other hand, Figure D.3.3 shows that a high proportion (45%) of moving (e.g., on road driving) used engine loads greater than 80%, especially at the high RPM.

The analysis of the effects of PuriNOx on speed and acceleration at the Roadeo indicates that Gradall cruises are 15% slower and accelerations are 25% slower when PuriNOx is used and when engine load and accelerator position are 100%. If we average the effects for acceleration and cruise, we could say that when the engine load is at 100% (on regular diesel fuel), cruising speeds and accelerations take 20% more time. We also assume that there is no effect at engine loads less than or equal to 80% and that for engine loads between 80% and 100% the extra time is linear with engine load. For example, we would expect that at 90% engine load, the loss of time would be 10%. The extra time required to perform each second of driving can be expressed as:

$$= 0, \qquad \text{for engine loads} \leq 80\%$$

$$= K \bullet \left(\frac{\%\ \text{Engine Load} - 80\%}{100\%} \right), \qquad \text{for engine loads} > 80\% \qquad \text{(D.3.1)}$$

where:

$$K = 1, \qquad \text{for telescoping boom excavators}$$

When the above relationship is applied to the 19,528 seconds of moving, it estimates that 1,550 extra seconds would be required to drive the Gradall during the data collection period. This is 2.5% of the total time, 61,215 seconds, of Gradall operation. Thus, we estimate that the switch from regular diesel fuel to PuriNOx would result in a 2.5% loss of productivity.

Table D.43 Occurrence of High Engine Loads for Telescoping Boom Excavators

Vehicle	Operating Mode	Seconds of Operation	Percent of Operating Mode at >80% Engine Load
Gradall	Idling	22,355	0.06%
	Moving	19,528	45.06%
	Excavating	19,332	0.21%

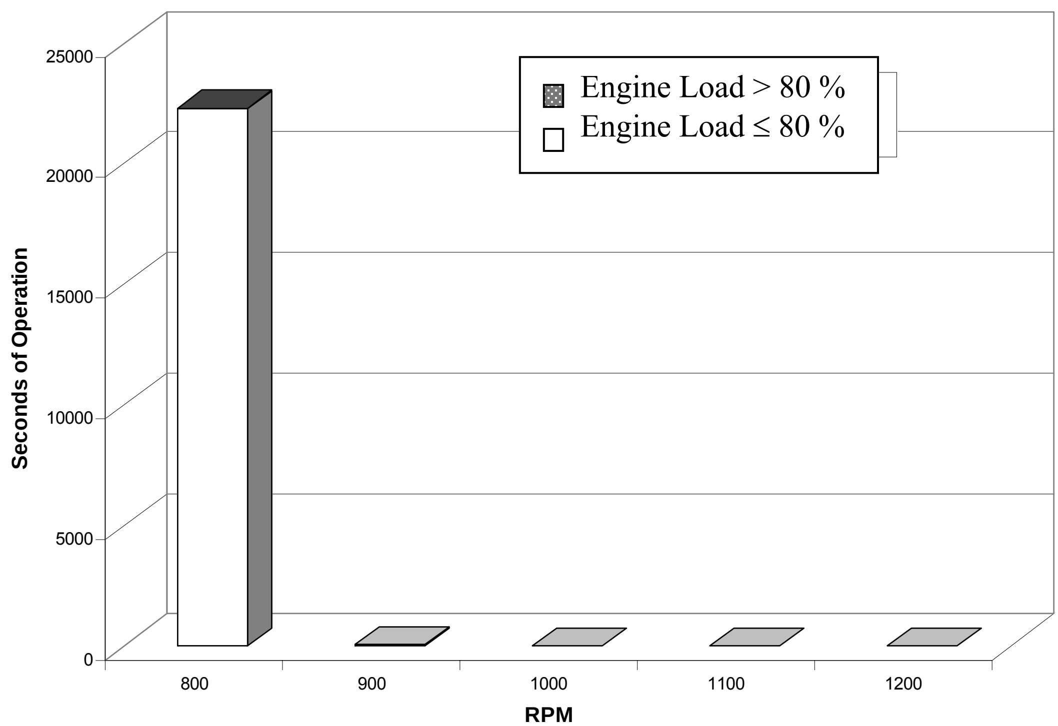

Figure D.3.1 Gradall engine loads categorized by RPM for idling

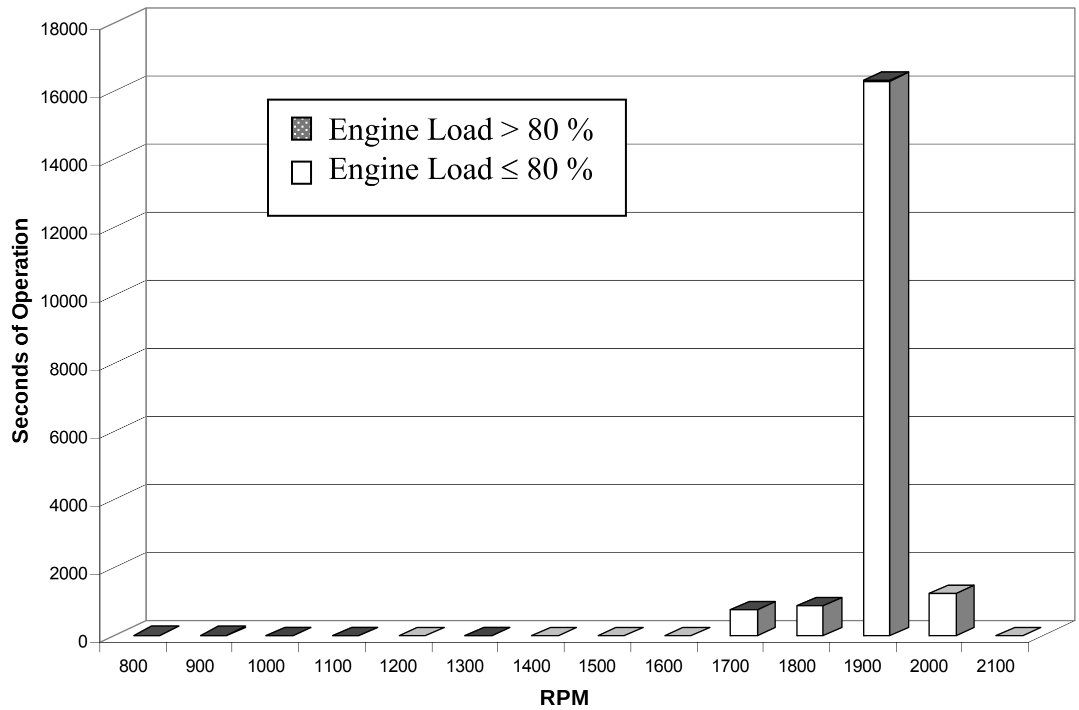

Figure D.3.2 Gradall engine loads categorized by RPM for excavating

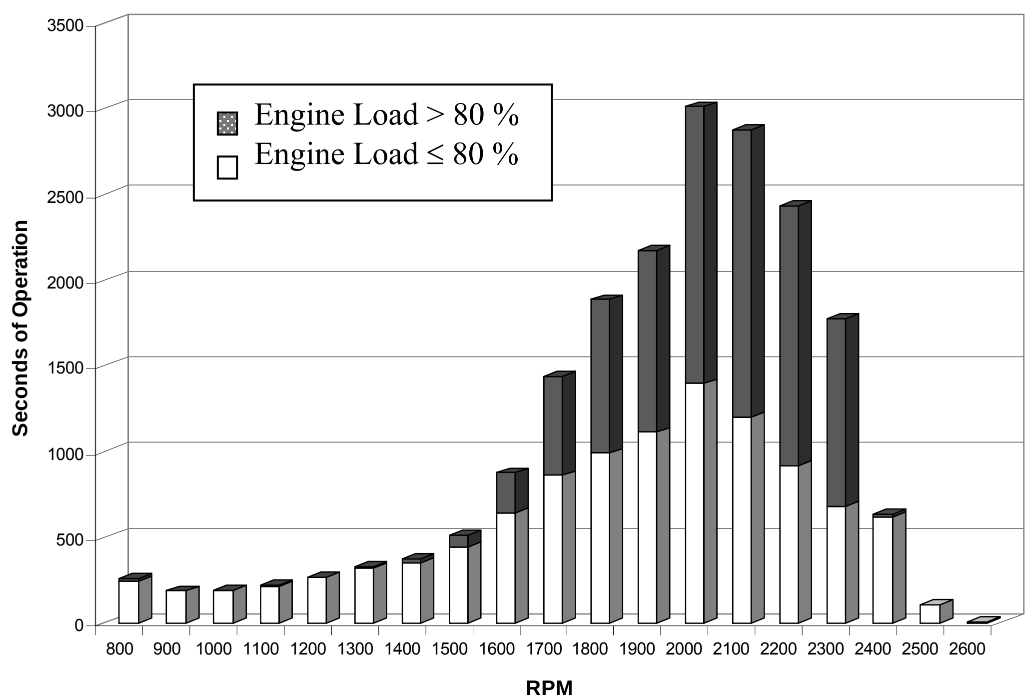

Figure D.3.3 Gradall engine loads categorized by RPM for moving

D.3.B. Single-Axle Dump Trucks

Dataloggers were installed on 2 single-axle dump trucks for a total of 3 weeks. Table D.44. shows the total seconds of operation and the percent of operation with engine loads greater than 80% for the 2 single-axle dump trucks.

Table D.44 Occurrence of High Engine Loads for Single-Axle Dump Trucks

Vehicle	Seconds of Operation	Average Speed (mph)	Percent of Operation at > 80% Engine Load
Single 3489	171,472	13.01	2.40
Single 3490	31,182	15.15	8.00

Figures D.3.4 and D.3.5 show the scatter plots of speed versus acceleration with a dot representing each second of operation. They show operation with engine loads greater than 80% with black dots. These high loads usually occur when the trucks are operating at moderate speeds with high acceleration or high speed. Tables D.45 and D.46 show the fraction of engine loads at greater than 80% in bins of speed and acceleration. They show that at higher speeds and higher accelerations the fraction of occurrences of engine loads greater than 80 percent increases substantially.

To estimate the loss in productivity for single-axle dump trucks, the Roadeo analysis indicated that the accelerations were about 20% slower with PuriNOx. In the Roadeo analysis no estimate of the effect of PuriNOx on single-axle dump truck speed was made. Nevertheless, we expect that PuriNOx will cause reduced cruising speeds whenever the engine loads are greater than 80%. We know these high engine loads occur during cruises by the presence of the black dots in Figures D.3.4 and D.3.5. For the telescoping boom excavators, where the effect of PuriNOx on speed was measured, the resulting average overall effect of PuriNOx at 100% load was a loss of performance of 20%, which is 0.8 times the acceleration effect of 25%. Next, we assume that the same factor holds for single-axle dump trucks. If the acceleration effect is 20% at 100% engine load, then we estimate that the overall effect (including acceleration and cruise effects) is 16% at 100% engine load. If 16% extra time is needed for 100% engine loads, the K factor for single-axle dump trucks for Equation D.3.1 is 0.8.

When Equation D.3.1 is applied to the second-by-second field data for the 2 TxDOT single-axle dump trucks, the estimated extra time attributed to PuriNOx would be 460 seconds for Single 3489 and 326 seconds for Single 3490. In terms of the total seconds of operation for each of these vehicles, these are 0.27% and 1.05% for an average of 0.66%. Thus, the switch to PuriNOx is estimated to cause single-axle dump trucks to use about 0.66% more time to do their jobs. The average speeds for the dump trucks, which are given in Table D.44, can be used to calculate operating total time when using regular diesel fuel. Then, the extra time for a switch to PuriNOx is calculated by multiplying that by 0.66%.

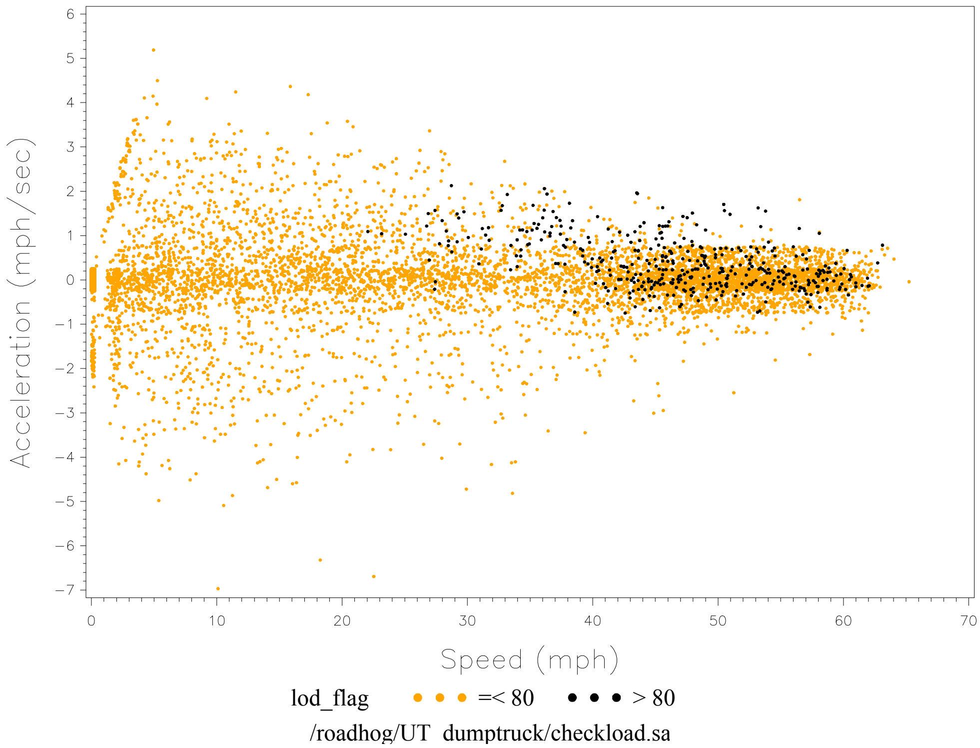

Figure D3.4 Scatter plot of vehicle speed versus acceleration for single-axle 3489

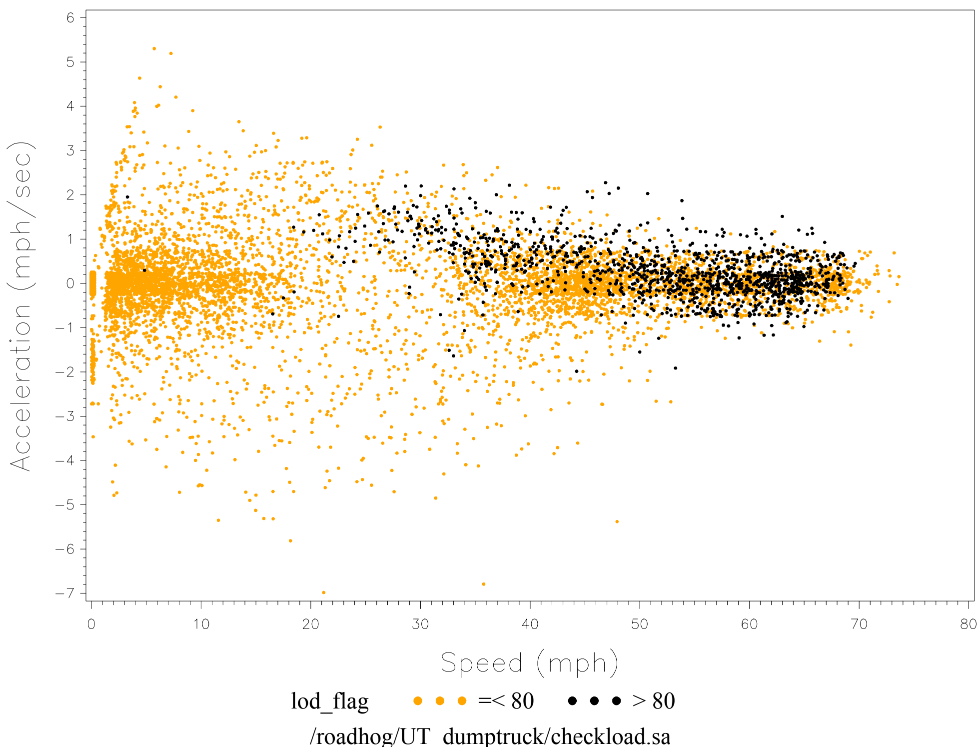

Figure D.3.5 Scatter plot of vehicle speed versus acceleration for single-axle 3490

