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16. Abstract

Emissions that lead to the formation of ozone have distinctive temporal patterns, and the chemistry of ozone formation is non-linear and introduces time lags between emissions and ozone formation. As the transition is made between the 1-hour ozone National Ambient Air Quality Standard (NAAQS) and the 8-hour NAAQS, critical questions arise about the effectiveness of potential new mobile source control strategies for reducing 8-hour averaged ozone concentrations in Texas non-attainment areas. This project had two primary objectives. The first objective was to examine the relative effectiveness of potential new emission control measures, primarily from mobile sources, on 1-hour and 8-hour ozone concentrations and population exposure metrics in the Houston and Dallas areas. The second objective was to conduct a pilot-scale study to examine how portable emissions monitoring system (PEMS) technology can be used to characterize exhaust emissions from heavy-duty diesel vehicles and equipment during real-world driving conditions. The overall goal of the research was to provide a foundation for effective transportation and air quality policy decisions in eastern Texas. A total of thirty-eight modeling simulations were conducted to examine a range of emission control strategies. This modeling indicated that even with reductions in on-road and non-road mobile source emissions greater than 40 percent, at least one monitor in each area is still predicted to remain in non-attainment. Given these challenges, it is recommended that TxDOT continue to investigate eligibility for Texas Emission Reduction Program (TERP) funding to reduce NOx emissions from on-road heavy-duty diesel vehicles and non-road equipment (particularly diesel construction equipment) and continue to pursue effective emission control strategies that can be adopted both locally and statewide to assist in obtaining regional NOx reductions. The pilot-scale PEMS study demonstrated the successful deployment of the Sensors, Inc. SEMTECH-D PEMS on single-axle and tandem-axle dump trucks during typical TXDOT operations. Idling accounted for the most significant fraction (20 percent–46 percent) of the duty cycle and had the highest average and median fuel-specific emission factors for all pollutants. TxDOT should continue to examine the idling practices of its dump trucks with respect to the impacts on both emissions and fuel consumption. Differences in emissions between non-idling modes of operation varied by pollutant. CO_2 and NOx emissions were reasonably consistent between non-idling modes; CO and THC emissions exhibited greater variability with differences of a factor of two, or three in some cases. The range of NOx emission factors measured in this study showed very good agreement with emission factors measured through chassis dynamometer testing of the same engine types by Baker et al., (2004), and were well within the range of values reported in other studies. TxDOT should continue to characterize baseline emissions from other on-road and non-road equipment besides dump trucks during typical operations, as well as examine the effectiveness of new fuels and fuel additives and new after-market emission reduction technologies that will be emerging from TERP, the New Technology Research and Development (NTRD) Program, and similar state or national-scale incentive programs.

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Evaluation of Emission Control Strategies for the 8-Hour Ozone Standard in the Houston and Dallas Areas and A Pilot-Scale Study of In-Use Emissions from Heavy-Duty Diesel Dump Trucks using a Portable Emissions Monitoring System (PEMS)

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Executive Summary

Emissions that lead to the formation of ozone have distinctive temporal patterns, and the chemistry of ozone formation is non-linear and introduces time lags between emissions and ozone formation. As the transition is made between the 1-hour ozone National Ambient Air Quality Standard (NAAQS) and the 8-hour NAAQS, several critical questions arise:

1. Certain emission control strategies for mobile sources have been adopted in the State Implementation Plans for reducing ozone concentrations averaged over 1 hour. Will the strategies be equally effective in reducing ozone concentrations averaged over 8 hours?
2. What is the magnitude of emission reductions from potential new mobile source control measures and how will these measures affect 1-hour and 8-hour averaged ozone concentrations in eastern Texas?

This project had two primary objectives and components. The first objective was to examine the relative effectiveness of potential new emission control measures, primarily from mobile sources, on 1-hour and 8-hour ozone concentrations and population exposure metrics in the Houston and Dallas areas. The second objective was to conduct a pilot-scale study to examine how portable emissions monitoring system (PEMS) technology can be used to characterize exhaust emissions from heavy-duty diesel vehicles and equipment during real-world driving conditions. The overall goal of the research was to provide a foundation for effective transportation and air quality policy decisions in eastern Texas.

The first objective was addressed using the Comprehensive Air Quality Model with Extensions (CAMx), which is the only photochemical grid model currently used by the State of Texas for developing air quality plans. Two modeling episodes developed by the State of Texas for use in the State Implementation Plan (SIP) were also used in this project:

- Houston/Galveston and Beaumont/Port Arthur: August 22–September 6, 2000
- Dallas/Fort Worth: August 13–22, 1999

Emission inventories that were developed by the Texas Commission on Environmental Quality (TCEQ) for the year 2010 were used as the basis for future control scenarios. On-road mobile source emissions were based on the Environmental Protection Agency's (EPA) MOBILE6.2 model (EPA, 2003), and non-road mobile source emissions (with the exception of aircraft, locomotive, and commercial marine sources) were based on EPA's NONROAD 2002 model (EPA, 2002). A total of thirty-eight modeling simulations, summarized briefly in Table ES-1, were conducted to examine a range of emission control strategies selected through collaborative efforts with the Texas Department of Transportation (TxDOT) during project brainstorming sessions, through emerging research efforts at The University of Texas at Austin, and through control strategy lists developed by the Texas Transportation Institute (TTI), the Houston-Galveston Area Council (H-GAC), and the North Central Texas Council of Governments (NCTCOG).

Table ES-1. Summary of 2010 modeled scenarios in the Houston/Galveston and Dallas/Fort Worth areas

Modeling Run	Description
Base 2010	Future year (2010) run with no additional reductions
VMT05LDV	5% reduction in light-duty vehicle emissions
VMT05HDV	5% reduction in heavy-duty vehicle emissions
VMT15LDV	15% reduction in light-duty vehicle emissions
VMT15HDV	15% reduction in heavy-duty vehicle emissions
VMT25LDV	25% reduction in light-duty vehicle emissions
VMT25HDV	25% reduction in heavy-duty vehicle emissions
VMT100HDV	100% reduction in heavy-duty vehicle emissions
I/M (Inspection & Maintenance)	Expand OBD program statewide, reinstate I/M program in Chambers, Liberty, and Waller Counties
Idle [HGB only]	Eliminate emissions attributed to extended idling from heavy-duty diesel trucks
LEVII	Estimated potential emission reductions from adopting California Low Emission Vehicle (LEV II) standards in Texas over current Tier 2 standards
RVP	Reduce statewide RVP to 7.0 psi in all Texas counties that currently allow RVP above this value
CBCP [DFW only]	Estimated potential emission reductions from a credit-based congestion pricing (CBCP) scenario for Dallas
Construct_Shift [HGB only]	Restrict construction equipment from operating from 6 a.m. through 12 noon
Zero_Construct	Eliminate emissions from construction equipment
15dieselNOx	15% reduction from on-road and non-road diesel mobile source NOx
Zero_Marine [HGB only]	Eliminate emissions from commercial marine vessels
Bundle 1	Includes RVP, I/M, VMT05LDV, VMT05HDV, Idle
Bundle 2	Includes RVP, I/M, VMT15LDV, VMT15HDV, Idle, LEVII, 15dieselNOx
Bundle2.areapt25	Same as Bundle2 with additional 25 % reduction to area and elevated point source emissions
Bundle 3	Includes RVP, I/M, VMT25LDV, VMT100HDV, Idle, LEVII, 15dieselNOx, Zero_Construct, Zero_Marine

Modeling results with and without the modeled control scenario were evaluated using various metrics, including differences in daily maximum predicted 1-hour and 8-hour average ozone concentrations in the non-attainment areas, future 8-hour ozone design values at each monitor in the non-attainment areas, and total daily population exposure.

In the Houston/Galveston area, average differences in daily maximum predicted 1-hour and 8-hour average ozone concentrations ranged from 0.0 to 13.9 ppb and 0.0 to 8.0 ppb, respectively. The future design value at the Bayland Park monitor, which has the highest value of all monitors in the Houston area (100 ppb), is reduced by approximately 11 ppb in the "Bundle3" scenario, which includes 160 tpd NOx reductions in on-road and non-road mobile sources. In the Dallas/Fort Worth area, average differences in daily maximum predicted 1-hour and 8-hour average ozone concentrations range from 0.0 to 8.7 ppb and 0.0 to 5.9 ppb, respectively. The future design value at the Frisco monitor, which has the highest value of all monitors in the Dallas/Fort Worth area (92 ppb), is reduced by approximately 5 ppb in the "Bundle3" scenario, which includes 130 tpd NOx reductions in on-road and non-road mobile sources. This modeling indicates that even with reductions in on-road and non-road mobile source emissions (as in "Bundle3") greater than 40 percent, at least one monitor in each area is still predicted to remain in non-attainment. Given these challenges, it is recommended that TxDOT continue to investigate eligibility for Texas Emission Reduction Program (TERP) funding to reduce NOx emissions from on-road heavy-duty diesel vehicles and non-road equipment (particularly diesel construction equipment) and continue to pursue effective emission control strategies that can be adopted both locally and statewide to assist in obtaining regional NOx reductions.

Earlier emissions testing programs were conducted primarily in laboratory settings using engine or chassis dynamometers. Now, however, new federal rules require measurement of exhaust emissions from on-road and, in the future, non-road heavy-duty diesel engines during *real-world driving conditions* using PEMS. The second objective of this project was to conduct a pilot study to examine how PEMS technology can be used to characterize exhaust emissions from TxDOT heavy-duty diesel vehicles/equipment during typical operations. This pilot-scale study demonstrated the successful deployment of the Sensors, Inc. SEMTECH-D PEMS on single-axle and tandem-axle dump trucks. These trucks consume approximately 40 percent of the diesel fuel used by on-road equipment in the TxDOT fleet in the 12 major ozone non-attainment counties in Texas (Baker et al., 2004). Exhaust emissions were measured during typical TxDOT duty cycles, and a modal emissions analysis was conducted. Idling accounted for the most significant fraction (20 percent–46 percent) of the duty cycle and had the highest average and median fuel-specific emission factors for all pollutants. Although emissions during this mode of operation may represent a smaller fraction of the total emissions on a mass basis, TxDOT should continue to examine the idling practices of its dump trucks with respect to the impacts on both emissions and fuel consumption.

Differences in emissions between non-idling modes of operation varied by pollutant. CO_2 and NOx emissions were reasonably consistent between non-idling modes; CO and THC emissions exhibited greater variability with differences of a factor of two, or three in some cases. The range of NOx emission factors measured in this study showed very good agreement with emission factors measured through chassis dynamometer testing of the same engine types by Baker et al. (2004), and were well within the range of values reported in other studies. TxDOT should continue to characterize baseline emissions from other on-road and non-road equipment besides dump trucks during typical operations. Future PEMS-based testing programs offer a significant advantage not only because emissions can be characterized under real-world conditions, but also because PEMS testing is considerably less expensive than dynamometer-based testing. New fuels and fuel additives as well as new after-market emission reduction technologies, will be emerging from TERP, the New Technology Research and Development (NTRD) Program, and similar state or national-scale incentive programs. The pilot-scale testing program under TxDOT Project 0-5191 focused only on characterization of baseline emissions from dump trucks as a demonstration of the PEMS technology; strategies for achieving emissions reductions have not been evaluated. Emission reduction technologies and/or fuels/fuel additives should be selected for in-use evaluation on TxDOT equipment. Inter-comparison of results study with other national (EPA) or state-level emission inventories for heavy-duty diesel engines should be conducted.

1. Evaluation of Emission Control Strategies for the 8-Hour Ozone Standard in the Houston and Dallas Areas

1.1 Background

The Houston/Galveston (HGB) and Dallas/Fort Worth (DFW) areas have been designated as non-attainment with respect to the National Ambient Air Quality Standard (NAAQS) for 8-hour average ozone concentrations. Eight counties in the HGB area (Brazoria, Chambers, Fort Bend, Galveston, Harris, Liberty, Montgomery, and Waller) and nine counties in the DFW area (Collin, Dallas, Denton, Tarrant, Ellis, Johnson, Kaufman, Parker, and Rockwall) are classified as moderate 8-hour non-attainment areas. While implementation of air quality regulations in these areas has gradually reduced the frequency of 1-hour exceedances during the last two decades, both areas are faced with the challenge of requiring stringent emission controls, in addition to federally mandated controls, in order to achieve compliance with the 8-hour standard by the June 15, 2010 attainment date.

Ozone is a secondary pollutant formed by the reaction of volatile organic compounds (VOCs) and nitrogen oxides (NOx) in the presence of sunlight. Because ozone formation is a non-linear process that depends on the concentrations of VOCs and NOx, photochemical grid models are used to evaluate the sensitivity of ozone concentrations to reductions of these precursor emissions. This study focuses on evaluating the air quality impacts of new emission control strategies, primarily for on-road and non-road mobile sources, on both 1-hour and 8-hour average ozone concentrations in the Houston/Galveston and Dallas/Fort Worth areas.

1.2 Photochemical Modeling

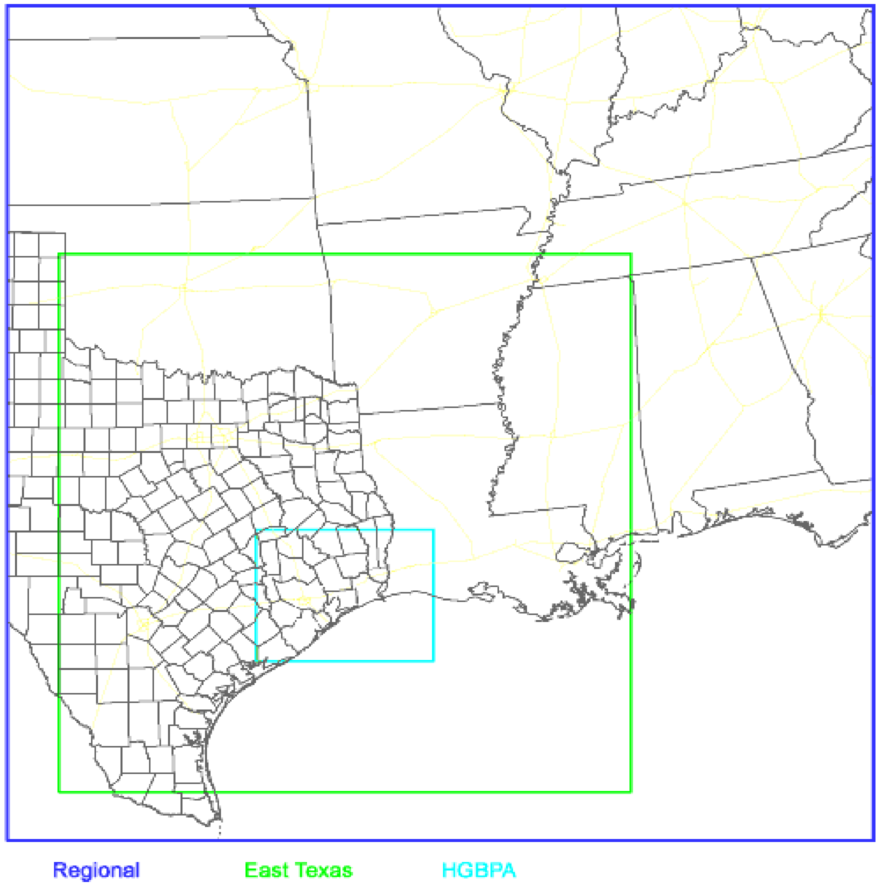
The State of Texas is currently using the Comprehensive Air Quality Model with extensions (CAMx) for its attainment demonstrations in the State Implementation Plan (SIP). CAMx, which has been approved by the U.S. Environmental Protection Agency (EPA) for regulatory applications, is a three-dimensional Eulerian photochemical grid model that determines pollutant concentrations by simulating processes associated with emissions, transport, chemistry, and deposition (ENVIRON, 2004). The following modeling episodes have been developed by the State of Texas for use in the SIP:

- Houston/Galveston and Beaumont/Port Arthur: August 22–September 6, 2000
- Dallas/Fort Worth: August 13–22, 1999

These historical air pollution episodes have been modeled by the Texas Commission on Environmental Quality (TCEQ), and the modeling meets U.S. EPA performance criteria. The meteorology from these episodes, which is representative of conditions favorable to the formation and accumulation of ground-level ozone, is then used in concert with future emission projections to estimate the potential impacts of future regulations. These models undergo constant refinement, and the future year modeling described here used CAMx version 4.03 with the latest available meteorological data and attainment year inventories at the time this study was initiated.

The Houston/Galveston model configuration is based on the Houston-Galveston-Brazoria ozone SIP mid-course review modeling used in support of the 1-hour ozone standard (TCEQ, 2004). The hybrid base case for 2000 combines two meteorological characterizations: MM5-GOES for the period of August 22–September 1 and MM5-ATMET for September 2–6. The hybrid base case also includes the terminal olefins-to-NOx adjustment. Details regarding this adjustment, the meteorological model configurations, as well as other input parameters can be found in the TCEQ's mid-course review SIP documentation (2004). The modeling domain for the Houston/Galveston episode is shown in Figure 1.1. It includes a 36-km regional scale grid that extends north to the lower Ohio River Valley and east to include Atlanta and the Tennessee Valley. The 12-km domain incorporates eastern Texas and Louisiana, and a 4-km urban scale grid includes the Houston/Galveston and Beaumont/Port Arthur areas.

The Dallas/Fort Worth model configuration is based on the run34 configuration using an expanded 36-km domain as well as a modified version of the CB4 chemical mechanism that includes extended inorganic chemistry with "NOx recycling" reactions (ENVIRON, 2005). The meteorological characterization is based on MM5 Run 6, which uses the ETA PBL scheme. Additionally, this configuration includes the "Kv100" vertical mixing adjustment, in which vertical diffusivities in the lowest 100 m were modified to the largest value within each column below 100m. Details regarding this adjustment, the meteorological model configurations, as well as other input parameters can be found in the Phase 2 Report for HARC Project H35 submitted by ENVIRON (2005). The modeling domain for the Dallas/Fort Worth episode is shown in Figure 1.2. The expanded 36-km domain extends the eastern boundary to the Atlantic coast and the northern boundary into parts of Canada. The 12km-nested grid covering eastern Texas and Louisiana is the same as in the Houston/Galveston episode, and a 4-km nested grid covers the Dallas/Fort Worth non-attainment area and surrounding counties.