Table D.45 Percent Distribution of Engine Loads Greater than 80 Percent Categorized by Speed and Acceleration For Single-Axle 3489

Acceleration	**Speed (mph)**														
(mph/s)	**0**	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**	**55**	**60**	**65**	**70**
6		0													
5		0													
4	0	0	0	0	0										
3	0	0	0	0	0	0	0								
2	0	0	0	0	0	0	.1	.2	.6	.3	0	0			
1	0	0	0	0	0	.1	.2	.4	.4	.4	.4	.6	.8		
0	0	0	0	0	0	0	0	0	.1	.1	0	0	.1	.1	
-1	0	0	0	0	0	0	0	0	0	0	0	0	0		
-2	0	0	0	0	0	0	0	0	0	0	0	0			
-3	0	0	0	0	0	0	0	0	0	0	0				
-4	0	0	0	0	0	0	0	0	0	0	0				
-5	0	0	0	0	0	0	0	0							
-6	0	0	0	0	0	0	0		0						
-7		0	0	0	0	0									
-8		0	0	0		0	0								

Table D.46 Percent Distribution of Engine Loads Greater than 80 Percent Categorized by Speed and Acceleration For Single-Axle 3490

Acceleration (mph/s)	**Speed (mph)**														
	0	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**	**55**	**60**	**65**	**70**
6															
5		0													
4	0	0	0	0											
3	0	0	0	0	0	0	0								
2	0	0	0	0	0	.2	.1	.3	.1	.7	.9	.9			
1	0	0	0	0	.1	.3	.5	.5	.6	.4	.6	.8	.7	.9	
0	0	0	0	0	.1	0	.2	.2	.1	.1	.3	.4	.5	.3	0
-1	0	0	0	0	0	0	0	0	0	0	.2	.4	.4	.2	0
-2	0	0	0	0	0	0	0	0	0	0	.2	.9		0	
-3	0	0	0	0	0	0	0	0	0	0	0				
-4	0	0	0	0	0	0	0	0	0	0					
-5	0	0	0	0	0	0	0		0						
-6		0	0	0		0				0					
-7			0		0			0							
-8						0									

D.3.C. Tandem-Axle Dump Trucks

Dataloggers were installed on the tandem-axle dump trucks 5577 and 3871 for a total of 4 weeks. Table D.47 shows the total seconds of operation and the percent of operation with engine loads greater than 80% for the 2 tandem-axle dump trucks.

Table D.47 Occurrence of High Engine Loads for Tandem-Axle Dump Trucks

Vehicle	Seconds of Operation	Average Speed (mph)	Percent of Operation at >80% Engine Load
Tandem 5577	268,209	17.04	3.38
Tandem 3871	238,718	15.47	2.15

Figures D.3.6 and D.3.7 show the scatter plots of speed versus acceleration for each second. As for single-axle dump trucks, the engine loads greater than 80% usually occurred when the vehicle has larger accelerations and speeds higher than 20 mph. More incidences can be seen at moderate and high speeds (30-65 mph) with high accelerations (2-3 mph/second). Tables D.48 and D.49 show the fraction of engine loads greater than 80% in bins of speed and acceleration. The results support the statement that the percentage of the engine loads greater than 80% does increase when a vehicle is driving at moderate to high speeds with a heavy acceleration.

To estimate the loss in productivity for tandem-axle dump trucks, the Roadeo analysis indicated that the accelerations were about 27% slower with PuriNOx. In the Roadeo analysis no estimate of the effect of PuriNOx on tandem-axle dump truck speed was made. Nevertheless, we expect that PuriNOx will cause reduced cruising speeds whenever the engine loads are greater than 80%. We know these high engine loads occur during cruises by the presence of the black dots in Figures D.3.6 and D.3.7. For the telescoping boom excavators, where the effect of PuriNOx on speed was measured, the resulting average overall effect of PuriNOx at 100% load was a loss of performance of 20%, which is 0.8 times the acceleration effect of 25%. Next, we assume that the same factor holds for tandem-axle dump trucks. If the acceleration effect is 27% at 100% engine load, then we estimate that the overall effect (including acceleration and cruise effects) is 22% at 100% engine load. If 22% extra time is needed for 100% engine loads, the K factor for single-axle dump trucks for Equation D.3.1 is 1.1.

When the equation is applied to the second-by-second field data for the 2 TxDOT tandem-axle dump trucks, the estimated extra time attributed to PuriNOx would be 1519 seconds for Tandem 5577 and 761 seconds for Tandem 3871. In terms of the total seconds of operation for each of these vehicles, these are 0.57% and 0.32% for an average of 0.45%. Thus, the switch to PuriNOx is estimated to cause single-axle dump trucks to use about 0.45% more time to do their jobs. The average speeds for the dump trucks, which are given in Table D.47, can be used to calculate operating total time when using regular diesel fuel. Then, the extra time for a switch to PuriNOx is calculated by multiplying that by 0.45%.

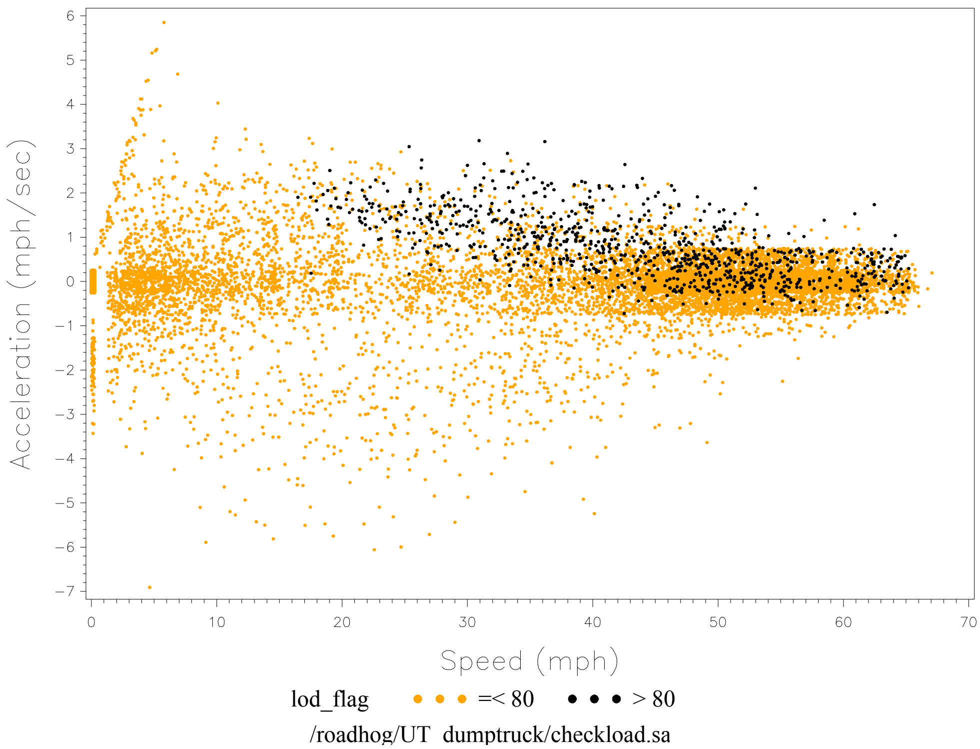

Figure D.3.6 Scatter plot of vehicle speed versus acceleration for tandem-axle 5577

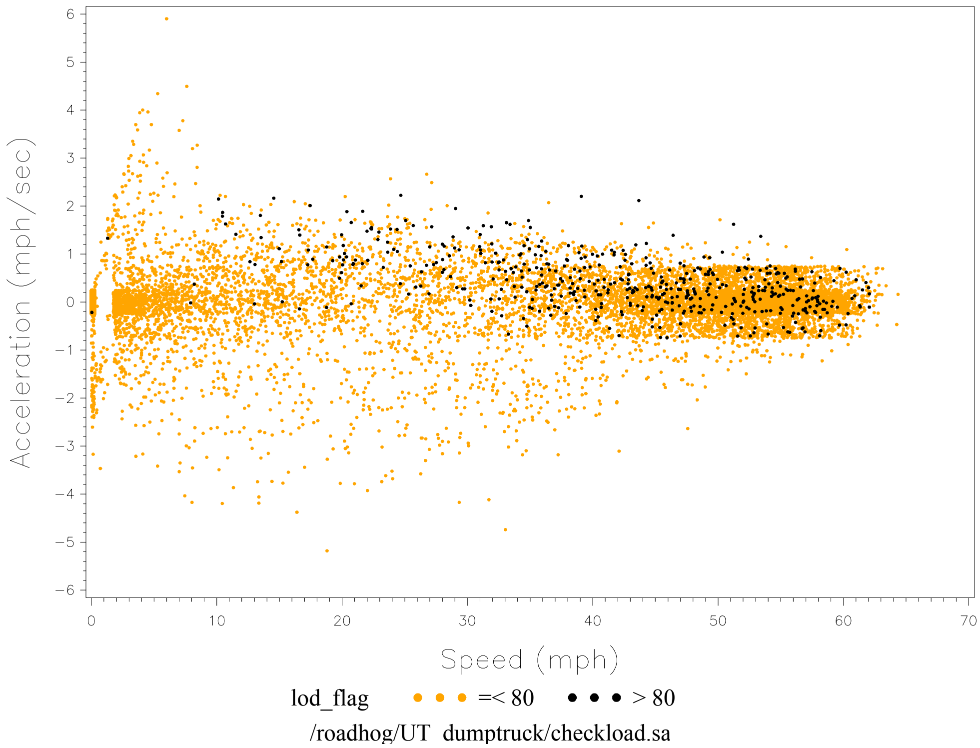

Figure D.3.7 Scatter plot of vehicle speed versus acceleration for tandem-axle 3871

Table D.48 Percent Distribution of Engine Loads Greater than 80 Percent Categorized by Speed and Acceleration For Tandem-Axle 5577

Acceleration (mph/s)	**Speed (mph)**														
	0	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**	**55**	**60**	**65**	**70**
6		0													
5		0													
4	0	0	0												
3	0	0	0	0	.1	.3	.9	.9							
2	0	0	0	.1	.4	.5	.6	.8	.8	.8	.9	.9			
1	0	0	0	0	.3	.4	.5	.5	.5	.5	.4	.6	.6	.9	
0	0	0	0	0	0	0	.1	.1	.1	0	0	0	.1	0	
-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
-2	0	0	0	0	0	0	0	0	0	0	0	0	0		
-3	0	0	0	0	0	0	0	0	0	0	0	0			
-4	0	0	0	0	0	0	0	0	0	0	0				
-5	0	0	0	0	0	0	0	0	0	0					
-6		0	0	0	0	0	0	0							
-7			0	0		0									
-8				0											

Table D.49 Percent Distribution of Engine Loads Greater than 80 Percent Categorized by Speed and Acceleration For Tandem-Axle 3871

Acceleration	**Speed (mph)**														
(mph/s)	**0**	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**	**55**	**60**	**65**	**70**
6		0													
5		0													
4	0	0													
3	0	0	0		.9		.9								
2	0	0	.2	.2	.3	.4	.5	.5	.9	.9					
1	0	0	0	.1	.2	.2	.2	.2	.2	.3	.3	.2	.4		
0	0	0	0	0	0	0	.1	.1	0	0	0	0	0	0	
-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
-2	0	0	0	0	0	0	0	0	0	0	0	0			
-3	0	0	0	0	0	0	0	0	0	0	0				
-4		0	0	0	0	0	0	0	0		0				
-5		0	0	0	0	0	0			0					
-6			0				0								
-7															
-8															

D.3.D. AGC Wheeled Loaders

A datalogger was installed on the Caterpillar 980G wheeled loader during normal operation for 1 week. The dataset contained 45,552 seconds of operation. Overall, 12 percent of the operation used engine loads greater than 80%. Figure D.3.8 shows the distribution of RPMs categorized by engine load. It shows that a high percentage (20-25%) of the engine loads greater than 80% occurred between 1,700 and 1,900 rpm.

Table D.50 Occurrence of High Engine Loads for Wheeled Loader

Vehicle	Seconds of Operation	Percent of Operation at >80% Engine Load
Wheeled Loader	45,552	12.56

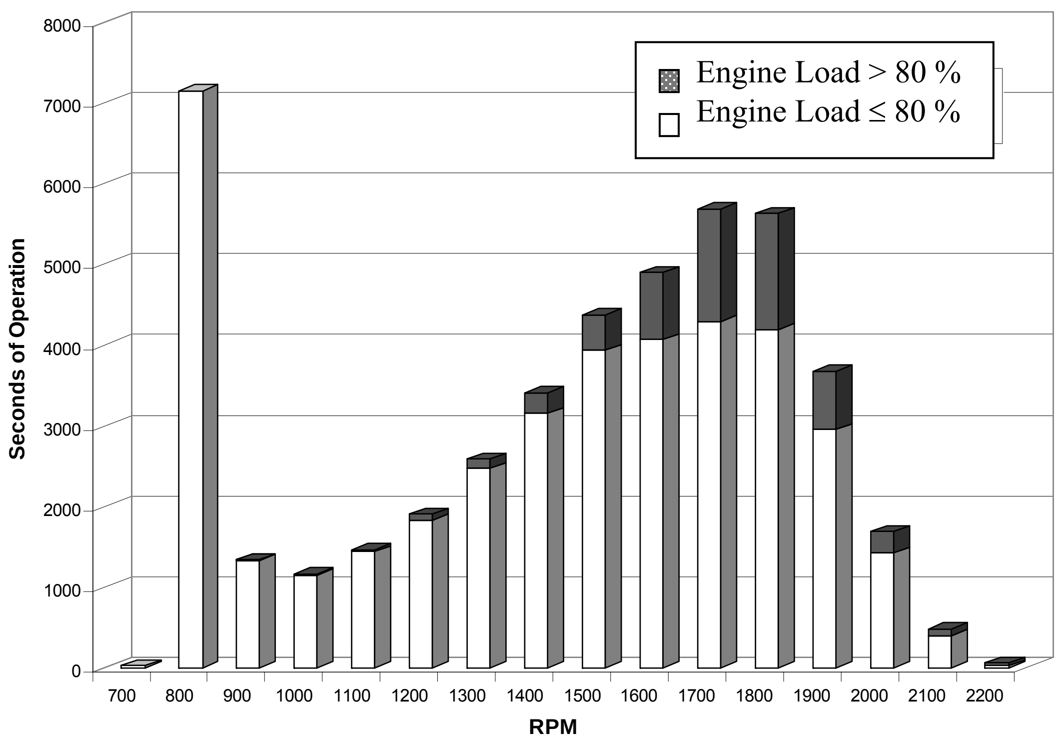

Figure D.3.8 Wheeled loader engine loads categorized by RPM

One estimate of the effect on wheeled loader productivity is from the Roadeo analysis. In that situation, where a loader was loading dump trucks from a hard-packed pile of material, loaders using PuriNOx were 20% slower than those fueled with regular diesel fuel.

The effect of PuriNOx on loss of productivity can also be estimated from the Caterpillar 980G data. In this work situation, dump trucks were loaded with heavy material that was perhaps less hard packed. A brief analysis of the dynamometer test cycle that mimics that field data will provide the other estimate.

The loader cycle is 919 seconds long. From the percent engine load and RPM traces of the cycle, we calculated the total work that was done for engine loads greater than 80% and the average rate of work done for engine loads less than or equal to 80%. By dividing the total work done for engine loads greater than 80% by the average rate of work done for engine loads less than or equal to 80%, we obtained the amount of extra time that the loader would have to work to finish the job that could not be done at the high loads that PuriNOx could not produce. This extra time was 42 seconds, or 4.6% of the 919 second cycle. Consequently, this method estimates that a loader will require 4.6% more time when using PuriNOx.