Domain Name	Range (km)		Number of Cells		Cell Size (km)	
	Easting	Northing	Easting	Northing	Easting	Northing
Regional Domain	(-108,1512)	(-1584,72)	45	46	36	36
East Texas Subdomain	(-12,1056)	(-1488,-420)	89	89	12	12
HGBPA Subdomain	(356,688)	(-1228,-968)	83	65	4	4

Figure 1.1: CAMx 36/12/4-km nested grids for the HGB episode

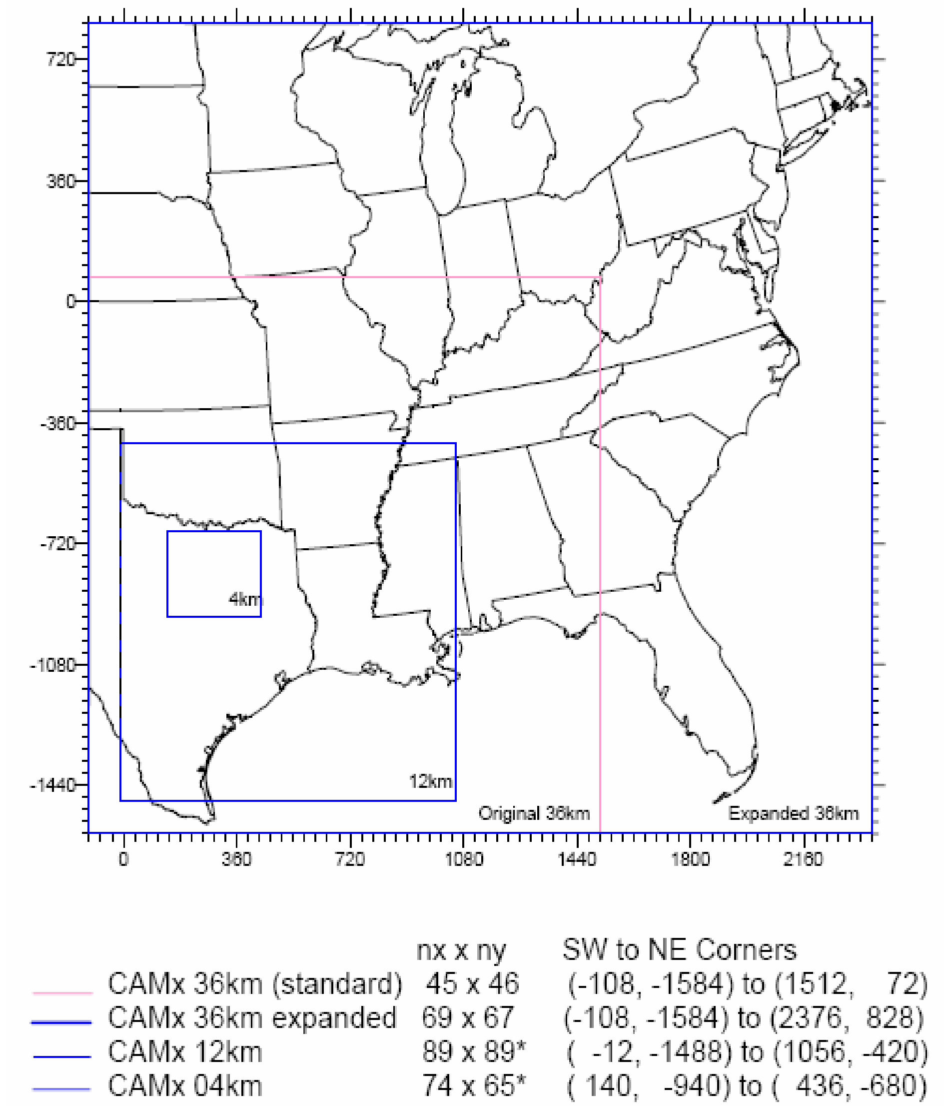


Figure 1.2: CAMx 36/12/4-km nested grids for the DFW episode

1.3 Mobile Source Emission Inventories

This study focuses on evaluating the air quality impacts of new emission control strategies, primarily for on-road and non-road mobile sources, on both 1-hour and 8-hour average ozone concentrations in the Houston/Galveston and Dallas/Fort Worth areas. Emission inventories that were developed by the Texas Commission on Environmental Quality (TCEQ) for the year 2010 were used as the basis for future control scenarios. On-road mobile source emissions were based on EPA's MOBILE6.2 model (EPA, 2003), and non-road mobile source emissions (with the exception of aircraft, locomotive, and commercial marine sources) were based on EPA's NONROAD 2002 model (EPA, 2002).

Table 1.1 lists the mobile source controls included in the 2010 emission inventories. HGB-8 refers to Brazoria, Chambers, Fort Bend, Galveston, Harris, Liberty, Montgomery, and Waller Counties. DFW-9 refers to Collin, Dallas, Denton, Ellis, Johnson, Kaufman, Parker, Rockwall, and Tarrant Counties.

Table 1.1: Mobile source controls included in the 2010 emission inventories

Emission Control Strategy	Description
Vehicle Inspection/ Maintenance (I/M)	Requires regular inspection of gasoline-powered vehicles 2- to 24-years-old in Brazoria, Fort Bend, Galveston, Harris, and Montgomery Counties and DFW-9.
Reformulated Gasoline (RFG)	Designed to reduce air toxins and VOC emissions. Summer month Reid Vapor Pressure (RVP) may not exceed 7.2 psi in HGB-8; also applies to Collin, Dallas, Denton, and Tarrant Counties.
Texas Low Emission Diesel (TxLED)	Rule covers 110 counties in eastern half of Texas including HGB-8 and DFW-9. Requires that diesel fuel for both on-road and non-road use contain less than 10% by volume of aromatic hydrocarbons and must have a cetane number of 48 or greater. Beginning in 2006, ULSD rule requires that sulfur content must not exceed 15 ppm.
Texas Emission Reduction Plan (TERP)	A comprehensive set of incentive programs aimed primarily at reducing NOx emissions from mobile sources (e.g,. diesel retrofit systems, equipment replacement)
Voluntary Mobile Emissions Reduction Program (VMEP)	Voluntary measures aimed at reducing emissions from on-road mobile sources beyond the mandated reductions (e.g., clean vehicles program, commute solutions program)
Transportation Control Measures (TCM)	Transportation projects and related activities designed to achieve on-road mobile source emission reductions (e.g., signal and intersection improvements, HOV lanes, bike/pedestrian facilities)
Large Non-Road Spark Ignition Engine Standards	Statewide rule requiring manufacturers to ensure that all affected spark-ignition engines are certified to California LSI standards.

The air quality impacts of individual strategies included in the 2010 inventory were not evaluated separately because, during project brainstorming sessions, TxDOT deemed that the analysis should primarily focus on the relative effectiveness of new mobile source control strategies. The UT team worked with TxDOT staff to identify new on-road and non-road mobile source control measures for evaluation with the photochemical models. A range of emission control strategies were selected from emerging research efforts at The University of Texas at Austin and from control strategy lists developed by the Texas Transportation Institute (TTI), the Houston-Galveston Area Council (H-GAC), and the North Central Texas Council of Governments (NCTCOG).

1.4 Modeled Control Scenarios

A series of modeling runs were performed with the Houston/Galveston and Dallas/Fort Worth episodes to evaluate the effectiveness of select mobile source control scenarios. The control scenarios, described here in more detail, were modeled as sensitivity runs designed to assess the ozone impact of emission reductions from specific source groups.

1. VMT Scenarios

Many on-road mobile source control strategies, such as pricing measures and alternative transportation modes, are aimed at reducing vehicle miles of travel (VMT). Further detail regarding these types of strategies and estimating their potential VMT reductions can be found in Appendix A. Quantifying the associated emission reductions, as well as temporally and spatially allocating them, is challenging given the diverse nature of these types of controls. Additionally, assessing the effect of VMT reductions in an area requires rerunning the travel demand model to estimate the associated changes in vehicle speeds. An alternative to these detailed analyses is to perform a set of modeling runs spanning a range of reductions. This approach was used for both the HGB and DFW episodes to provide an estimate of the sensitivity of ozone concentrations to these types of controls. A total of fourteen modeling runs were completed, with emission reductions ranging from 5 to 25 percent for light-duty vehicles and from 5 to 100 percent for heavy-duty vehicles as summarized in Table 1.2:

Table 1.2: Emission Reductions

VMT05LDV	5% reduction in light-duty vehicle emissions
VMT05HDV	5% reduction in heavy-duty vehicle emissions
VMT15LDV	15% reduction in light-duty vehicle emissions
VMT15HDV	15% reduction in heavy-duty vehicle emissions
VMT25LDV	25% reduction in light-duty vehicle emissions
VMT25HDV	25% reduction in heavy-duty vehicle emissions
VMT100HDV	100% reduction in heavy-duty vehicle emissions

* Reductions were made in the 8-county HGB and 5-county DFW areas (Collin, Dallas, Denton, Tarrant, Rockwall)

2. Inspection and Maintenance (I/M) Program

The 2010 inventory includes I/M programs in the five-county HGB and nine-county DFW areas. Two modeling runs were completed to assess the effects of reinstating the I/M program in three HGB counties (Chambers, Liberty, Waller) as well as expanding the program to include OBD-only statewide. OBD (on-board diagnostics) is a computer-based system built into all model year 1996 and newer light-duty cars and trucks. OBD monitors the performance of some of the engine's major components, including individual emission controls. Emission reductions from OBD-only implementation statewide were estimated using U.S. EPA's MOBILE6.2 model. For Texas counties without an I/M program, an exhaust and evaporative OBD program with gas cap check was modeled for light-duty gasoline vehicles assuming a start year of 2009.

3. Idle Reduction (Idle)

One modeling run was completed for the HGB area to assess the effects of truck stop electrification or similar controls by eliminating emissions attributed to extended idling from heavy-duty diesel trucks (HDDV8a/b) in the eight-county area. Following U.S. EPA guidance, long duration truck idling emissions are estimated to be 3.4 percent of the total emissions for Class 8 trucks. (EPA, 2004)

4. LEV II Program (LEVII)

This proposed statewide program was withdrawn before adoption and would have required all vehicles sold in Texas beginning with model year 2007 to meet California Low Emission Vehicle II standards. The state opted instead to follow Federal Tier 2 motor vehicle standards. Both programs reduce exhaust emissions of VOCs, NOx, CO, diesel particulate matter (PM), and formaldehyde (HCHO) and include limits on evaporative emissions; however, the targeted pollutants and program structure differ in several ways. Tier 2 standards focus on NOx reductions while LEV II standards focus on NMOG (non-methane organic gas) reductions. Under Tier 2, auto manufacturers can certify vehicles in one of eleven emission bins as long as they meet the fleet-wide average NOx standard, while under LEV II auto manufacturers must certify vehicles in one of four emission bins to meet the fleet-wide average NMOG standard that becomes more stringent by year. The most significant difference is the ZEV (zero-emission vehicle) component required by the California LEV II program, which can be met with a combination of ZEV and partial ZEV credits. Under contract to the Houston Advanced Research Center (HARC), Eastern Research Group (ERG) and Cambridge Systematics (CS) provided a preliminary assessment of LEV II program benefits for Texas (ERG, 2004). Those assumptions were used in this study to estimate potential emission reductions; however, details regarding the provisions of the program and additional modeling would be required to obtain a more accurate estimate of potential benefits. Two modeling runs were completed to assess the effects of adopting LEV II standards in Texas over the current Tier 2 standards using midpoint estimates from the Connecticut study (3.1 percent NOx and 7.4 percent VOC, assuming the ZEV component) as an upper bound for the incremental benefits of the LEV II program (ERG, 2004).

5. RVP Reduction (RVP)

Summer month Reid Vapor Pressure (RVP) may not exceed 7.8 psi in eastern Texas counties except in the 8-HGB and 4-DFW counties, where reformulated gasoline (RFG) applies. Two modeling runs were completed to assess the effects of reducing the statewide RVP to 7.0 psi in all Texas counties that currently allow RVP above this value. Emission reductions from lowering RVP statewide were estimated using U.S. EPA's MOBILE6.2 and NONROAD 2004 models.

6. Credit-Based Congestion Pricing (CBCP)

One modeling run was completed to assess the effects of a credit-based congestion pricing (CBCP) scenario implemented in the nine-county DFW area. CBCP provides eligible travelers with travel budgets that can then be used to travel on priced roads. The scenario was originally developed by Gullipalli and Kockelman (2006) for the 1999 DFW road network and includes estimates of VMT reductions by time of day (temporal) and roadway (spatial). Details of the modeling and results can be found in Appendix B. Reductions were applied only on weekdays and were applied proportionally in 2010 to estimate the ozone impacts from this strategy.

7. Construction Equipment Operating Restrictions (Construct_Shift)

One modeling run was completed to assess the effects of adopting a rule in the five-county HGB area to restrict heavy-duty diesel construction equipment from operating from 6:00 a.m. through 12 noon during the ozone season. This rule had been adopted by the TCEQ under the Texas SIP and has since been repealed and replaced by the Texas Emission Reduction Plan (TERP).

8. Zero-out Emissions from Construction Equipment (Zero_Construct)

Two sensitivity runs were completed to assess the impacts of eliminating emissions from construction equipment in the eight-county HGB and nine-county DFW areas.

9. Reduce On-road and Non-road Diesel Mobile Source NOx Emissions (15dieselNOx)

Two sensitivity runs were completed to assess the impacts of reducing on-road and non-road diesel mobile source NOx emissions by 15 percent in 110 counties in eastern Texas as a surrogate for potential reductions obtained from using an improved TxLED.

10. Zero-out Emissions from Marine Vessels (Zero_Marine)

One sensitivity run was completed for the Houston/Galveston area in which NOx emissions from commercial marine vessels in the Houston Ship Channel area were eliminated. These emissions were primarily treated as elevated point source emissions in the inventory.

11. Control Bundles

Several control bundles were modeled to assess the effects of combinations of the source controls described. These control bundles are not intended to represent realistic control scenarios but rather provide a range of reductions to evaluate associated impacts on ozone concentrations.

- Bundle1: RVP, I/M, VMT05LDV, VMT05HDV, Idle (HGB only)
- Bundle2: RVP, I/M, VMT15LDV, VMT15HDV, Idle (HGB only), LEVII, 15dieselNOx
- Bundle3: RVP, I/M, VMT25LDV, VMT100HDV, Idle (HGB only), LEVII, 15dieselNOx, Zero_Construct, Zero_Marine (HGB only)

An additional run (Bundle2.areapt25) was performed for each area, which included the controls listed for Bundle2 along with a 25 percent reduction of NOx and VOC emissions from area and elevated point sources in the local area (either eight-county HGB or nine-county DFW area). A total of eight modeling runs were completed.

Table 1.3 summarizes weekday emission reductions for August 31 in the eight-county Houston/Galveston area and for August 17 in the nine-county Dallas/Fort Worth area associated with each of the modeling runs described.

Table 1.3: Summary of 2010 emission reductions in 8-HGB and 9-DFW counties (tons per day)

Modeling Run	Houston/Galveston		Dallas/Fort Worth	
	NOx (tpd)	VOC (tpd)	NOx (tpd)	VOC (tpd)
Base 2010 EI*	253	121	289	142
VMT05LDV	2.8	3.4	3.6	3.8
VMT05HDV	3.5	0.3	3.0	0.2
VMT15LDV	8.4	10.1	10.9	11.3
VMT15HDV	10.4	0.8	9.0	0.7
VMT25LDV	14.0	16.9	18.2	18.9
VMT25HDV	17.4	1.4	15.0	1.1
VMT100HDV	69.4	5.2	60.0	4.2
I/M	0.8	0.7	0.0	0.0
Idle	1.8	0.1	n/a	n/a
LEVII	1.7	5.0	2.4	6.1
RVP	0.0	0.0	0.0	0.3
CBCP	n/a	n/a	3.8	2.1
Construct_Shift**	0.0	0.0	n/a	n/a
Zero_Construct	27.4	4.7	45.6	5.4
15dieselNOx	15.0	0.0	19.2	0.0
Zero_Marine	44.6	0.0	n/a	n/a
Bundle1	8.9	4.4	6.6	4.4
Bundle2	36.3	15.8	39.9	17.4
Bundle2.areapt25	84.1	80.2	71.7	77.3
Bundle3	159.9	30.1	130.1	34.2

*Base 2010 EI: includes on-road and non-road mobile sources only
Total 2010 EI: HGB ~ 443 tpd NOx, DFW ~ 425 tpd NOx (anthropogenic emissions)
**Results in shift of approximately 7.3 tpd NOx and 1.1 tpd VOC

Figure 1.3 shows the reductions summarized in Table 1.2 in order of increasing NOx reductions.