D.3.E. Conclusions Regarding Loss of Productivity

The potential exists for the switch from regular diesel fuel to PuriNOx to affect productivity. Because of the 20% water content of PuriNOx, we expect and have observed a 8-38% reduction in full load torque of diesel engines. A rough average of 20% was used to estimate the loss of productivity. If during normal operation, an engine never exceeds 80% engine load at its normal RPM used for a particular activity, we would expect that the use of PuriNOx would not affect the productivity of the diesel-powered machine. However, if an engine does exceed 80% engine load, use of PuriNOx may affect the productivity of the machine.

In the analysis of the in-use data for single- and tandem-axle dump trucks, telescoping boom excavators, and the wheeled loader, we specifically evaluated the portion of the time that each of these vehicle types spent above 80% engine load and the operating modes under which this condition occurred.

In the case of dump trucks, the analysis indicated that 80% engine loads occurred from 2% to 8% of the time. These high load conditions occurred at high accelerations at moderate to high speeds or at high speeds with substantial cargo. The inability to be able to access the top 20% engine loads while using PuriNOx will result in slower accelerations in moderate to high speed situations and slower cruising speeds while hauling substantial cargo weights.

In the case of the telescoping boom excavators, the analysis of in-use data indicated no problem with using PuriNOx for excavating tasks. However, even with regular diesel fuel, Gradalls are underpowered during driving. With a switch to PuriNOx, Gradalls, which have 45% of their driving time above 80% engine load, will be severely affected. Reduced acceleration rates and reduced cruising speeds can be expected in almost all driving situations if the Gradall XL3100 data collected in this study is representative of typical telescoping boom excavator operation.

For wheeled loaders loading dump trucks with aggregate, such as the Caterpillar 980G, 12% of the operating time was at engine loads over 80%. Because the operating mode of this loader in such a dump truck loading activity involves both generating power for the hydraulic system as well as motive power to force the vehicle's scoop into the pile of aggregate and carry it to the truck, the influence of a switch to PuriNOx is estimated to be 4.6%. This is conservative compared to the results of the Roadeo testing of loaders in this operating mode, which indicated a 20% loss in the rate at which trucks can be loaded.

D.4 Engine Noise

To determine if the use of PuriNOx has any effect on engine operating noise levels, sound pressure level testing was performed on a 1999 Navistar International tandem-axle dump truck (TxDOT ID 15-5186-G) as it underwent emissions testing at the SwRI heavy-duty dynamometer laboratory and on a small utility diesel engine during testing at UT.

The dump truck testing was performed by logging second-by-second sound pressure level measurements from inside the vehicle's cabin. Sound pressure level readings were recorded when the truck was operated on PuriNOx and again when the truck was operated on low sulfur diesel (using a similar drive trace). Analysis was performed on the data at regions of similar engine speed/load points between the 2 fuels to see if any significant difference could be seen in the sound pressure level measurements. All other test conditions were held constant during testing so any difference in sound pressure level measurements could be attributed to the type of fuel.

An ERG Autologger was used to record second-by-second data from a CEL model 328 sound pressure level (SPL) meter. Because the ERG Autologger is normally used to measure vehicle speed, engine RPM, and manifold absolute pressure (MAP), datalogger modifications were necessary to allow the unit to record input signals from the SPL meter. Circuit board modifications were made to the MAP channel of the datalogger, and the datalogger and CEL 328 were connected for the study.

All SPL measurements were made with A-weighting using the A scale sound level filter (output of dBA). A-weighting simulates the sensitivity of human hearing to different sound frequencies. Since the SPL readings were recorded on the datalogger's MAP channel, a calibration curve was created to allow the MAP data values to be converted to dBA values. This was accomplished by using a CEL 114 dB calibrator to provide a known sound pressure level to the SPL meter. This value was compared with the SPL digital display to verify accuracy. Then, various sound pressure levels were input into the SPL meter microphone, and the digital display readings were manually recorded. After this, the datalogger MAP values were downloaded and compared with the manually recorded SPL readings. Table D.51 shows the resulting calibration data.

Table D.51 Autologger SPL Calibration

Input SPL (dBA)	Recorded Autologger MAP Value
64.2	111.9
81.7	151.6
92	175.9
103	188.9

To perform the sound level measurements, the SPL meter/datalogger unit was placed on the passenger's seat with the microphone facing forward toward the dash. Power/signal wires and cables required for dynamometer testing were passed into the cab through the driver's side wing vent window. The vent window was then closed as much as possible by pushing it against the wires and cables. All other windows were closed, and the truck driver was instructed to perform testing with all accessories (radio, air conditioning, fan, etc.) turned off. Testing staff were also asked to minimize noise in the cab and test bay (no yelling, drilling, grinding, etc.).

To compare sound pressure levels between the 2 fuels, SPL measurements were compared at equivalent drive-trace points. To gather this drive trace information, the tandem-axle dump truck was instrumented with the QuickCheck datalogger.

The analysis is based on sound pressure level testing performed January 20 and January 21, 2003 at SwRI. Sound pressure level and vehicle operating information was recorded as the vehicle was driven on distance-equivalent tandem dump truck cycles developed for the emissions evaluation portion of this project. On January 20, 5 tests were performed with the vehicle operating on low sulfur diesel, and on January 21, 5 tests were performed with the vehicle operating on PuriNOx.

After testing was complete, data from each datalogger was downloaded for analysis. The speed versus time data for each of the 10 tests were converted to speed versus distance. Then, for each fuel type, the second-by-second speed versus distance values for each of the 5 runs were averaged to produce an average speed versus distance drive trace. These average traces are shown in Figure D.4.1. When using low sulfur diesel, the vehicle is seen to have a better ability to follow the higher acceleration portions of the driving cycle than when using PuriNOx.

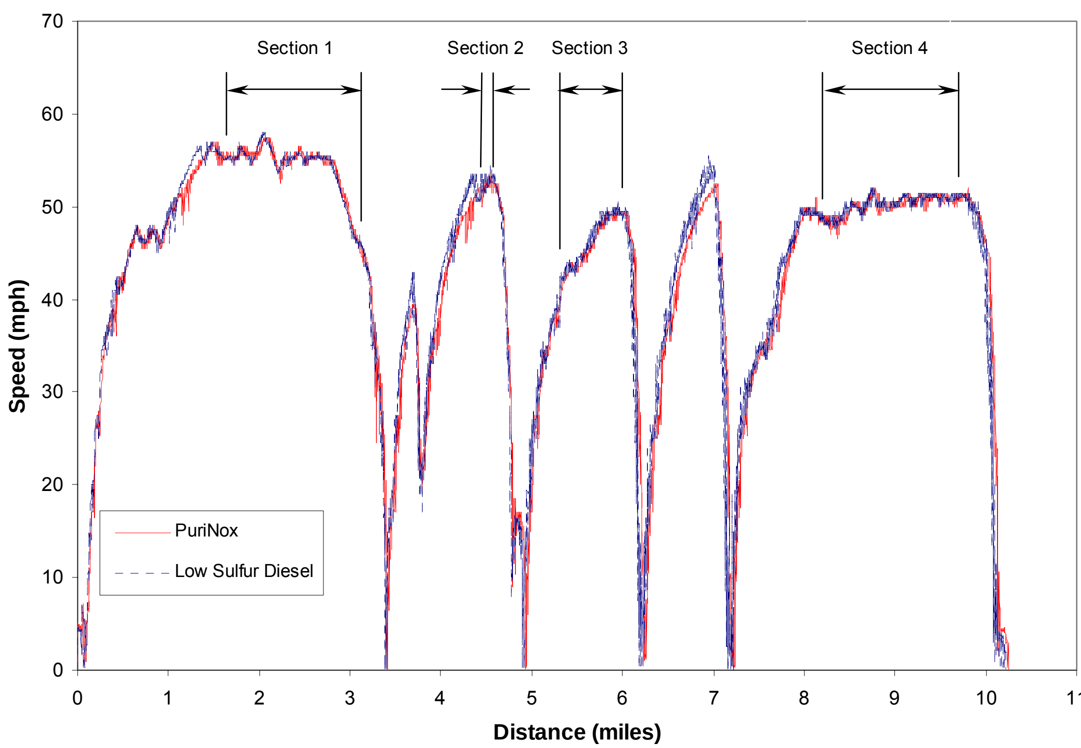

Figure D.4.1 Comparison of average vehicle speed traces for the two test fuels

Comparison of noise level measurements were made at regions of the drive trace where driving and engine conditions are similar. For example, making a sound pressure level comparison where the vehicle is under hard acceleration would not be appropriate, since the vehicle performs differently under acceleration using the 2 different fuel types. Four common-operation sections of the drive trace were selected for the sound pressure level analysis. These sections, shown as Sections 1, 2, 3, and 4 of Figure D.4.1, were selected based on the criteria of a speed difference between the 2 traces of less than 3 miles per hour.

Just as the speed values for each fuel type were averaged for each of the 5 runs, sound pressure level measurement values were also averaged to obtain an average sound level measurement trace for each fuel type. Since all logged data was time stamped, these time stamps were used to convert logged sound pressure level measurement values from a time basis to a distance basis, as shown in Figure D.4.2. From this figure, it can be seen that the vehicle appeared to produce slightly lower sound pressure levels when it was operated on PuriNOx compared to low sulfur diesel.

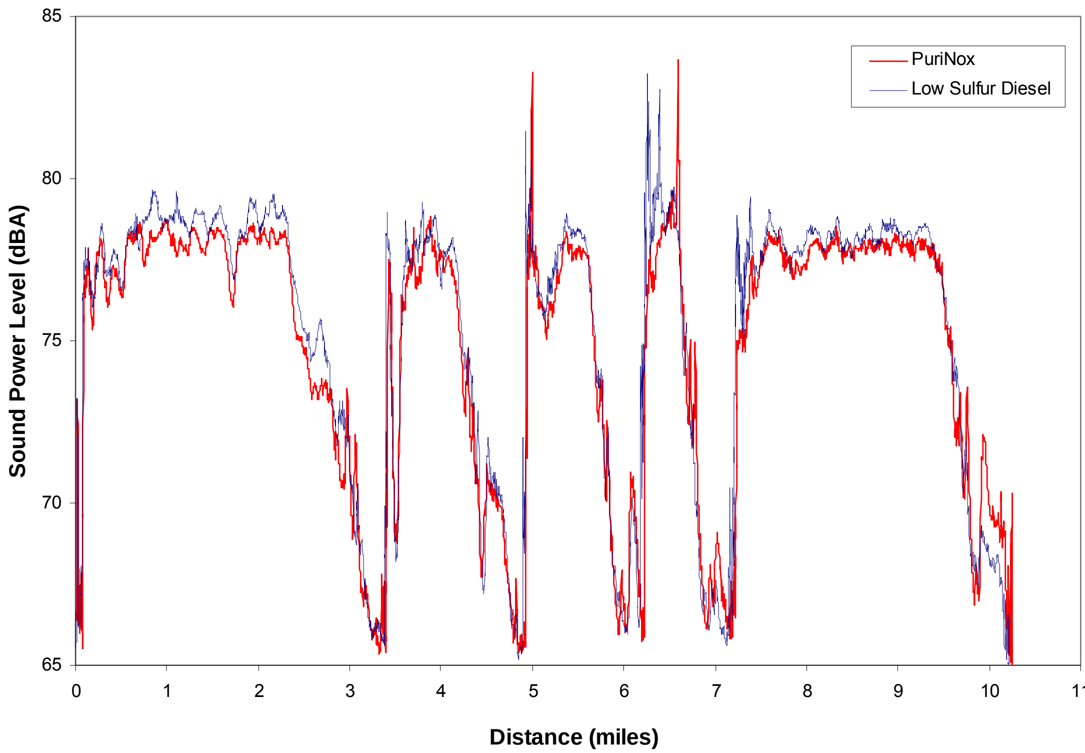

Figure D.4.2 Comparison of average cabin SPL traces for the 2 test fuels

Table D.52 presents results of the sound pressure level measurements for each of the 10 runs averaged over the 4 sections of data shown previously in Figure D.4.1. Table D.52 also shows the average of the averages for each fuel type. From this table, it can be seen that the PuriNOx has a 0.5 dBA lower average SPL than the low sulfur diesel fuel for those periods when the vehicle was at the same operating conditions for both fuels.

Table D.52 Sound Pressure Levels Averaged Over Sections 1 - 4

Fuel Type	**Test No.**	**Average of Sound Power Level by Test Number (dBA)**	**Overall Average Sound Power Level (dBA)**
Low Sulfur Diesel	1	76.5	76.3
	2	76.4	
	3	76.2	
	4	76.1	
	5	76.2	
PuriNOx	1	75.9	75.8
	2	76.3	
	3	75.8	
	4	75.5	
	5	75.4	

Although the sound pressure levels measured during PuriNOx testing were slightly lower than levels measured during low sulfur testing, the difference between these 2 values is quite small. This small difference may not be distinguishable by the human ear.

In addition, several factors should also be noted when considering this data. During testing, overall ambient noise levels (non-vehicle noises) in the heavy-duty dynamometer laboratory are quite high. This is owing to operation of systems necessary for testing, such as the dynamometer power absorption unit, the cooling fan for the test vehicle's engine, and the laboratory's constant volume sampling system. Although efforts were made to minimize these noises, such as keeping the vehicle's windows shut, these background noises could still affect cabin noise levels differently from day to day. It was observed that at higher roller speeds the dynamometer power absorption unit dominated vehicle noise — at least from the outside-of-the-cab perspective. At lower speeds, the engine noise seemed to dominate. These dynamometer and other background noises could tend to mask the differences of engine noise levels at higher speeds attributable to the fuels.

To verify the results observed in the SwRI laboratory of the tandem-axle dump truck cabin, we measured the sound levels of the single cylinder diesel engine on the engine dynamometer in the University of Texas engine laboratory. The sound was measured at four different engine loads for PuriNOx and pump diesel fuel, that is, not the baseline 2D low sulfur diesel fuel. The same sound meter that was used for the sound testing at SwRI was used for these tests. Since the single cylinder engine tests were made at constant load, the sound levels were simply recorded from the meter's display rather than through an analysis of second-by-second recorded value on a datalogger.

Table D.53 shows the results of those tests. For each load, PuriNOx produced slightly less noise than the regular diesel fuel. Overall, the average sound power level for PuriNOx was 0.7 dBA less than for regular diesel fuel. This result is very close to the SPL difference of 0.5 dBA seen in the SwRI tests.

These sound measurements confirm that, at least for steady-state engine loads and engine speeds, diesel engines using PuriNOx are slightly quieter than when using regular diesel fuel.

Table D.53 Summary of Noise Measurements of Single Cylinder Diesel Engine

Test Date	Test Start Time	Fuel	Load (lb-ft)	Average Sound Power Level by Test (dBA)	Overall Average Sound Power Level (dBA)
2/11/2003	20:00	Regular Diesel	11.5	94.4	93.7
	20:05	Regular Diesel	8.5	94.4	
	20:10	Regular Diesel	5.5	94.0	
	20:18	Regular Diesel	3.3	91.9	
2/10/2003	13:49	Summer PuriNOx	11.3	93.8	93.0
	14:23	Summer PuriNOx	8.6	93.7	
	14:33	Summer PuriNOx	5.5	92.9	
	14:41	Summer PuriNOx	2.8	91.7	

D.4. Specific TxDOT Experience

Table D.4.1 provides a list of the equipment that was either never converted to PuriNOx or was converted back to diesel because of performance concerns.