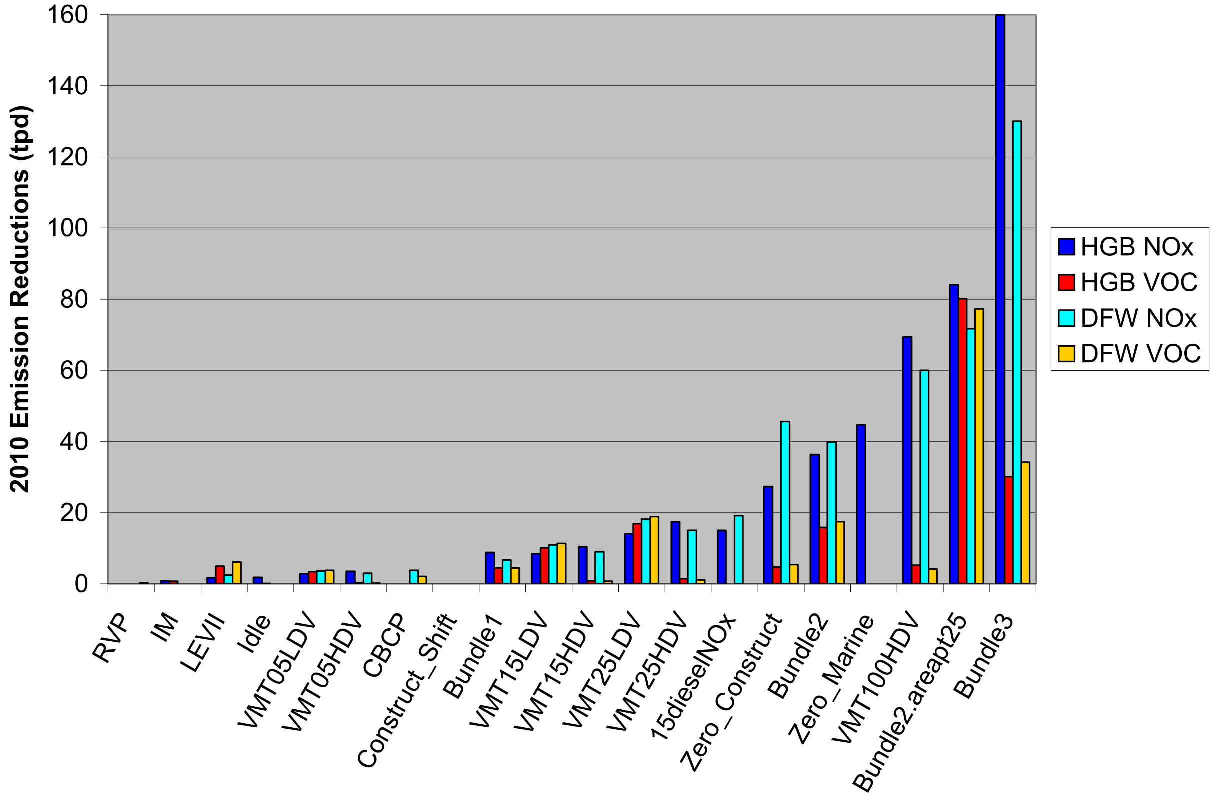


Figure 1.3: Summary of 2010 emission reductions in 8-HGB and 9-DFW counties

1.5 Analysis and Results

Results from the modeling runs were analyzed to determine the impact that the magnitude as well as spatial and temporal distributions of the emission reductions potentially have on ozone formation in the Houston/Galveston and Dallas/Fort Worth areas. Attainment demonstrations under the 8-hour ozone NAAQS are fundamentally different than under the 1-hour ozone NAAQS. The attainment test under the 1-hour NAAQS is passed if the predicted daily maximum ozone concentration everywhere in the non-attainment area is less than 124 ppb on every episode day. In contrast, attainment under the 8-hour NAAQS is determined based on the relative response of the model. The U.S. EPA guidance for attainment demonstrations under the 8-hour NAAQS describes the methodology in detail (EPA, 2005); a brief summary is provided here. The methodology depends on three critical elements: baseline design values (DVB), relative reduction factors (RRF), and future design values (DVF). Future design values for monitors in an area are determined by scaling baseline design values by relative reduction factors:

1. For each monitor in an area, the baseline design value (DVB) is calculated as the average of the three design value periods that straddle the baseline inventory year. The design value is calculated as the three-year average of the fourth-highest-monitored daily 8-hour maximum value at each monitoring site. For example, given a baseline inventory of 2000, the DVB would be calculated as the average of the design

values for 1998-2000, 1999-2001, and 2000-2002. Baseline design values for the Houston/Galveston and Dallas/Fort Worth episodes were obtained from the TCEQ.

2. For each day in the modeled episode, the peak predicted daily maximum 8-hour average ozone concentration (in a 7x7 grid array) near each monitor is obtained for both the baseline and future cases. For this study, days when the baseline daily maximum 8-hour average ozone concentration was below 85 ppb are excluded. The daily maximum 8-hour average ozone concentrations are then averaged across all relevant days for both the baseline and future cases. RRFs for each monitor are calculated as the ratio of the average value for the future case to the average value for the baseline case.

3. For each monitor in the area, the future year design value is calculated as follows: (DVF) = (DVB) * RRF. The attainment test is passed if the future design value at all monitors in the non-attainment area is less than 85 ppb.

The locations of the monitors used in the design value calculations for the Houston/Galveston and Dallas/Fort Worth areas are shown in Figures 1.4 and 1.5, respectively.

Figure 1.4: Location of Houston/Galveston area monitors

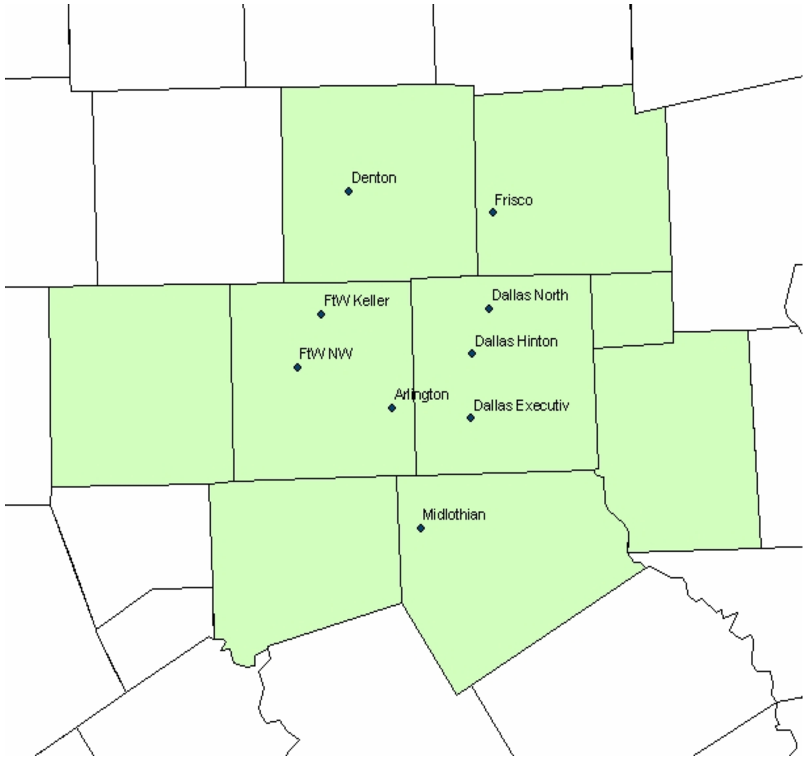


Figure 1.5: Location of Dallas/Fort Worth area monitors

The modeling results were evaluated using the following metrics:

1. Difference in daily maximum predicted 1-hour and 8-hour average ozone concentrations in the non-attainment area with and without the modeled control scenario

$$M1 = \underset{g,h}{Max}\{c_{g,h}\}_{2010base} - \underset{g,h}{Max}\{c_{g,h}\}_{2010scenario}$$

where $c_{g,h}$ is the modeled ozone concentration (in ppb) in grid cell (g) at hour (h).

2. Future 8-hour ozone design values at each monitor in the non-attainment area with and without the modeled control scenario (M2 calculated as described above)

3. Maximum reductions in 1-hour and 8-hour average ozone concentrations in the non-attainment area for the modeled control scenario

$$M3 = Max\{(c_{2010base} - c_{2010scenario})_{g,h}\}$$

4. a. Total daily dosage—calculated by multiplying the area of exceedance above the threshold ozone concentration (85 ppb) in the non-attainment area by the excess ozone concentration above the threshold

$$M4a = \sum_h \sum_g \alpha_g \delta_{g,h}$$

$$\delta_{g,h} = \begin{cases} 0, c_{g,h} \leq 85, \\ c_{g,h} - 85, c_{g,h} > 85 \end{cases}$$

where α_g is the area of grid cell (g; in km^2)

b. Total daily population exposure—calculated by multiplying the population exposed to ozone concentrations above a threshold ozone concentration (85 ppb) in the non-attainment area by the excess ozone concentration above the threshold

$$M4b = \sum_h \sum_g p_g s_{g,h}$$

$$s_{g,h} = \begin{cases} 0, c_{g,h} \leq 85, \\ c_{g,h} - 85, c_{g,h} > 85 \end{cases}$$

where p_g is the population in grid cell (g; in thousands) based on 2000 U.S. Census data

These additional metrics are useful for evaluating the potential benefit of ozone reductions not occurring near the daily maximum but still occurring over a large area or in a densely populated zone.

Figures 1.6 and 1.7 show average differences in daily maximum predicted 1-hour and 8-hour ozone concentrations (M1) in the eight-county Houston/Galveston area and the nine-county Dallas/Fort Worth area, respectively. The daily differences in 1-hour and 8-hour ozone concentrations in the Houston/Galveston area are summarized in Tables C.1 and C.2 in Appendix C. Corresponding summaries for the Dallas/Fort Worth area are included as Tables C.3 and C.4.

Figures 1.8 and 1.9 show future year 8-hour ozone design values (M2) for monitors in the eight-county Houston/Galveston area and the nine-county Dallas/Fort Worth area, respectively. The model configuration and emission inventories undergo constant refinements, which results in changes to the absolute value of the future design values; thus, the values presented here should be compared in a relative sense to determine the sensitivity of ozone concentrations to the various control scenarios.

Maximum reductions (M3) in 1-hour and 8-hour average ozone concentrations in the Houston/Galveston and Dallas/Fort Worth areas are summarized in Tables C.7 through C.10. While these are the largest decreases predicted to occur in the non-attainment area, typically they do not occur at the time and location of the highest predicted ozone concentrations.

Figure 1.10 shows the average differences in daily dosage (M4a) and daily population exposure (M4b) in the Houston/Galveston area. Figure 1.11 shows the corresponding results for the Dallas/Fort Worth area.

The modeled scenarios in Figures 1.6–1.11 are listed in order of increasing NOx reductions. The trends generally indicate that greater emission reductions result in larger decreases in peak ozone concentrations and 8-hour design values. In the Houston/Galveston area, average differences in daily maximum predicted 1-hour and 8-hour average ozone concentrations range from 0.0 to 13.9 ppb and 0.0 to 8.0 ppb, respectively. The run in which NOx emissions from commercial marine vessels were eliminated ("Zero_Marine") results in relatively larger differences in 1-hour ozone concentrations as compared to 8-hour ozone concentrations. This is consistent with the fact that the ozone impact from these emissions, which are primarily located in the ship channel, are highly dependent on meteorology and the associated timing of the ozone formation. Similarly, monitors in the vicinity of the ship channel are more often impacted by the "Zero_Marine" scenario; thus, 8-hour design values for those monitors are predicted to be relatively lower (as compared to the base case) than design values for monitors in the Houston urban core such as Bayland Park. The dosage and population exposure metrics follow the same general trends as reductions in peak ozone concentrations and future design values. For example, emission reductions associated with "Bundle2" result in associated reductions in dosage and population exposure of 29 percent and 35 percent, respectively.

Reductions in the future design value at the Bayland Park monitor, which has the highest value of all monitors in the Houston area (100 ppb), are at most 4 ppb under most of the scenarios. The design value at Bayland Park is reduced by approximately 11 ppb in the "Bundle3" scenario, which includes 160 tpd NOx reductions in on-road and non-road mobile sources, but even under this extreme scenario the monitor is still predicted to remain in non-attainment. Likewise, reductions in the design value at the Deer Park monitor (96 ppb) are predicted to be at most 4 ppb in the "Bundle3" scenario, which suggests continued non-attainment status.

In the Dallas/Fort Worth area, average differences in daily maximum predicted 1-hour and 8-hour average ozone concentrations range from 0.0 to 8.7 ppb and 0.0 to 5.9 ppb, respectively. As in Houston, the dosage and population exposure metrics follow the same general trends as reductions in peak ozone concentrations. For example, emission reductions associated with "Bundle2" result in associated reductions in dosage and population exposure of 25 percent and 22 percent, respectively. Reductions in future design values at the Frisco monitor, which has the highest value of all monitors in the Dallas/Fort Worth area (92 ppb), are at most 2 ppb under most of the scenarios. The design value at Frisco is reduced by approximately 5 ppb in the "Bundle3" scenario, which includes 130 tpd NOx reductions in on-road and non-road mobile sources, but even under this extreme scenario the monitor is still predicted to remain in non-attainment. While other monitors in the Dallas/Fort Worth area are closer to attainment, this modeling suggests that significant reductions will still be needed to bring these monitors into compliance.

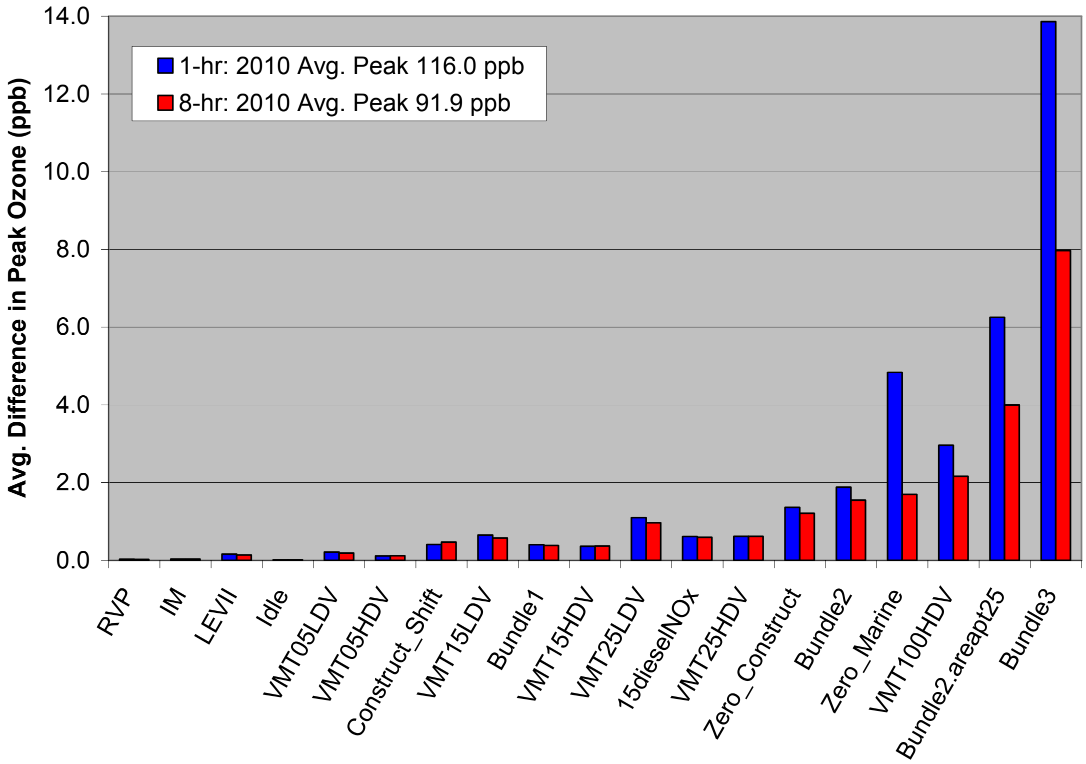


Figure 1.6: Average differences in daily maximum predicted 1-hour and 8-hour ozone in HGB

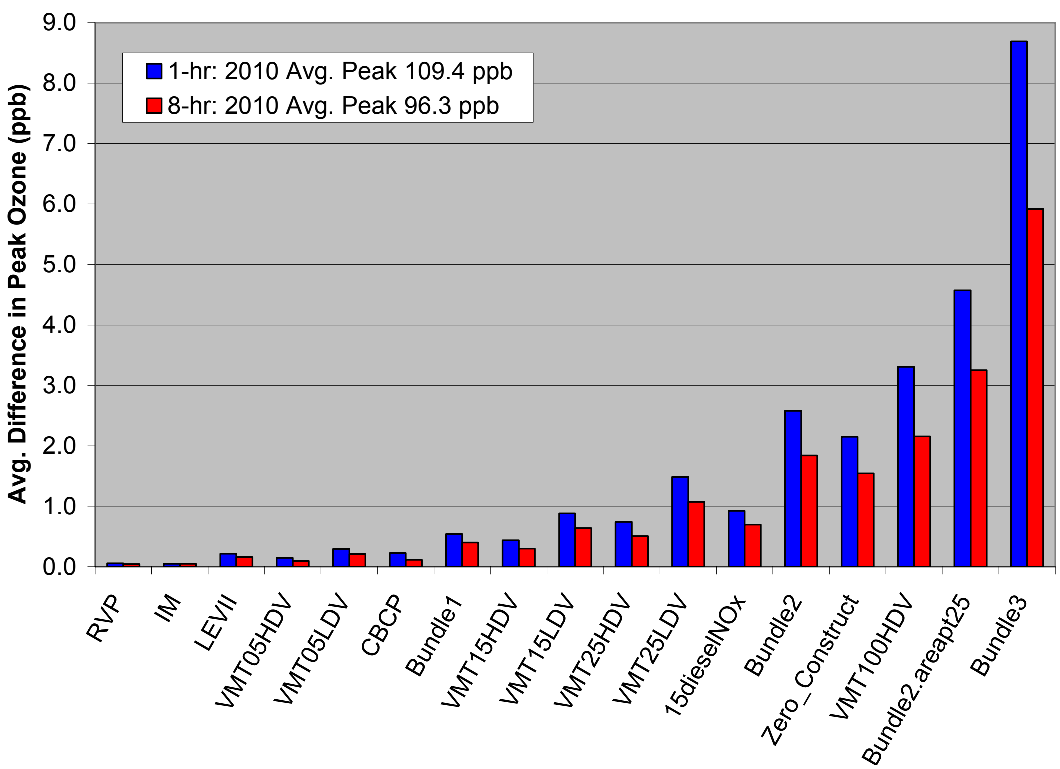


Figure 1.7: Average differences in daily maximum predicted 1-hour and 8-hour ozone in DFW