Table D.4.1 Diesel Equipment in the Houston District

Number of Equipment	Equipment Description	Reason for Diesel Use
4	1 ton bucket truck	6.5 liter engine
1	1 ton dump truck	6.5 liter engine
6	3/4 ton utility truck	6.5 liter engine
1	arrowboard	low power
1	bridge inspection truck	low power
2	carry deck crane	exempt (ferry operations)
1	core drill truck	not in service yet (will be converted later)
1	dragline	low power
1	forklift	exempt (ferry operations)
9	herbicide truck	6.5 liter engine
1	light duty truck	out of service
17	light duty truck	6.5 liter engine
1	mower	out of service
4	platform truck	6.5 liter engine
1	roller	on loan out of the district
1	Single-axle dump truck	out of service
7	T444E crane truck	low power
3	tractor	out of service

As can be seen from Table D.4.1., 41 pieces of equipment were never converted to PuriNOx, because this equipment has hydroscopic optical sensors to detect water in fuel, which require the fuel to be clear. In addition, 11 pieces of equipment were either exempt, out of service, or not in service at the time the equipment was converted to PuriNOx. Ten pieces of equipment — 7 T444E crane trucks, one arrowboard, one bridge inspection truck (Caterpillar engine) and one Detroit 3-71N dragline — had to be converted back to diesel because of low power.

Appendix E.
Effects on Maintenance

Maintenance issues are discussed in this appendix. The results of maintenance personnel surveys are presented in Section E.1. Section E.2 presents the results from fuel filter tests. Experiments related to separation, hard starting, and the requirement to start the engines often are discussed in Section E.3. The results of our corrosion experiments are presented in Section E.4. Durability issues are discussed in Section E.5. Section E.6 is a summary of the findings presented in this appendix.

E.1. Maintenance Personnel Surveys

The objectives of these interviews were to assess changes made to PuriNOx fueled vehicles and equipment and to assess additional maintenance requirements. The approach involves surveying maintenance personnel in the Houston District who oversee the outsourcing of work orders, and the mechanics at each of the surveyed sites during the driver/operator surveys conducted in August/September and November, where available.

In general, the maintenance personnel interviewed felt that TxDOT's equipment changed from "low maintenance" to "high maintenance" since switching to PuriNOx. Also, the transition effects have been much longer than anticipated. Specific concerns included

- an increase in maintenance expenditure (e.g., fuel filters and injectors),
- a need to start the vehicles/equipment at least twice each week when not used, and
- ether/starting fluid is required when the vehicle has not been started for a week.

The reported increase in maintenance expenditure has been significant, specifically relating to fuel filters and injectors. The maintenance personnel interviewed could not attribute specific maintenance requirements to specific types of equipment or engines. For example, fuel filters have had to be changed 3–4 times already in some Gradalls, although not in others.

Some of the minor issues (e.g., fuel filter changes) are attributed to the cleaning effect of PuriNOx. In the smaller engine tanks (e.g., arrowboards), many years of diesel use have resulted in deposits in the fuel tank. The cleaning effect of PuriNOx has thus resulted in plugged fuel lines and filters.

One of the Houston maintenance personnel reported significant maintenance expenses on fuel injectors. Fuel injectors had to be replaced in 10 vehicles/equipment (3 of which had Cummins and 7 of which had Caterpillar engines) since switching to PuriNOx. In one case, all 6 injectors in one vehicle had to be replaced. Normally, only 1 or 2 injectors are replaced in a year, usually in very old equipment.

Many pieces of equipment were reported to be harder to start. To counter the starting problems, mechanics were starting equipment twice a week. A number of the maintenance personnel interviewed during the PuriNOx user surveys reported the need to use starting fluid when vehicles/equipment had not been started for a week.

TxDOT maintenance personnel increased the idle speed for some engines to alleviate starting and idling problems. On some small utility engines, they changed the fuel injection timing to correct for some of the torque loss. However, TxDOT is not considering "repowering" the engines (e.g., adjusting the fuel rack stop to allow a greater mass of fuel at full load), because this could void the warranty and may be considered tampering by the EPA since it would result in exceedingly high smoke if the engine were refueled with diesel.

Finally, specific concerns were expressed about the use of PuriNOx in traffic-alerting signals, because these signals are not used for long periods of time.

E.2. Fuel Filter Tests

Some diesel fuel filters are not compatible with PuriNOx. Lubrizol maintains a list of replacement filters that are compatible. To increase our understanding of this problem, UT assessed whether PuriNOx might chemically attack and degrade materials inside of diesel fuel filters. To make this assessment UT acquired six different fuel filters from a TxDOT supplier and soaked them in summer-grade PuriNOx for four months. UT requested three filters that were considered to be PuriNOx compatible and three considered not compatible with PuriNOx. The six filter models tested are listed below along with a description of their filtering material according to the manufacturer:

Donaldson P550105	Primary Fuel Filter, Cellulose base but treated
Donaldson P550440	Secondary Fuel Filter, Cellulose base but treated
Donaldson P551000	Water Separator Filter, Cellulose
Fleetguard FS1000	Cellulose and glass filter
Baldwin BF1257	Cellulose and glass media
Baldwin BF1226	Cellulose and glass media

The UT researchers were initially told that the first three filters on the list were PuriNOx compatible and the last three were not. Subsequent inquiries to Lubrizol and the filter manufacturers revealed that only the Donaldson P551000 was considered incompatible with PuriNOx due to its water separation function.

After soaking in PuriNOx for four months the six filters were cut open and their filter media examined for signs of deterioration. No evidence of deterioration was found in any of the six filters. A photo of the six filters is shown in Fig. E.2.1.

Figure E.2.1. Fuel filters after four months of soaking in PuriNOx.

E.3. Separation, Hard Starting, and Requirement to Start Engines Often

Over a period of time, the water and diesel fuel in the emulsion can become layered, with the lighter diesel fuel diffusing to the top and the denser water diffusing toward the bottom. Obviously, this layering can cause performance problems such as hard starting, rough operation, or a complete inability to start the engine. To prevent separation, the stationary storage tanks are recirculated each time a vehicle is refueled. The fuel in the vehicle's tank is automatically recirculated whenever the engine is running. However, much of TxDOT's equipment may be used regularly for extended periods and then parked for weeks or months until it is needed again. Because there is no means for agitating the fuel during these idle periods, separation can occur. In turn, this can lead to extreme difficulty in starting the equipment or a complete inability to get it started. Therefore, TxDOT has found it necessary to start each piece of equipment at least twice per week, even when the equipment is not needed. This results in both fuel consumption and emissions that should be accounted for in a cost-effectiveness analysis, as discussed in Appendix B.7. Concerns, however, remain about separation and how various factors might affect it. The studies undertaken to examine separation and hard starting are discussed in the following subsections.

E.3.A. Separation - The characteristics of the diesel/water separation behavior of the fuel were studied at UT. Beakers and test tubes containing summer-grade and winter-grade PuriNOx were stored, unagitated, at 3 temperatures: 35 ˚F, 73 ˚F, and 130 ˚F. The separation was observed visually, and measurements of specific gravity at 3 different depths within the beakers were made to quantify the degree of separation. After only 1 week, measureable differences in specific gravity were found. After 2 weeks visible separation was observable (Figure E.3.1). The separation was significantly faster at 130 ˚F than at the lower temperatures (Figure E.3.1c). After 3 weeks the separation was quite pronounced: At the 130 ˚F temperature, a thick viscous component had settled to the bottom of the containers (Figure E.3.2).

The 4-week photos are shown in Figure E.3.3. After 5 weeks, the most separated samples of both winter- and summer-grade PuriNOx (those from the 130 ˚F box) were tested for the presence of free water using "Kolor Kut" water-finding paste. This paste turns a bright red in the presence of free water. The 2 paste samples immersed in each beaker remained unchanged in color, indicating no free water was present despite what appeared to be almost complete separation. At 5-weeks, 2 of the beakers from the 130 ˚F box (winter- and summer-grade) were stirred to observe whether they would remix. Both samples appeared to remix to a homogeneous state (Figure E.3.4). The reseparation of these 2 samples was observed after 1 day (Figure E.3.5) and after 2 weeks (Figure E.3.6). The fuel appeared relatively well mixed after 1 day but was highly reseparated after 2 weeks. The degree of reseparation of the summer-grade after 2 weeks was similar to that observed after the original 2-week period. However, the winter-grade appeared to reseparate more quickly, and after 2 weeks it looked similar to the original unstirred sample at 6 weeks.

Figure E.3.7 is a graphical representation of the results from Figures E.3.1-E.3.3. This graph is for summer-grade PuriNOx, but the results were almost the same for winter-grade. This graph illustrates the non-linear effect of temperature on the separation rate. Figure E.3.8 presents the specific gravity measurements of the summer-grade at 130 ˚F as a function of the time it is allowed to separate. This figure shows the density of samples extracted from the top, middle, and bottom of the beakers for settling times from 1 week to 8 weeks. As noted above, there is relatively little separation after 1 week, with the samples from the bottom and middle of the beaker having densities near that of well-mixed PuriNOx, but the sample near the top having a density that is closer to that for diesel fuel. The stratification is seen to increase with time, which is consistent with the photos, and appears to have reached an equilibrium state at about 4 weeks. It is interesting to note that the specific gravity of the white fluid at the bottom of even the most highly separated samples remains below 1.0 (the specific gravity of water). This observation, along with the free water test, suggests that the water remains in an emulsion even though the fluid is highly stratified and appears to be almost completely separated. However, the concentration of water in the portion that is still emulsified is higher than that for the original, well-mixed emulsion. Also, the specific gravity of the transparent liquid near the top, which has the appearance of diesel fuel, is smaller than the specific gravity of pure 2D diesel. This indicates that the liquid at the top is not diesel fuel that has completed separated out, but instead contains an abundance of lighter components.

(a)

(b)

(c)

Figure E.3.1. Photos of beakers containing PuriNOx after a settling time of 2 weeks at 3 different temperatures. (a) 35 ˚F, (b) 73 ˚F, and (c) 130 ˚F

(a)

(b)

(c)

Figure E.3.2. Photos of beakers containing PuriNOx after a settling time of 3 weeks for 3 different temperatures. (a) 35 ˚F, (b) 73 ˚F, and (c) 130 ˚F

(a)

(b)

(c)

Figure E.3.3. Photos of beakers containing PuriNOx after a settling time of 4 weeks at 3 different temperatures; (a) 35 ˚F, (b) 73 ˚F, and (c) 130 ˚F

Figure E.3.4. Beakers of PuriNOx immediately after remixing following 5 weeks of settling time

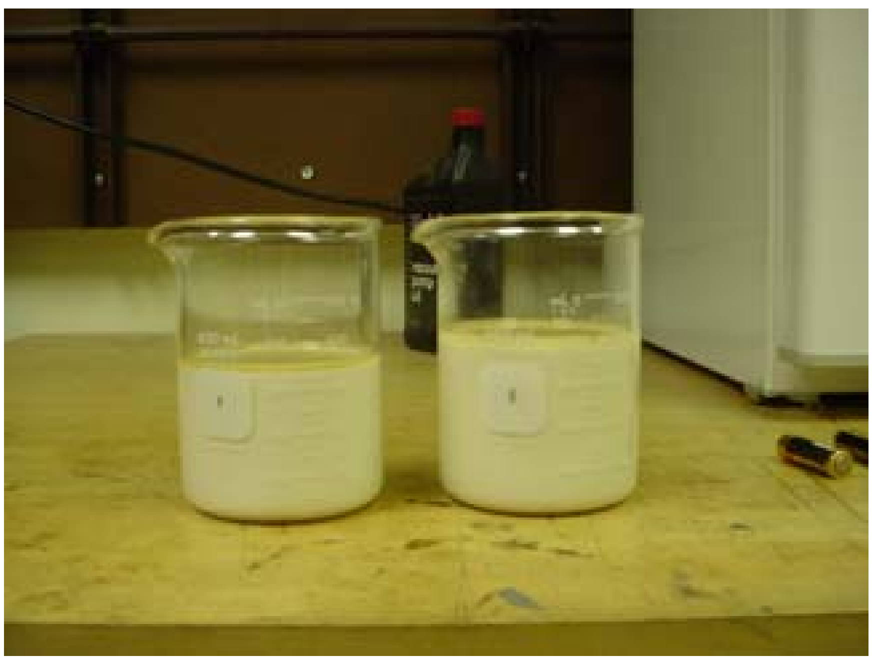

Figure E.3.5. Remixed beakers after 1 day of settling time

Figure E.3.6. Remixed beakers after 1 week of settling time at a temperature of 130 ˚F (two beakers on the left).
The leftmost is winter-grade and the 2nd from left is summer-grade.

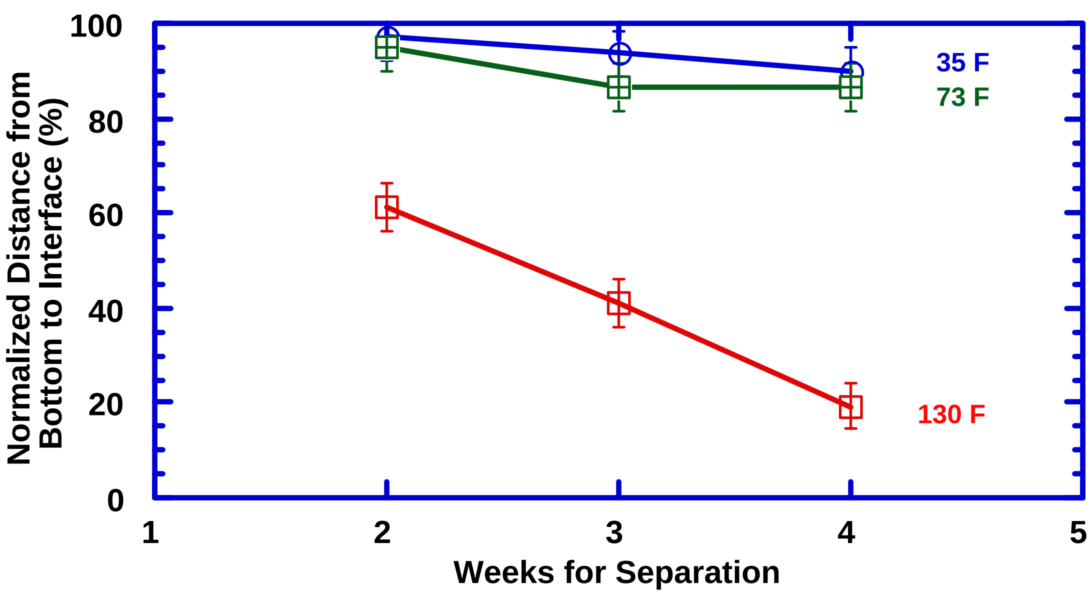

Figure E.3.7. Effect of temperature and settling time on the separation rate of summer-grade PuriNOx

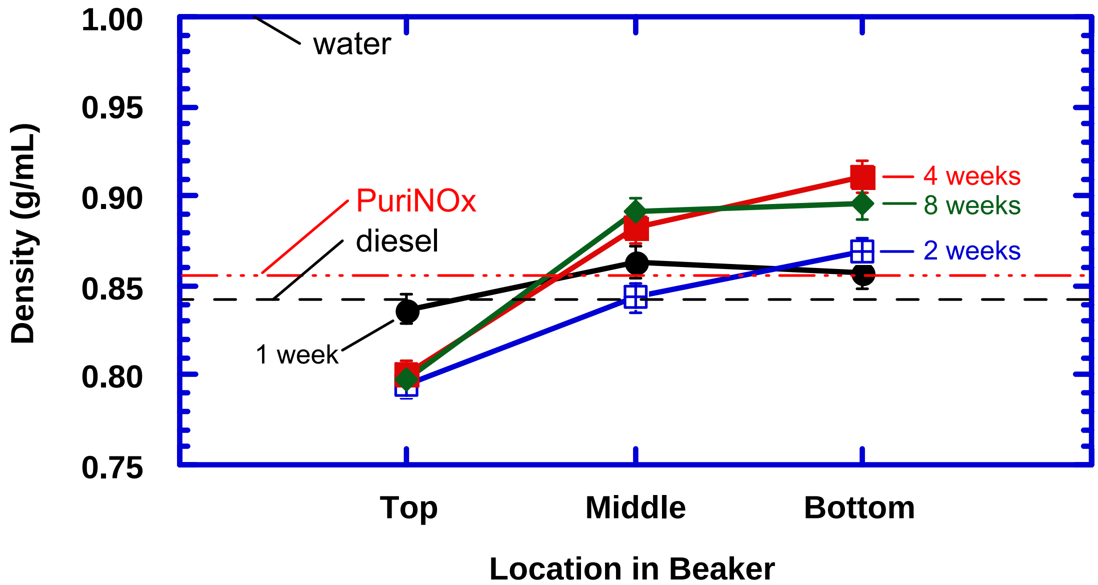

Figure E.3.8. Specific gravity (density) of the summer-grade PuriNOx as a function of time allowed for separation at 130 ^{o}F.

E.3.B. Hard Starting - Some users of PuriNOx have reported that their equipment is difficult to start if left idle for more than a few days. This was also observed for the 10 hp engine tested by UT. An attempt was made to measure fuel separation in the fuel line of the 10 hp engine at UT to see if separation in the fuel delivery system might be the cause. For this test, the engine at UT was first run until it was fully warmed up. It was then shut down, and reference samples of fuel were taken from the fuel line. This was done by removing the fuel injector from the engine and reassembling the fuel system with the injector outside the engine. Samples of fuel were injected into test tubes for later observation. Each of 4 test tubes was filled with fuel from 12 consecutive injections (about 1 ml of fuel). The engine was then run again until fully warmed up. After a period of 5 days, during which the engine was not touched, the same procedure was followed, and 10 test tubes were filled with fuel (again, 12 injections per test tube). The suggestion was that, if the fuel had separated during the 5-day period, the different compositions would be visible in the test tubes. Figure E.3.9 is a photo of the 4 samples taken immediately after running the engine, and Figure E.3.10 is a photo of the samples taken after the 5 days without operation. The photos were taken after the samples were allowed to settle for a period of 6 days. The separation in the 4 reference test tubes looks very similar. This is not the case for the samples taken after the 5-day period of not running the engine. The fraction of the sample that is clear versus that which is white varies noticeably among the samples taken after the 5-day period. It appears, for example, that test tubes 3 and 4 have a greater fraction of white liquid than the others, suggesting a higher water content. The specific gravities of the samples were measured after the photos were taken. The results indicate that this is the case, with Sample 3 having the highest specific gravity, as is seen in Figure E.3.11. Thus it appears that significant fuel separation can occur in fuel lines and over a relatively short period of time, that of several days.

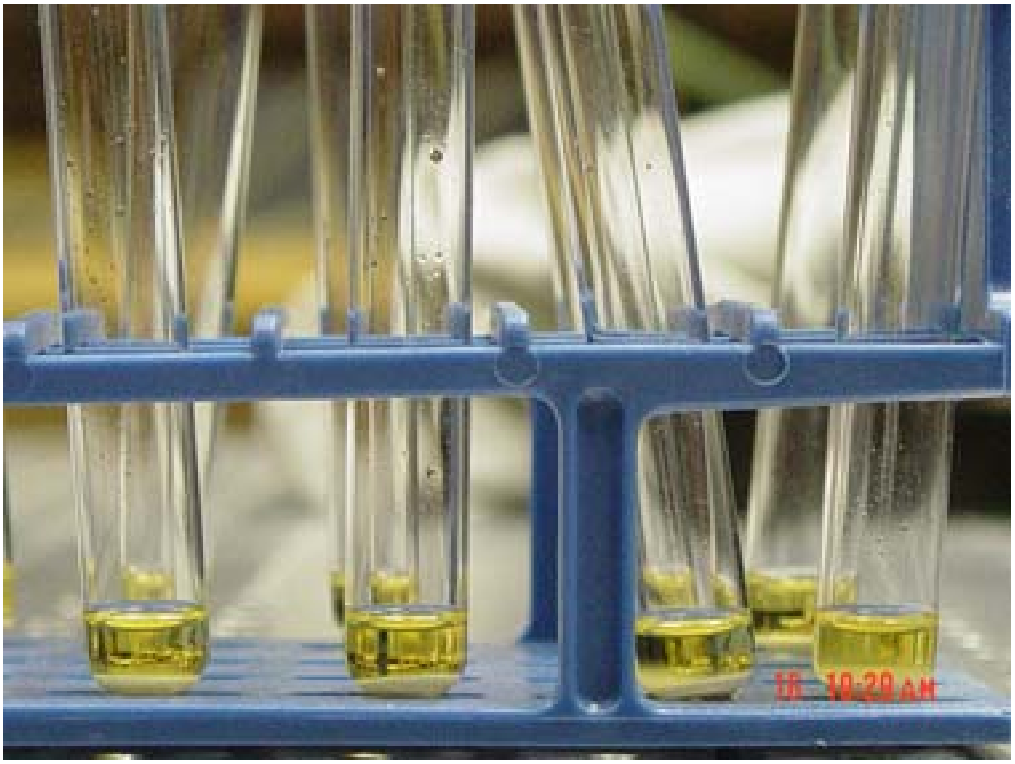

Figure E.3.9. Photo of 4 PuriNOx samples removed from the fuel line before the engine sat idle for 5 days (after settling time of 6 days)

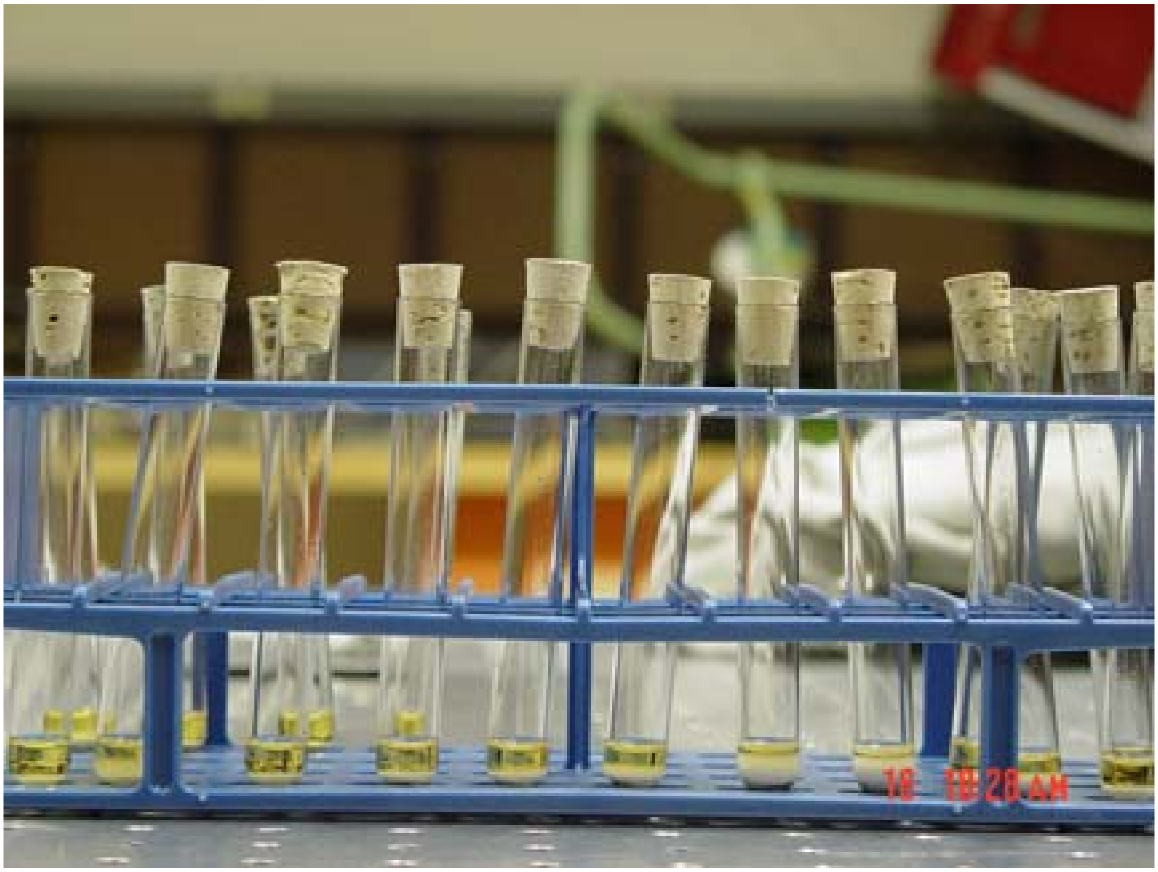

Figure E.3.10. Photo of 10 PuriNOx samples removed from the fuel line after the engine sat idle for 5 days (after settling time of 6 days). The order in which the samples were taken is from right to left.

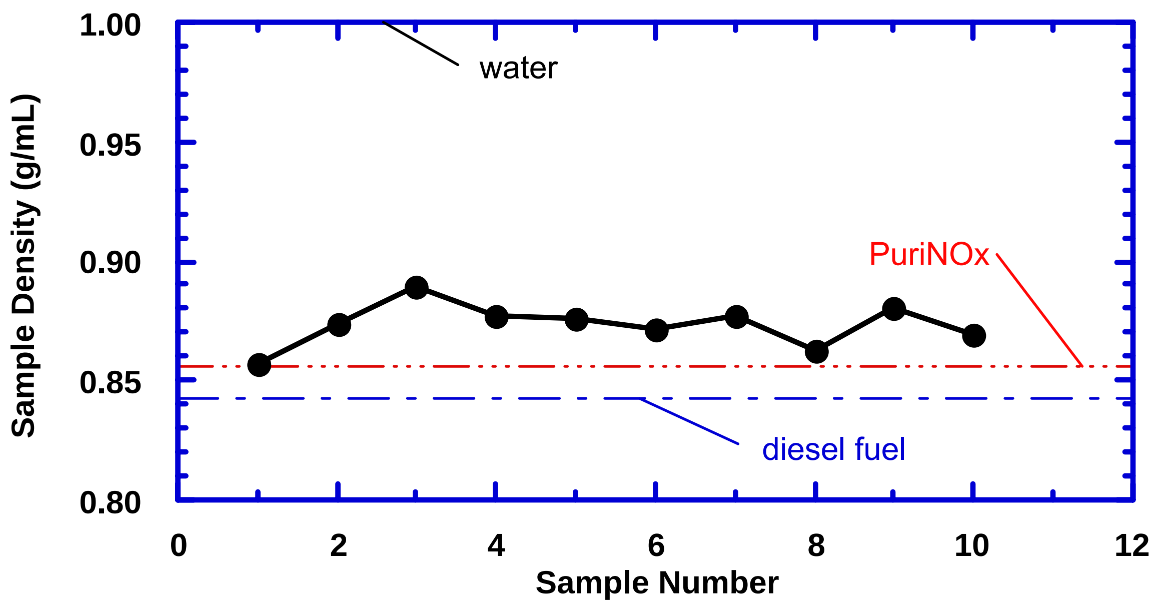

Figure E.3.11. Densities of PuriNOx Samples 1–10 taken after the engine sat idle for 5 days. Sample 1 is a collection of the first 12 injections and sample 10 is a collection of injections 109-120.

E.4. Corrosion

A fundamental corrosion study was included in the research plan due to concerns about fuel tank compatibility. However, it soon became apparent that failures of fuel injectors and fuel pumps was also a concern. This corrosion study is also relevant to the materials in injectors and pumps. The corrosion experiments are discussed in this appendix.

The objective of this study was to investigate the materials compatibility of PuriNOx using the compatibility of 2D on-road diesel fuel as a reference. In particular, the concern was potential corrosion problems. Several known tests are available for studying the corrosion behavior of fuels and/or petroleum products. Two tests in particular are SAE J1747 DEC94, "Recommended Methods for Conducting Corrosion Tests in Gasoline/Methanol Fuel Mixtures," and ASTM D130-94, "Standard Test Method for Detection of Copper Corrosion from Petroleum Products by the Copper Strip Test." Both tests require elevated temperatures, and the latter one even requires a corrosion test bomb. Because very little is known about the corrosion behavior of PuriNOx, it was decided to gain initial information by using a simplified approach: steel strips immersed in test tubes containing the fuel at room temperature. From the results of this initial study, additional tests were planned and performed.

E.4.A. Experimental Procedure - In the first set of experiments, the proposed procedure was tried on polished and unpolished strips of a stock steel (Lot 1) from the UT Mechanical Engineering Machine Shop. This test was performed in order to determine how the specimens would be immersed, removed, dried, and weighed. In typical tests in which metallic materials are exposed to salt water or acids, the metallic materials are removed after some time, and any corrosion products are removed by a metal-specific cleaning procedure and cleaning solution according to ASTM guidelines. This is done prior to weighing the specimens to observe the weight change (usually a weight loss), from which a corrosion rate can be determined. However, in this case the fuel is more viscous than most electrolytes, and it was not clear how the specimens would have to be handled and weighed.

The samples were 2.75 x 0.325 x 0.25 inches, and the polished specimens were polished to a surface finish of 600 grit using SiC paper. The unpolished specimens were used in the as-received condition. Three sets of specimens (each containing 7 steel strips), which had previously been weighed, were completely immersed in individual test tubes containing either 2D diesel fuel, summer-grade PuriNOx, or winter-grade PuriNOx. In all there were 42 specimens, 21 polished and 21 unpolished. A cork was placed on each test tube, and the test tubes were kept in the upright position. They were not agitated during exposure. Specimens were removed after 1 day, 2 days, and so on; up to 5 days. The specimens were removed from the fuels and placed in another clean, dry test tube so that the viscous fuel adhering to the specimens could drip off. The next day, they were dried, weighed, and placed in an envelope. (This procedure was modified after some interesting observations were made, as discussed later.) The remaining 12 specimens were left in the test tubes to be removed at some later time.

In the second set of experiments, 1018 steel was used. This steel is a plain carbon steel containing 0.18 percent by weight carbon and the balance iron, which would be more typical of the type of steel that might be used in the construction of fuel tanks. The same procedure as that described above was used on this set of specimens except that only polished specimens were used. However, there were duplicate specimens, and thus there were again 42 specimens.

The third set of experiments involved a planned interval test. The idea is to determine the corrosion rate based on weight change and to use that information to determine whether the corrodibility of the metal changes with time and whether the corrosiveness of the electrolyte changes with time. The interval of time was taken to be 1 week, and the duration of the test was 4 weeks. In this case, polished 1018 specimens were used, and each test involved triplicate specimens. In this test 9 specimens were placed in 2D diesel fuel, 9 were placed in summer-grade PuriNOx, and 9 were placed in winter-grade PuriNOx. After 1 week, 3 specimens were removed from each fuel; after 2 weeks 3 more specimens were removed from each fuel; after 3 weeks the final 3 specimens were removed from each fuel. In the 4th week, 9 new specimens were placed in the fuel that the last 3 specimens had been removed from. They were removed after 3 weeks. The fourth set of experiments involved immersion of coil springs in the three fuels at 50 ºC for 15 days. This was done to observe the effects of temperature on spring steel such as might be used in injectors. The final set of experiments involved immersing 3 fuel injector springs at 50 ºC. These injector springs were removed from the 3 Caterpillar injectors that were replaced in the dump truck that experienced engine problems during the Roadeo. They were not available until relatively late in the project.

E.4.B. Results - The summer- and winter-grade PuriNOx started showing signs of separation after about 3 days at room temperature.

In specimens that were exposed to summer-grade PuriNOx, winter-grade PuriNOx, and 2D diesel fuel for up to 5 days, there was no visible evidence of corrosion. In addition, the weight changes were negligible, on the order of micrograms or less for specimens that initially weighed about 16 grams. In fact, in most cases, there was a slight increase in weight, on the order of micrograms or less. This is probably because the fuels were allowed to drip off the specimens; no solvent was used to remove the fuels.

No evidence of corrosion was observed until at least 3 weeks of exposure. Figures E.4.1 and E.4.2 show the early fuel separation and the progressive separation after about 40 days, respectively. Sometimes very small black flakes could be seen suspended in the white (emulsion) portion of the fuel after longer periods of exposure. The location was right below the diesel/emulsion interface (as seen in Figure E.4.2, the upper, transparent portion of the separated mixture has the appearance of diesel fuel, and thus is referred to as diesel for simplicity, but does not have the same corrosive properties as 2D diesel). These were presumably corrosion products, but no microscopy to identify them has been performed at this time. Figure E.4.3 shows evidence of corrosion extending upward from the "diesel"/emulsion interface after more than 30 days of exposure.