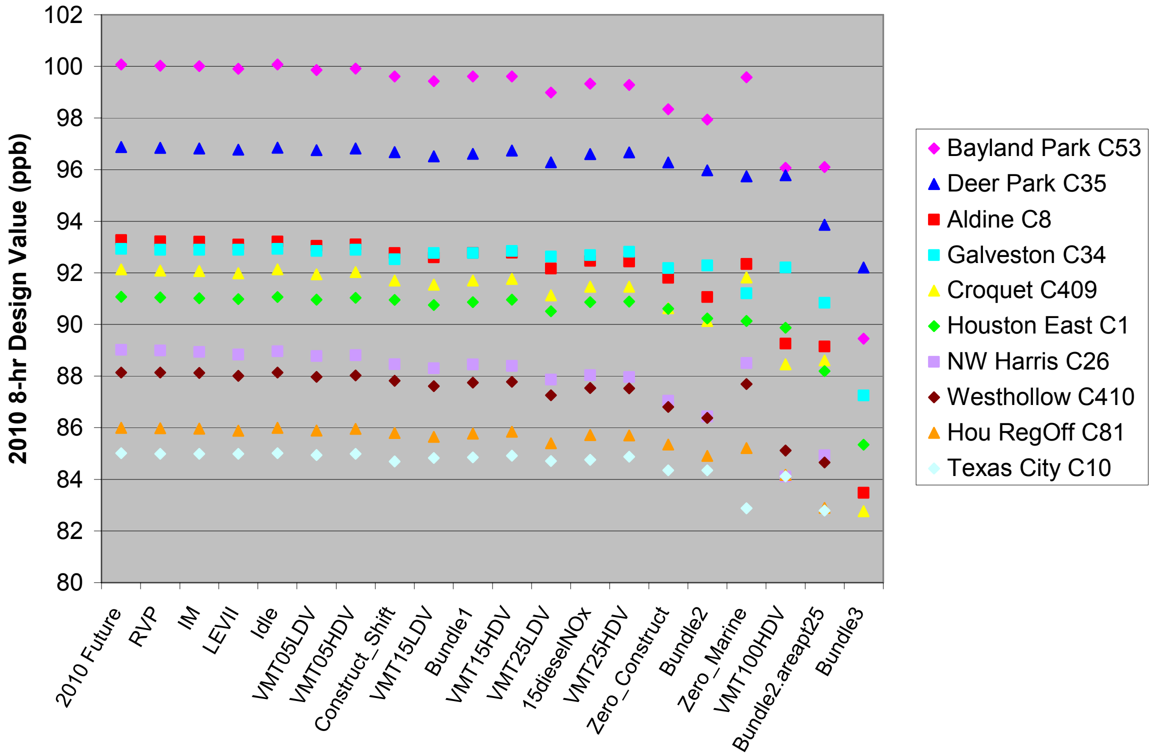


Figure 1.8: Future year 8-hour ozone design values for monitors in HGB

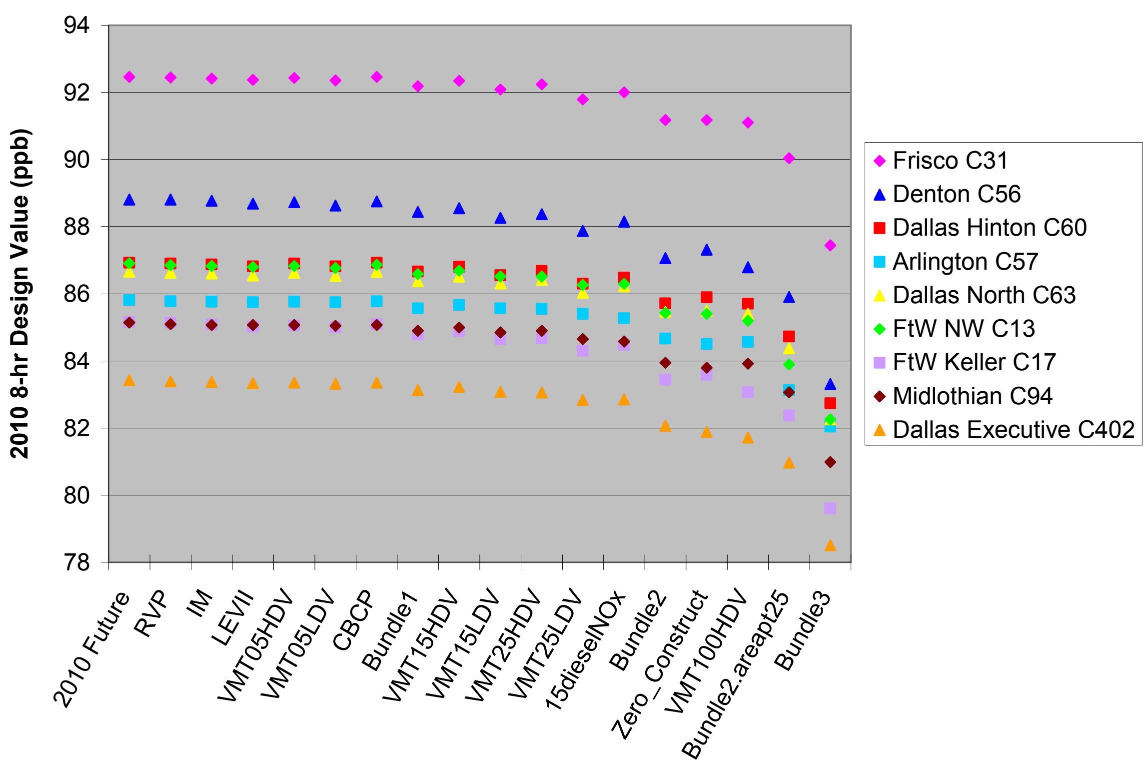


Figure 1.9: Future year 8-hour ozone design values for monitors in DFW

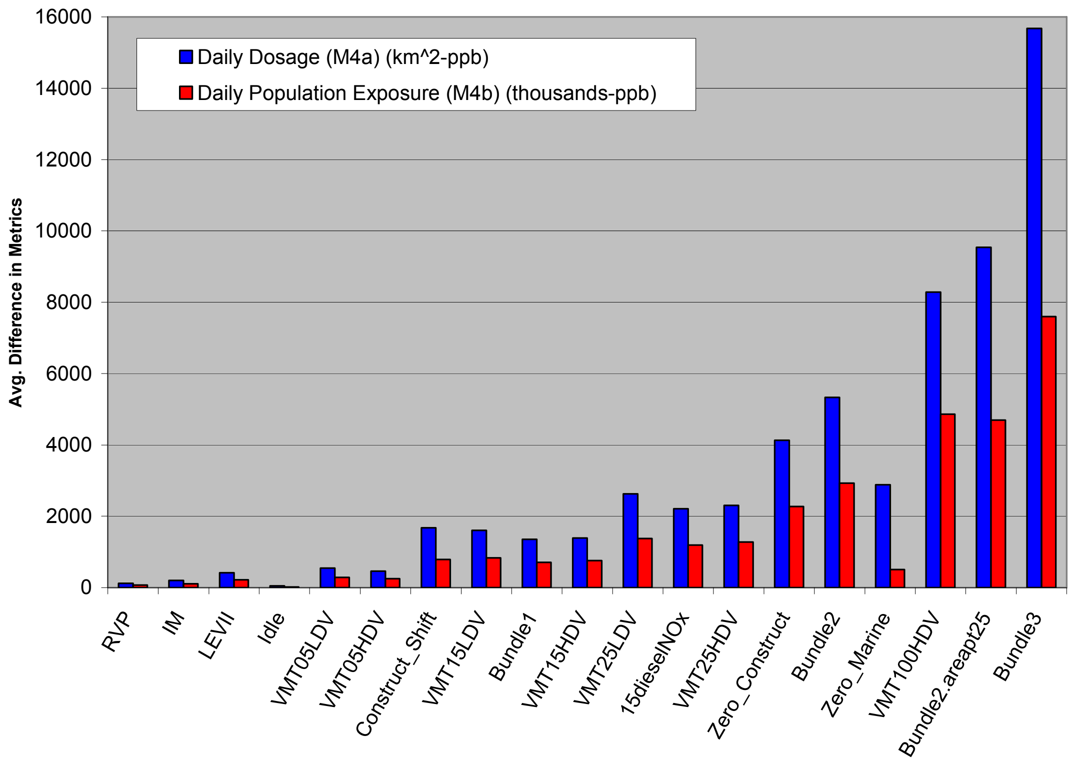


Figure 1.10: Average differences in daily dosage and population exposure in HGB

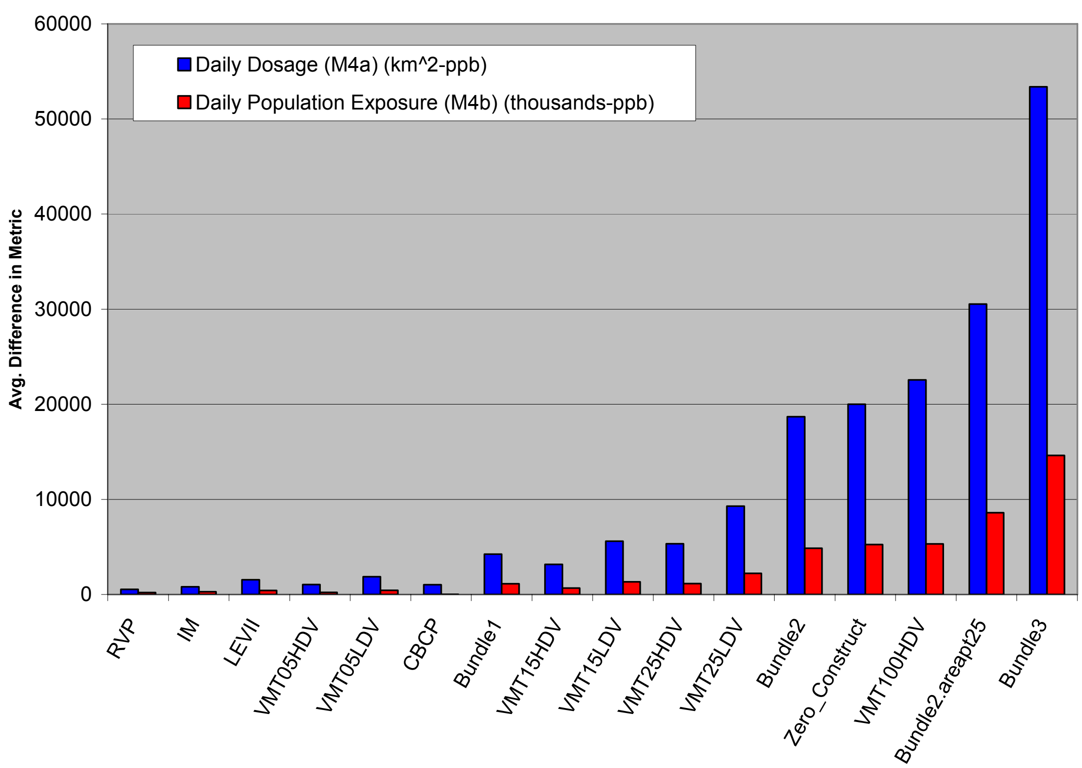


Figure 1.11: Average differences in daily dosage and population exposure in DFW

1.6 A Perspective on Implementation Costs

Reductions from scenarios involving on-road heavy-duty diesel trucks and non-road sources, such as construction equipment and marine vessels, would most likely be obtained under the TERP. TERP is a comprehensive set of incentive programs aimed primarily at reducing NOx emissions from mobile sources and can include controls such as diesel retrofit systems or equipment replacement. Under contract to the Houston Advanced Research Center (HARC), ENVIRON International Corporation (2004[b,c], 2005[a]) has performed detailed reviews of the TERP program in the DFW and HGB areas. According to these estimates, an enhanced TERP program could result in additional emission reductions from 25 to 50 tpd NOx in the DFW area and up to 15 tpd NOx in the HGB area at an average cost effectiveness of $5,000 to $10,000 per ton of NOx. Additional reductions in the HGB area are smaller than in the DFW area because the majority of TERP reductions in the HGB area are already accounted for in the baseline emissions inventory.