Specimens that were removed from exposure to summer- or winter-grade PuriNOx and were allowed to remain in the fuel as it dripped off showed evidence of corrosion in the portion that remained in the fuel. Figure E.4.4 shows a specimen with corrosion only on the bottom portion.

Specimens that were exposed to the 2D diesel fuel showed no evidence of corrosion after periods of exposure similar to those for PuriNOx. Figure E.4.5 shows specimens removed from the diesel fuel.

The results of the planned interval test are shown in Figures E.4.6, E.4.7, and E.4.8. The corrosion process in the used fuel (the fuel that had settled) progressed at a faster rate.

Results from the fourth set of experiments involving the coil springs are shown in Figures E.4.9, E.4.10, E.4.11 and E.4.12. As noted previously, these tests were performed using coil springs and a temperature of 50 ºC. Corrosion began earlier at the elevated temperature used for this set of experiments. However, as for the prior, lower temperature tests, no corrosion was noted for the coil springs immersed in 2D on-road diesel fuel.

For the fifth set of experiments, the poppet springs were removed from within the 3 Cat injectors that were replaced for the dump truck that developed engine problems during the Roadeo. These springs appear to be coated with a hard material that has the appearance of nickel or chrome. Due to concern that injector failures often occurs due to opening when the fuel pressure is too low, the spring constants were measured for each of these 3 springs both before and after the corrosion experiments. As shown in Table E.1, at the beginning of the experiments none of the springs had a spring constant that was significantly lower than the others. Because there was no basis for comparison (the spring constant for an injector that is known to be good), this either means that the injector problems were not related to the springs or that all three springs were equally weak. As also shown in Table E.1, the spring constants did not change appreciably over the duration of the experiments (16 days at 50 ºC). As shown in Figures E.4.13 and E.4.15, no corrosion was evident after 16 days at 50 ºC for any of the 3 fuels.

Table E.1. Spring Constants Measured Before and After Immersion

Specimen No.	Immersed in	Initial spring constant (kips/in)	Final spring constant (kips/in)	% Change in spring constant
1.	Pure Diesel	1.6179	1.5521	-4.06
2.	Winter-grade PuriNOx	1.6310	1.5872	-2.68
3.	Summer-grade PuriNOx	1.5788	1.6003	1.36

E.4.C. Conclusions - Based on the data to date, exposure of 1018 steel (and presumably other similar steels) to summer- or winter-grade PuriNOx at room temperature indicates that prolonged exposure could be a potential problem. It should be pointed out that relatively long periods seem to be required at room temperature, as no evidence of corrosion was obvious until about 3 weeks.

The problem seems to accompany fuel separation, because the corroded surface seems to coincide with the extent of separation.

Even though there is evidence of corrosion, the corrosion rates based on weight changes, after allowing the fuel to drip off, are very low at 25 ºC. Weight changes, as a result of removal of the fuel and any accompanying corrosion products with a suitable solvent, would probably provide more accurate information.

It was generally observed that the winter-grade PuriNOx was more corrosive than the summer-grade PuriNOx when kept at a constant temperature of 25 ºC. When specimens were immersed in used PuriNOx (fuel which has been allowed to separate), the corrosion progressed at a faster rate.

Corrosion takes some time to initiate; in this case about 3 weeks at room temperature. The higher temperature of 50 ºC resulted in faster separation of the PuriNOx, especially the winter-grade. There was enhanced corrosion of the plain steel coil springs after 15 days in the winter-grade PuriNOx, compared to the summer-grade. There was no evidence of corrosion on these springs in the diesel fuel for the same amount of time.

Actual injector springs, from 3 Cat injectors that were believed to have failed in the field after several months of operation on summer-grade PuriNOx, became available late in the project. These springs appear to be coated. There were no significant differences in the spring constant between the 3 springs when received. Because there was no basis for comparison (the spring constant for an injector that is known to be good), this either means that the injector problems were not related to the springs or that all three springs were equally weak. Also, after 16 days of immersion at 50 ºC the spring constants had not changed and no corrosion was noted. This may mean that the relatively high rate of injector failures is not due to effects of PuriNOx on the injector springs or that more than 16 days is required to corrode injector springs and/or that the higher temperature environment within the injectors is important.

In summary, these tests revealed that corrosion does not occur in 2D diesel fuel for these test conditions, nor in a well-mixed emulsion, nor in the milky-white portion of the fuel after separation has occurred. Rather, corrosion only occurs in the transparent portion of the fuel after separation. Even though this upper portion has the appearance of diesel fuel, the fact that it corrodes whereas diesel fuel does not is strong indication that it contains one or more components that are not present in diesel fuel (possibly the additives) or is enriched in some diesel component(s) that may be corrosive. As discussed in Section E.3, the upper portion of the separated fuel has a lower specific gravity than either PuriNOx or pure diesel fuel. This is additional evidence that the upper portion of the separated emulsion in enriched in light components. It is not known what these components are, but they must be responsible for the corrosive nature of the emulsion once it separates. As found in the corrosion experiments, and also in the separation and hard starting studies discussed in Section E.3, PuriNOx separates faster at higher temperatures, and in a non-linear manner (the separation rates at 35 and 73 ºF are very similar, but the separation rate is much higher at 130 ºF). During normal engine operation, the fuel in the fuel delivery system is heated via conduction from the engine and by the relatively high underhood air temperature. Heated fuel then returns to the fuel tank, where it heats the fuel in the tank. Hotter fuel is then delivered to the engine. The result is that the temperatures in both the tank and the fuel delivery system are higher than ambient during normal operation. However, the emulsion is probably well-mixed via agitation from the fuel that returns to the tank. When the engine is turned off, many of the components of the fuel delivery system hot soak to near coolant temperature (approximately 200 ºF). Also, radiation from the asphalt or concrete surface that the truck is parked on can elevate the tank temperature. Thus, separation may occur relatively rapidly after engine shut down. In turn, this could lead to corrosion of the tanks, injectors, and injection pumps. No complaints of tank corrosion have been noted during the period of this study, but that is undoubtedly a longer-term problem compared to the duration over which TxDOT has been using PuriNOx. However, TxDOT has noted increased failures of injectors and pumps. The present results may explain these failures as possibly resulting from separation within these components.

Figure E.4.1. Set-up for 1018 steels. Strips of the steel were polished and completely immersed in the fuels for varying amounts of time at room temperature. Samples were removed, and the effects of the immersion were observed.

Figure E.4.2. Fuel separation after 40 days at room temperature. The most severe effects were noticed in specimens that had been immersed in PuriNOx for over 40 days. Sometimes very tiny black flakes, presumably corrosion products, could be seen suspended in the white portion of the fuel.

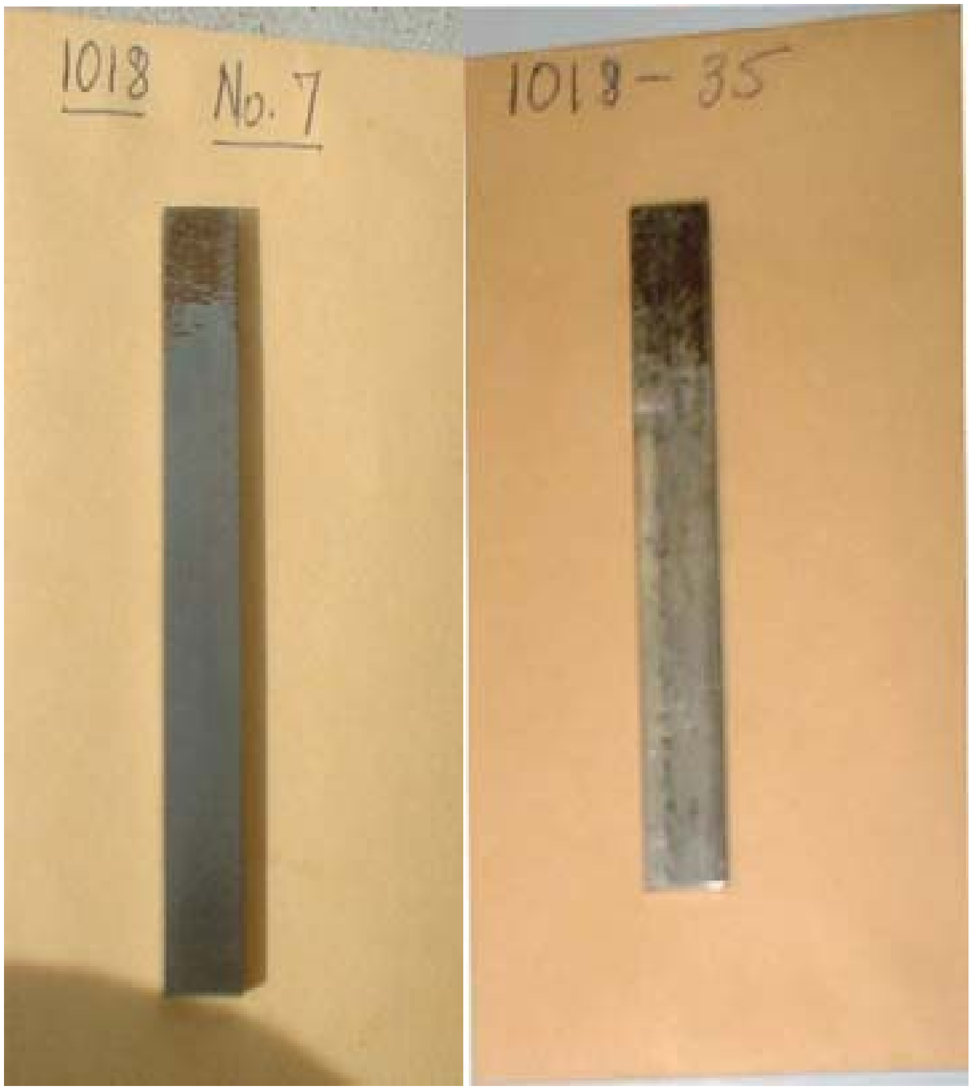

Figure E.4.3. Evidence of corrosion above the "diesel"/emulsion interface after exposure for more than 30 days at room temperature. The effects of separation are apparent in these photographs of two of the specimens. No. 7 was immersed in summer-grade PuriNOx for 31 days. No. 35 was immersed in winter-grade PuriNOx for 42 days. The top part shows evidence of corrosion. This is the part that remained above the "diesel"/emulsion interface.

Figure E.4.4. Evidence of corrosion after removal from immersion and storage in a test tube for 20 days at room temperature. Sample No. 26 of the 1018 steels was removed from summer-grade PuriNOx after 11 days of immersion. It was kept in a clean dry test tube so that the fuel could drip off the sample. After about day 20, corrosion was observed at the bottom of the sample. The rest of the body of the specimen was unaffected.

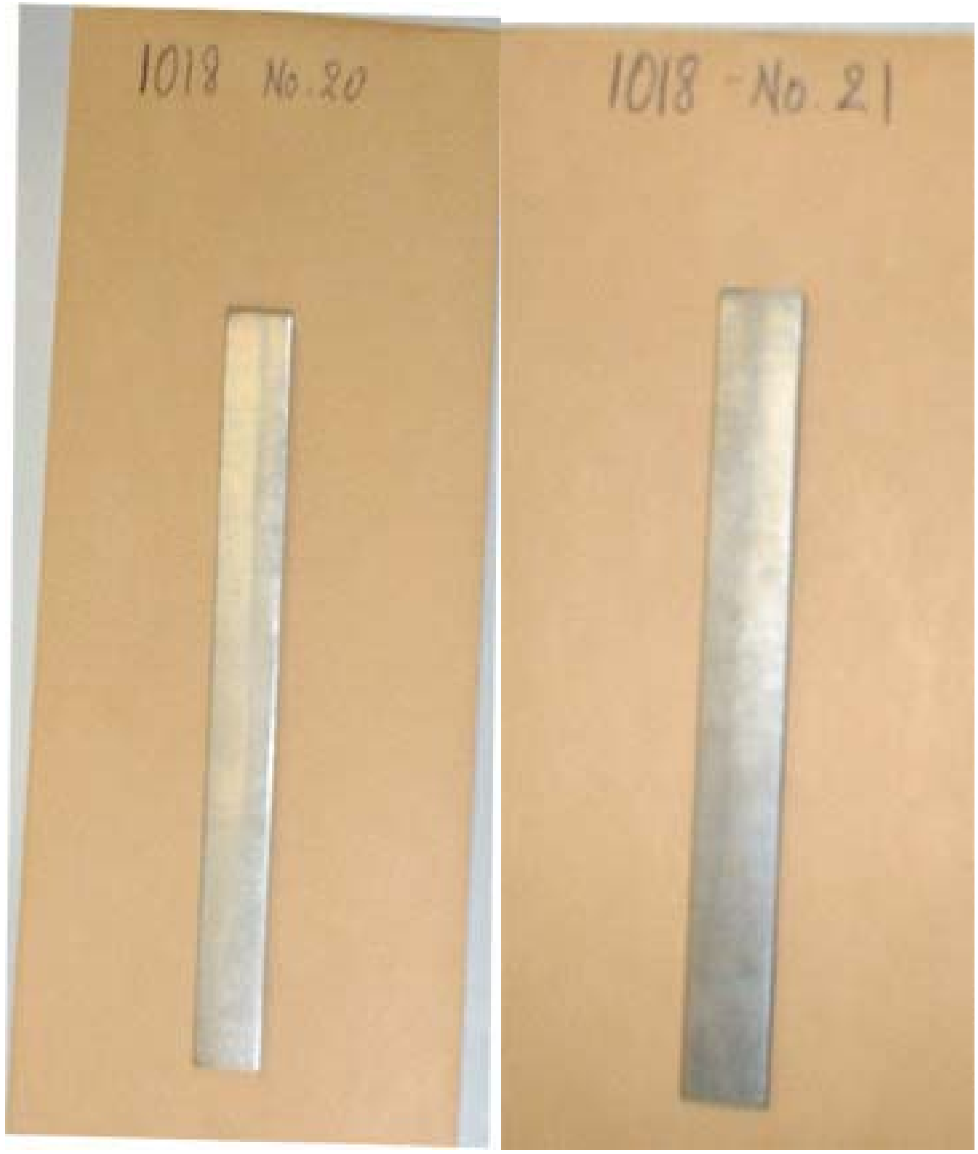

Figure E.4.5. Specimens removed after exposure to 2D diesel for 42 days at room temperature. Samples No. 20 and 21 were immersed in 2D diesel for 42 days. No corrosion was observed on these samples.

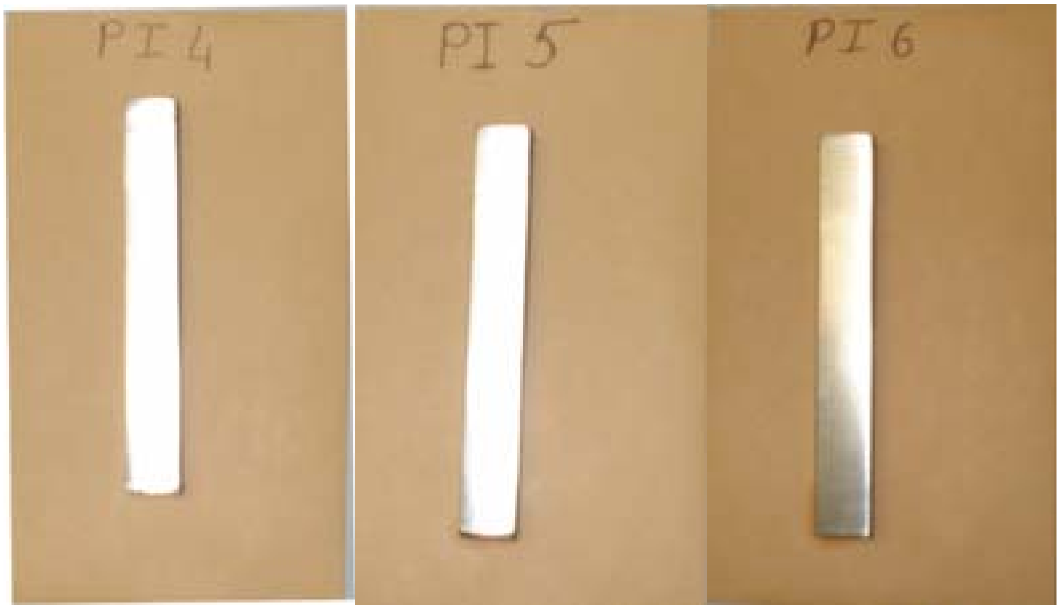

Figure E.4.6 : Specimens 4, 5 and 6 were removed from summer-grade PuriNOx, winter-grade PuriNOx and pure diesel fuel, respectively, after 14 days of immersion using the planned interval test at room temperature. Notice, corrosion is present only at the lower ends of the specimens, caused by the fuel which dripped off and accumulated at the bottom of the test tubes during the drying period.

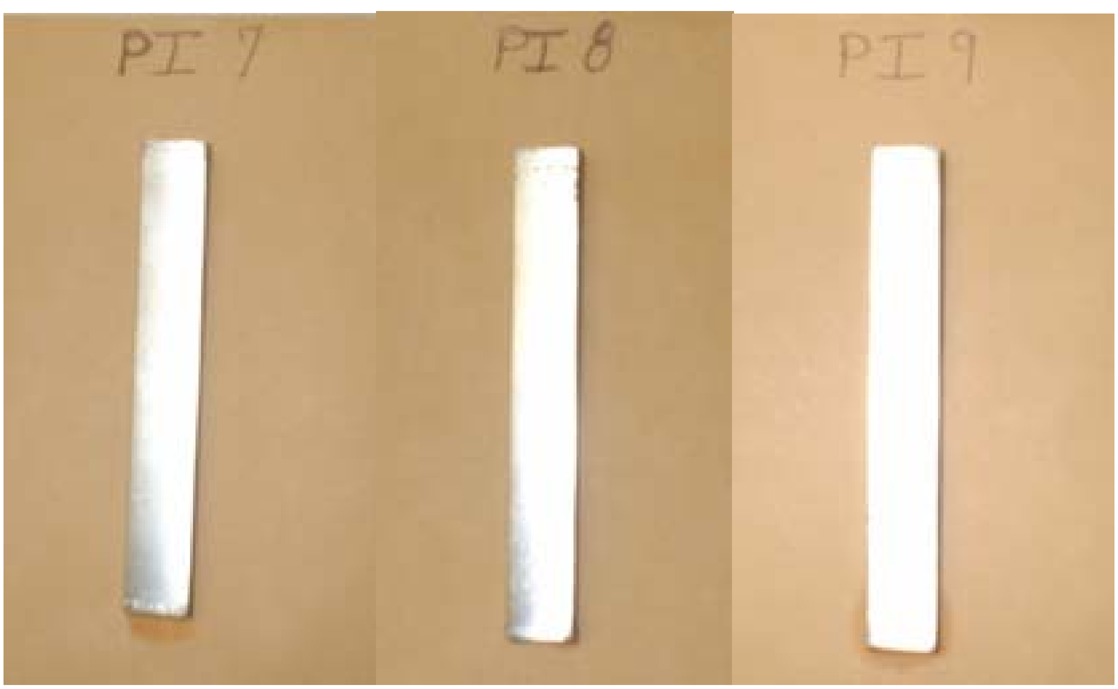

Figure E.4.7 : Specimens 7,8 and 9 were removed from summer-grade PuriNOx, winter-grade PuriNOx and pure diesel fuel, respectively, after 3 weeks of immersion using the planned interval tests at room temperature. In Specimen no. 7, we notice the beginning of corrosion above the "diesel"/emulsion interface. In Specimen no. 8, the corrosion is a little more severe, and in sample no. 9, no corrosion is observed.

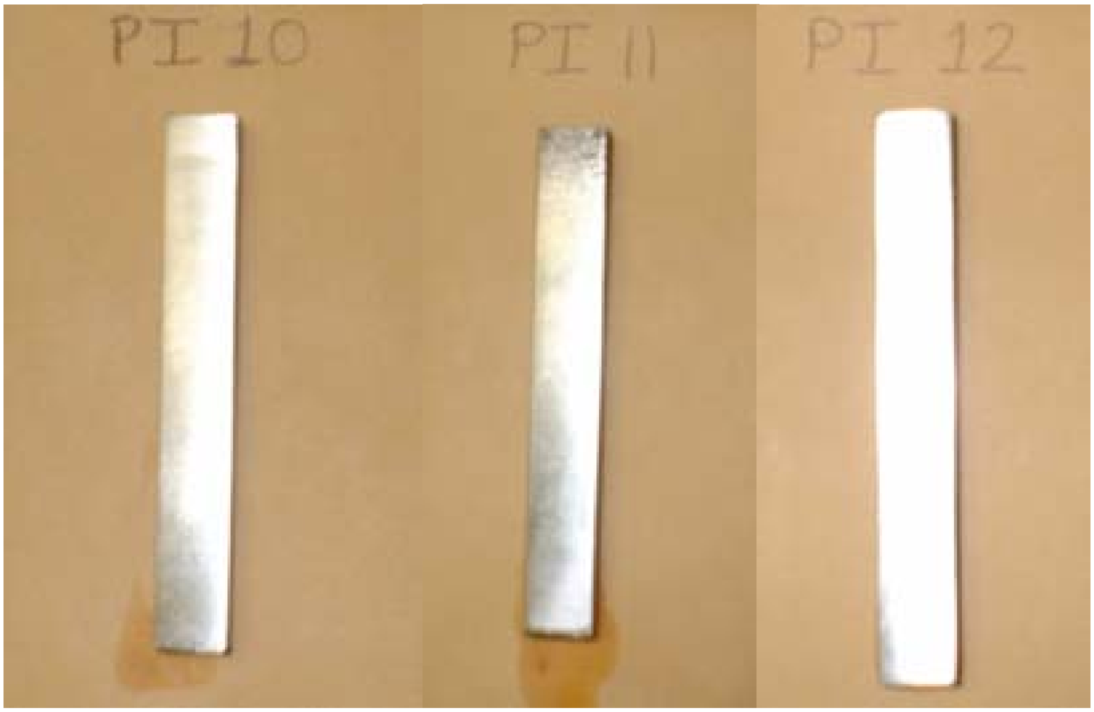

Figure E.4.8 : Specimens 10, 11 and 12 were removed from ***used*** *summer-grade PuriNOx,* ***used*** *winter-grade PuriNOx and* ***used*** *2D diesel fuel after 3 weeks of immersion at room temperature. The corrosion in this* ***used*** *fuel progressed at a faster rate. Specimen No. 11, which was immersed in winter-grade PuriNOx, suffered more corrosion than Specimen No. 8, which was kept in fresh winter-grade PuriNOx, for the same amount of time.*

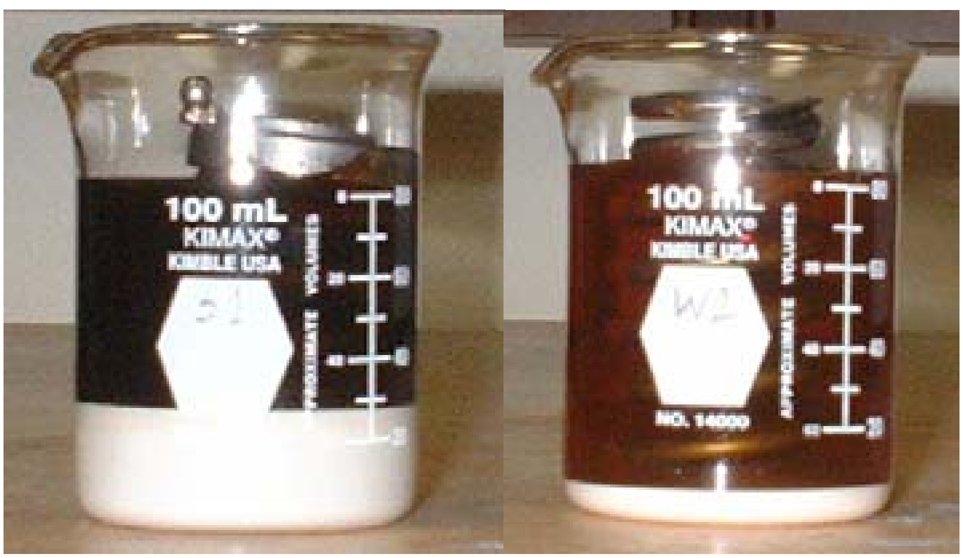

Figure E.4.9 : This photograph shows the separation that has taken place in summer-grade and winter-grade PuriNOx after the beakers were placed in an oven maintained at 50 ºC. In the previous immersion tests at room temperature, corrosion generally took place above the PuriNOx-diesel interface. In this case, because of such severe separation, almost the entire spring is above the interface after 15 days of immersion.

Figure E.4.10 : Coil springs removed from summer-grade PuriNOx after 15 days at 50 ºC. The increase in temperature resulted in an increase in the rate of the corrosion process. In the room-temperature tests, corrosion began after 3 weeks of immersion, but at the higher temperature, it began earlier.

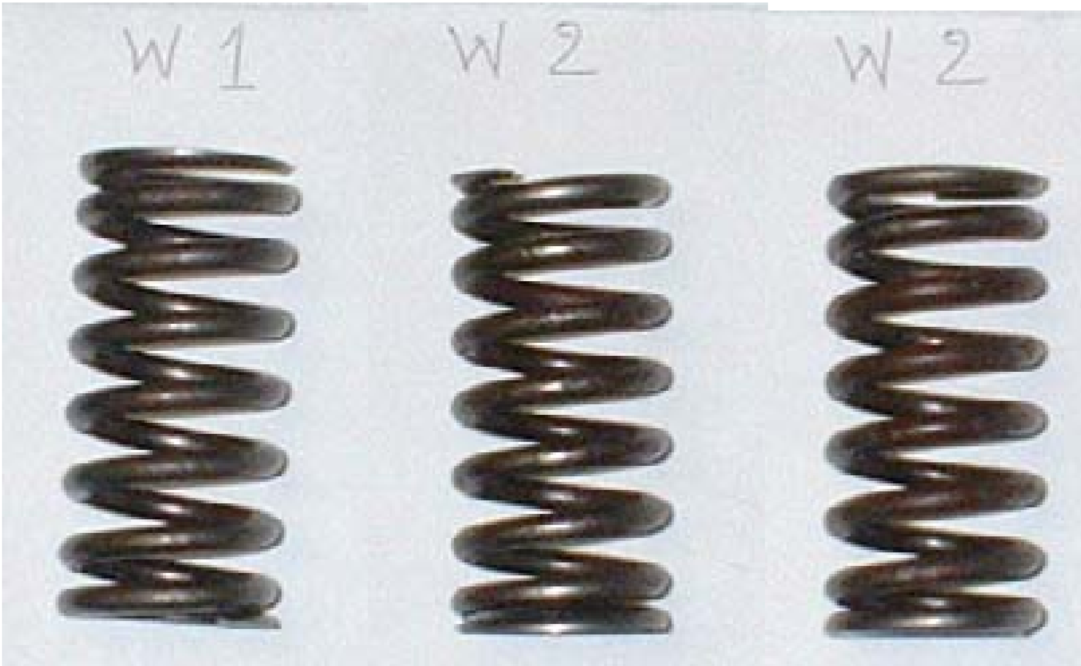

Figure E.4.11: These springs were immersed in winter-grade PuriNOx for 15 days at 50 ºC. Again, corrosion is noticeable.

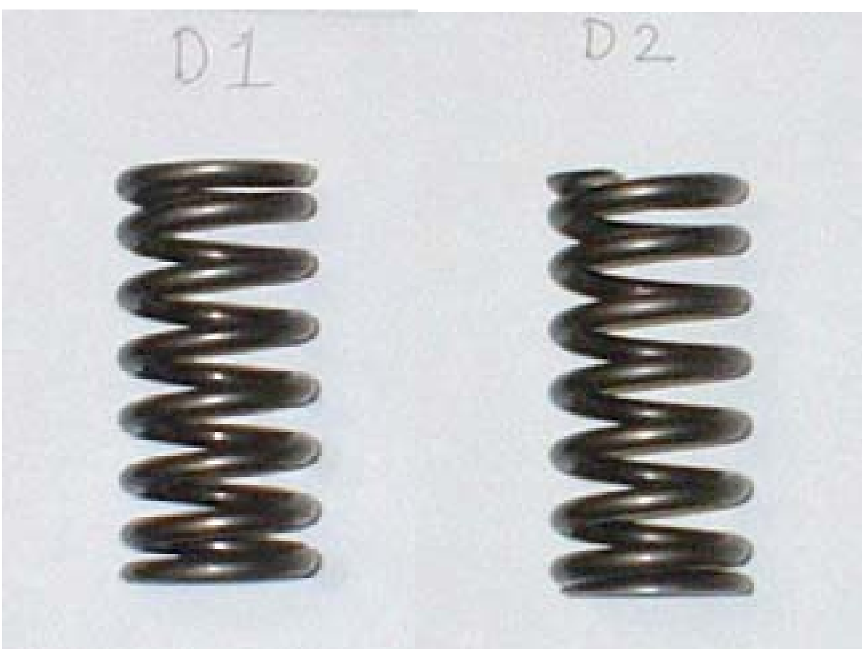

Figure E.4.12: These springs were immersed in 2D diesel for 15 days at 50 ºC. They do not show any signs of corrosion.

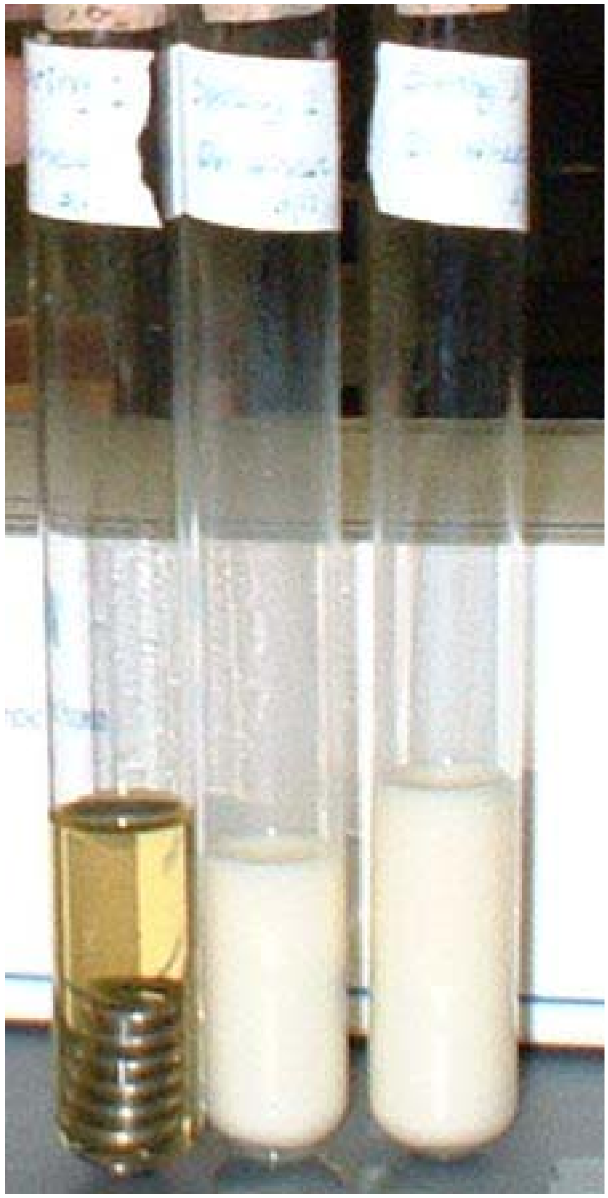

Figure E.4.13. Springs 1, 2 and 3 (from left to right) just after immersion in 2D diesel, winter-grade PuriNOx, and summer-grade PuriNOx.

Figure E.4.14. Springs 1, 2 and 3 (from left to right) after 16 days at 50 ºC in 2D diesel, winter-grade PuriNOx, and summer-grade PuriNOx.

E.5. Durability

As noted in Section 1.B, Lubrizol has commissioned two 1,000-hour durability studies, an injector deposit test, and a fuel lubricity test of PuriNOx in comparison with diesel fuel. The injector deposit test (Strete, 1998b) showed that PuriNOx will decrease deposits on the injectors. The 1,000-hour durability tests (Sarlo, 2001; Zaiontz, 2002) revealed less wear when using PuriNOx, especially of piston rings and liners. The lubricity test commissioned by Lubrizol (Strete, 1998a), plus information from the literature (Gonzalez et al. 2001), shows that stabilized emulsions such as PuriNOx have superior lubricity as compared with diesel fuel, in spite of the large fraction of water in the emulsion. This indicates that injector pump durability might not be adversely affected by the water in the emulsion. However, concern remains over the durability of fuel injectors and fuel pumps, especially for engines that use very high fuel injection pressures. To our knowledge, no durability studies of winter-grade PuriNOx have been performed. The methanol in winter-grade PuriNOx is very corrosive. This poses a significant concern about the effects of winter-grade PuriNOx on the durability of injection pumps and injectors.

Mack Trucks (which makes its own engines) approves the use of PuriNOx. Caterpillar has approved the use of PuriNOx in their older pump-line-nozzle group of engines (specifically the 3208, 3304, 3306, 3406B, 3406C, 3408B, 3408C, 3412B, and 3412C). However, Caterpillar has not approved the use of PuriNOx in their newer, electronically injected engines. For these engines, they found the same types of injector failures as when using diesel fuel, but with a higher failure rate when using PuriNOx. Caterpillar is still studying this issue. Cummins has found the same injector failure modes as those for diesel fuel, but with more frequent failures when using PuriNOx. In general, the heavy-duty diesel engine manufacturers will not cover any part, under warranty, that fails due to the use of PuriNOx (or any other unconventional fuel or additive). However, Lubrizol says that it will warranty these components.

During the first 6 months of this project, the research team observed 23 pieces of equipment operating on PuriNOx: 18 vehicles at the Roadeo, 2 Gradall engines on the engine dyno at SwRI, and 3 single-axle dump trucks on the chassis dyno at SwRI. We witnessed a failure rate of approximately 10%. One of the dump trucks began operating very roughly during the fourth driver's run during the Roadeo. A filter and three injectors were replaced. This dump truck had been operating on PuriNOx for 4 months prior to the Roadeo. The other failure was a Cummins 6BTA5.9 engine extracted from a Gradall for testing at SwRI. This engine had never run on PuriNOx previously, accumulating approximately 2,900 hours on 2D on-road diesel fuel. It ran satisfactorily during the preconditioning runs on diesel fuel on the engine dyno. However, when switched to PuriNOx, it operated very roughly. After changing filters a few times without curing this problem, SwRI called in local TxDOT mechanics, who in turn called in local Cummins representatives. All injectors and the pump were replaced, after which the engine operated satisfactorily on PuriNOx. The pump was later found, by Cummins, to be normal (O'Keefe, 2002). Cummins also volunteered to inspect the injectors but, owing to a communication breakdown, they were discarded by SwRI. However, it is obvious that at least one of the injectors worked satisfactorily with diesel fuel but not with PuriNOx. Cummins suspects that this may be due to a machining feature in the Bosch injectors used in this engine (O'Keefe, 2002). They have found that injectors that fail when using PuriNOx open at too low a fuel pressure (injection begins too early during these failures).

In the 6 months prior to converting to PuriNOx, the Houston District did not replace any injectors or injection pumps in any of their diesel equipment (448 engines). In the 6 months after switching to PuriNOx, they replaced 29 injectors and 4 pumps for the 386 engines that were converted. Because this is the largest fleet that has ever used PuriNOx, and because it is the only hard data that is available, it must suffice for the cost-effectiveness analysis. It is assumed that 2% of the pumps must be replaced annually and that 15 injectors are replaced annually for every 100 engines.

E.6. Summary of Maintenance Issues

The maintenance issues related to use of PuriNOx are increased maintenance costs and difficulty starting the engines. The hard-starting problem has resulted in TxDOT's starting all engines at least twice per week, even when the equipment is not needed for service. The need for frequent starting is a labor cost and also leads to a burden on fuel consumption and emissions.

The fuel system components that have required more frequent replacement are fuel filters, injectors, and fuel pumps. For the purposes of the cost analysis, it is assumed that 2% of the pumps must be replaced annually and that 15 injectors are replaced annually for every 100 engines. It is expected that durability problems will be worse for winter-grade PuriNOx because of the methanol in this fuel. However, there have been no durability studies for winter-grade PuriNOx.

Too little information is presently available to account for longer term effects in the cost analysis. Some of these long-term effects may be positive, such as the potential that PuriNOx results in fewer injector tip deposits and less wear of piston rings and liners. Some long-term effects may be negative, such as the possibility that PuriNOx might lead to fuel tank corrosion.

Our studies indicate, but do not prove, that hard starting, corrosion, and perhaps injector and pump failures are related to separation of the emulsion. We have found that separation is a strong nonlinear function of temperature, with much higher separation rates at higher temperatures. The highest temperature we examined was approximately 55 ˚C (130 ˚F), but fuel temperatures in the injectors can be much higher. When the engine is turned off after use, many of the components approach coolant temperature (approximately 200 ˚F), including the fuel in the injectors. Thus, we suspect that the fuel separates faster in the fuel delivery system than in the fuel tank. Our tests of this hypothesis indicate that it is valid. Therefore, we believe that the hard starting problem, after only a few days of not running the engine, may be due to fuel separation, so that the engine is trying to start and idle on a fuel that is rich in heavy fuel components and/or water. Our studies also indicate that corrosion rates are greatly enhanced in the upper, transparent portion of the separated emulsion. If so, and if the fuel is separating rapidly in the injectors as we also believe to be true, perhaps the injector springs are corroding. In turn, this might decrease the spring stiffness, explaining why the injectors open at a fuel pressure that is too low. However, our experiments with actual injector springs did not support this hypothesis. This means either that the increased rate of injector failures is not related to the springs or that the experiments were not conducted over a long enough period and/or at high enough temperature to produce the expected effects.

Appendix F. Fuel Properties

Typical properties for summer- and winter-grade PuriNOx and for 2D low sulfur diesel (LSD) are provided in Table F.1, from data provided by Lubrizol. As part of this project, SwRI tested the flash points of both summer- and winter-grade PuriNOx. The results of those tests are shown in Table F.1 and discussed in Section 4.B. Also, because of TxDOT complaints of hard starting, Lubrizol changed the specification of the diesel fuel from which they were blending PuriNOx. The Cetane Number for the original version of PuriNOx that TxDOT was using was measured by SwRI to be 36.9, as is shown in this table. However, Lubrizol notes that the Cetane Number of emulsified diesel fuels is not accurately measured using the normal technique (ASTM D613). The Cetane Number is a measure of the ignition delay of the fuel, normally measured in a standardized diesel engine. The ignition delay can also be measured in a pressurized combustion vessel. This is an Ignition Quality Test (IQT), and the results from this test correlate extremely well with the Cetane Number measured in the traditional manner for conventional diesel fuels. SwRI measured the Cetane Number, using the IQT technique, of the newer PuriNOx supplied to TxDOT as 47.9, and that of the summer-grade PuriNOx supplied by Lubrizol for the various tests at UT as 52.0, and that of the summer-grade PuriNOx supplied to SwRI for their emissions and fuel economy tests as 44.7. The baseline diesel fuel that was used for the UT tests, and from which the summer-grade PuriNOx used at UT was blended, had a Cetane Number of 45.5, as measured by SwRI using the IQT technique. The winter-grade PuriNOx used by UT had a Cetane Number of 47.6. However, SwRI measured the Cetane Numbers of the baseline diesel fuel supplied to them by Lubrizol for emissions and fuel economy testing as 51.5, which was higher than the 47.3 Cetane Number measured for a sample of commercial 2D on-road diesel from the Houston District. Due to concerns about the differences between the commercial and test versions of PuriNOx and of diesel fuel, tests were done for a dump truck using two versions of PuriNOx and two versions of diesel fuel. The results of these tests are reported in Appendix B.

Table F.1 Properties of Low Sulfur Diesel Meeting ASTM D975 Specifications and Typical Properties of PuriNOx (all from Lubrizol) Fuel Properties Measured for the Present Project are Also Listed.

Property	Units	2D On-Road LSD	Summer-Grade PuriNOx	Winter-Grade PuriNOx	ULSD - TxLED	High Sulfur Non-Road 2D Diesel	Low Sulfur Non-Road 2D Diesel
Flash Point, min	°F	126	162-203	≥100	-	-	-
Flash Point, SwRI tests for this project	°F	-	171	121	-	-	-
Water and Sediment, max	vol%	0.0500	NA(1)	NA(1)	-	-	-
Water and Sediment, typical	wt%	-	19-21	19-21	-	-	-
90% Distillation Temp., min/max	°F	540/640	NA(2)	NA(2)	554	-	-
Kinematic Viscosity at 40 °C, min/max	mm^2/s	1.9/4.1	4.0-5.8	3.1-4.6	2.37	-	-
Ash, max	wt%	0.01	0.00	0.00	0.0014	-	-
Sulfur, max	ppm(mass)	500	100-350	200-350	0.1	2570	360
Cu Strip Corrosion Rating, max 3 hr at 50 °C		No. 3	1A	1A	1A	-	-
Cetane No., min (ASTM D613-84)	-	40	48-52 (3)	43 (4)	52.3	46.1	51.3
Cetane No., SwRI IQT tests for Lubrizol	-	40	41-51	41-45	-	-	-
Cetane No., present SwRI tests, orig. PuriNOx (5)	-	-	36.9	-	-	-	-
Cetane No., present SwRI IQT tests, HOU fuels (6)	-	47.3	47.9	-	-	-	-
Cetane No., present SwRI IQT tests, UT fuels (6)	-	45.5	52.0	47.6	-	-	-
Cetane No., present SwRI IQT tests, SwRI fuels (6)	-	51.5	44.7	-	-	-	-
One of the following properties must be met for ASTM D975 specification LSD:							
Cetane Index, min	-	40	NA(7)	NA(7)	53.5		
Aromatics, max	vol%	35	13-27 (8)	13-27 (8)	0.51		
Cloud Point, max	°F	footnote A	NA(9)	NA(9)	-36		
Carbon residue, max (10)	wt%	0.35	0.04-0.18	0.01-0.23	0.01		
Additional properties (not specified for ASTM D975 LSD):							
Specific Gravity (15.6/15.6 °C)	-		0.856-0.890	0.855-0.890	0.824	0.8507	0.8318
Specific Gravity measured by UT	-	0.842 ±.002	0.856 ±.002	0.856 ±.002	0.825		
Cold Filter Plugging Point	°F		3 to 14	-26 to 9	-		
Pour Point	°F		-33 to -11	-49 to -31	-35		
Freeze Point	°F		-44 to -18	-62 to -35	-		
Freeze Point measured by UT	°F		-15±4	-34±4	-11±4		

(1) - ASTM D2709 (centrifuge method for determination of low water levels) is not applicable to water emulsified fuels since the emulsion is stable and is high in water content by design. ASTM D6304 is a coulometric titration method which can be used for the quantitation of high water levels in diesel fuels.

(2) - ASTM D86 cannot be run on water emulsified fuels since the automated distillation procedure terminates prematurely due to uneven distillation of the water/fuel mixture. The base diesel fuels used to blend PuriNOx adhere to the ASTM distillation specification.

(3) - limited data, CARB fuel only.

(4) - limited data.

(5) - ASTM D613-84 tests of a sample of PuriNOx originally supplied to TxDOT.

(6) - HOU fuels: commercial fuels in the Houston District; UT fuels: fuels provided by Lubrizol to UT for the present tests; SwRI fuels: fuels provided by Lubrizol to SwRI for the present tests.

(7) - Since CI (D976 and D4737) is calculated based on D86 and D4052 data, CI cannot be determined on emulsified fuels due to difficulties with the D86 distillation (See note 2).

(8) - ASTM D1319 cannot be run on the emulsified fuel due to interaction of the water with the GC column. Aromaticity can be estimated based on the aromatic content of the starting diesel fuel and diesel content of the emulsified fuel. Aromatic content of PuriNOx is always less than that of the base diesel fuel used to blend the emulsion.

(9) - The cloud point of the emulsified fuel cannot be determined due to the inherent opacity of the emulsion. The LTFT (ASTM D5439) or CFPP (ASTM D6371; manual) methods can be used to assess low-temperature properties (specifications dependent on geographical location).

(10) - Ramsbottom carbon residue on 10% distillation residue, ASTM D524.

A- geographical spec.

Except where noted as measured for this project: properties for LSD, summer-grade PuriNOx, and winter-grade PuriNOx provided by Lubrizol; TxLED properties from Valero; high and low sulfur off-road diesel from SwRI.

Appendix G. Photographs

Photo G.1 A telescoping boom excavator rests with the excavating arm on the ground. This Gradall XL3100 was equipped with a datalogger to measure how TxDOT operators ran the equipment on a second-by-second basis. This data was then used to develop an engine test cycle over which emissions and fuel economy were measured for the different fuels.

Photo G-2 A Caterpillar 980G wheeled loader with electronically controlled engine owned by Capital Aggregates was equipped with a datalogger to measure second-by-second usage patterns.

Photo G-3 On this first day of Roadeo exercises TxDOT employees begin a prescribed field exercise with a telescoping crane (bucket truck). Here, the employees are initiating the field activities by setting the crane's outriggers.

Photo G-4 After the outriggers are set, the crane arm is extended and exercised.

Photo G-5 A tandem-axle TxDOT dump truck waits at a traffic light during the on-road exercise of the first day of the Roadeo. Accelerations from stoplights were closely evaluated to determine the impact of fuel type on the vehicle's acceleration.

Photo G-6 Vehicle accelerations at freeway on-ramps were also analyzed to find the effect of fuel on the vehicle's acceleration. Since these trucks were typically operated at full throttle as they entered the freeway, performance at these common points of similar driving could be compared among the trucks.

Photo G-7 During the Roadeo this tandem-axle TxDOT dump truck is engaged in the driving exercise. Note that the truck is loaded.

Photo G-8 A telescoping boom excavator undergoes its work activity test by loading a tandem-axle dump truck with material excavated from the median during the first day of the Roadeo.

Photo G-9 Here, a wheeled loader is being outfitted with dataloggers to measure second-by-second vehicle speed and engine RPM during the second day of Roadeo activities.

Photo G-10 This photo shows dataloggers and associated wiring harnesses mounted on a forklift to be used during the second day of Roadeo activities.

Photo G-11 Please note the vehicle speed sensor mounted over the front wheel of this forklift. This speed sensor measures pulses from the six magnets mounted evenly around the perimeter of the forklift's front wheel. This information is sent to the dataloggers and converted to vehicle speed.

Photo G-12 Similarly, engine RPM is measured using a magnet/pickup coil assembly. Due to the small pulley size and the relatively high rate of rotation, only one magnet is necessary on this pulley.

Photo G-13 The dataloggers are calibrated to convert pulse information to vehicle speed and engine RPM.

Photo G-14 The outfitted forklift is ready to go!

Photo G-15 In addition to the electronically logged data, observers recorded activity information during Roadeo exercises. Here, observers witness second day Roadeo forklift exercises.

Photo G-16 Forklifts move loaded pallets during the forklift exercise. Operators were surveyed after the exercises to see if they could identify performance differences among the vehicles.

Photo G-17 Here, a TxDOT operator scoops material from a pile during the second day Roadeo wheeled loader exercises.

Photo G-18 After the material is scooped from the pile, the wheeled loader is driven to a dump truck where the load is transferred. Here too, observers recorded activity information during the Roadeo exercises.

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