Currently, all nine counties in the DFW area and five counties in the HGB area have implemented I/M programs to reduce emissions primarily from on-road light-duty gasoline vehicles. NCTCOG and HGAC have examined the effect of expanding I/M to surrounding counties: Clay, Montague, Cooke, Grayson, Fannin, Lamar, Delta, Hopkins, Hunt, Wise, Jack, Palo Pinto, Erath, Hood, Somervell, Bosque, Hill, Navarro, Henderson, Van Zandt, and Rains in the DFW area; Chambers, Liberty, and Waller in the HGB area. Different methodologies were used by NCTCOG and HGAC, and these estimates indicate that an additional 0.8 tpd NOx could be reduced in the DFW area at an average cost effectiveness of $4,044 per ton of NOx, and an additional 0.8 tpd NOx could be reduced in the HGB area at an average cost effectiveness of $48,000 per ton of NOx. Costs associated with implementation of I/M programs vary greatly depending upon the type of tests included (OBD, TSI, ASM), the number and type of vehicles tested, and assumptions regarding associated repair costs.

NCTCOG and HGAC estimates for implementing idle reduction infrastructure, such as truck stop electrification or similar controls, are 0.06 tpd NOx in the DFW area at an average cost effectiveness of $8,711 per ton of NOx, and approximately 1 tpd NOx in the HGB area at an average cost effectiveness of $1,700 per ton of NOx. Again, different methodologies were used including different assumptions for the cost of electrification technology units.

Adoption of California LEV II standards is expected to result in additional NOx reductions relative to the Federal Tier 2 standards. Estimating the magnitude and cost of reductions is challenging because details regarding provisions and implementation of the program are uncertain, specifically regarding the ZEV component. HGAC emission reduction estimates for implementing LEVII are based on a HARC report (ERG, 2004) providing upper bound reductions of 2.4 tpd NOx in the HGB area. Cost effectiveness values were based on CARB estimates of $1,600 to $3,000 per ton of NOx + ROG reduced. Using a different methodology, NCTCOG estimates emission reductions of up to 0.3 tpd NOx in the DFW area and an overall cost benefit if fuel savings are included in the analysis. Additional analyses are needed to obtain a more accurate estimate of potential benefits for LEVII implementation in Texas.

Currently, RFG is implemented in the eight-county HGB area as well as in the four DFW counties of Collin, Dallas, Denton, and Tarrant. Under RFG, the maximum RVP allowed is 6.8 psi. The remaining five DFW counties have a maximum RVP of 7.6 psi. RVP reductions result in VOC emission reductions only, therefore a cost analysis for NOx reductions is not included.

Many on-road mobile source control strategies, such as pricing measures and alternative transportation modes, are aimed at reducing VMT. Quantifying the associated emission reductions and costs is challenging given the diverse nature of these types of controls. Pricing measures include VMT taxes, fuel taxes, congestion pricing, and pay-as-you-drive insurance. Emission reductions and cost will vary depending upon the magnitude of fees and implementation method. Additionally, some pricing measures that include financial disincentives for driving are deemed to have limited public acceptability. Alternative transportation modes include carpooling, improved bicycle/pedestrian facilities, and transit incentives. Other controls, such as enhanced telecommuting and compressed workweeks, are often included as voluntary measures when enforceability is beyond local control. For control strategies with the greatest potential for implementation, more detailed analyses should be performed to determine associated emission reductions and cost.

1.7 Conclusions and Recommendations

The Houston/Galveston and Dallas/Fort Worth areas are faced with the challenge of requiring stringent emission controls in addition to federally mandated controls in order to achieve compliance with the 8-hour standard. Results of this modeling are consistent with results from previous studies showing that significant NOx reductions will be needed to attain the 8-hour standard in both areas. This modeling indicates that even with greater than 40 percent reductions in on-road and non-road mobile source emissions (as in “Bundle3”), at least one monitor in each area is still predicted to remain in non-attainment.

Given these challenges, it is recommended that TxDOT:

- continue to investigate eligibility for TERP funding to reduce NOx emissions from on-road heavy-duty diesel vehicles and non-road equipment (particularly diesel construction equipment),
- continue to pursue investigation of *in use* emissions from non-road diesel engines, which will lead to better understanding of actual emissions and will aid in refining associated emission inventories used for photochemical modeling, and
- continue to set an example for other agencies with statewide or regional fleets regarding effective emission control strategies that can be adopted both locally and statewide to assist in obtaining regional NOx reductions.

1.8 References for Part 1

ENVIRON International Corporation[a], "User's Guide: Comprehensive Air Quality Model with extensions (CAMx) v. 4.00," January 2004.

ENVIRON International Corporation[b], "Texas Emission Reduction Plan Assessment in the Houston-Galveston-Brazoria Region," prepared for Houston Advanced Research Center, May 2004.

ENVIRON International Corporation[c], "Texas Emission Reduction Plan Assessment in the Dallas-Fort Worth Area," prepared for Houston Advanced Research Center, November 2004.

ENVIRON International Corporation[a], "On-Road and Non-Road Emission Reductions from TERP in 2007 and 2010 in the Houston, Galveston, and Dallas-Fort Worth Areas," prepared for Houston Advanced Research Center, January 2005.

ENVIRON International Corporation[b], "Dallas/Fort Worth CAMx Modeling: Improved Model Performance and Transport Assessment (HARC Project H35: Phase2)," August 2005.

ERG and Cambridge Systematics, "Preliminary Assessment of LEV-II Program Benefits for Texas," December 2004.

Gulipalli, P. and K. Kockelman, "Credit-Based Congestion Pricing: A Dallas-Forth Worth Application," presented at the 85th Annual Meeting of the Transportation Research Board, January 2006.

Texas Commission on Environmental Quality (TCEQ, 2004), "Houston-Galveston-Brazoria Ozone SIP Mid-Course Review Modeling," available at http://www.tceq.state.tx.us/implementation/air/sip/dec2004hgb_mcr.html

U.S. EPA, "User's Guide for the EPA Nonroad Emissions Model Draft NONROAD 2002," December 2002.

U.S. EPA, "User's Guide to MOBILE6.1 and MOBILE6.2: Mobile Source Emission Factor Model," August 2003.

U.S. EPA, "Guidance for Quantifying and Using Long Duration Truck Idling Emission Reductions in State Implementation Plans and Transportation Conformity," January 2004.

U.S. EPA, "Guidance on the Use of Models and Other Analyses in Attainment Demonstrations for the 8-hour Ozone NAAQS," October 2005.

2. A Pilot-Scale Study of In-Use Emissions from Heavy-Duty Diesel Dump Trucks Using a Portable Emissions Monitoring System (PEMS)

2.1 Introduction

In June 2005, the United States Environmental Protection Agency (EPA) issued a final rule (EPA420-F-05-021) requiring in-use testing of heavy-duty diesel engines and vehicles. This rule, which is a result of a cooperative agreement between the U.S. EPA, the California Air Resources Board (CARB), and the Engine Manufacturers Association (EMA), is the latest in a series dating from 1999 that address emissions reductions from diesel engines. In contrast to earlier emissions testing programs that have been conducted primarily in laboratory settings using engine or chassis dynamometers, the new rule requires measurement of exhaust emissions from on-road heavy-duty diesel engines during *real-world driving conditions* using a portable emissions measurement system (PEMS). The rule becomes fully enforceable beginning in 2007 for *on-road* heavy-duty diesel engines; a future rule expected by 2010 will establish a similar in-use testing program for *non-road* heavy-duty diesel engines, such as those used in construction and mining equipment.

The need for testing programs that improve the understanding of emissions from heavy-duty diesel vehicles under real-world driving conditions was a key recommendation of the National Research Council (2000) in its assessment of the state of the science of mobile source emissions modeling. Heavy-duty diesel engines are significant sources of nitrogen oxides (NOx) and particulate matter (PM). In contrast to spark ignition engines, which intake a mixture of gas and air, compress and then ignite the mixture with a spark, diesel engines intake air, compress it and then inject fuel into the compressed air; the fuel evaporates and ignites as compression-heated air mixes with the fuel spray (Flagan and Seinfeld, 1988). Direct fuel injection used in diesel engines results in greater fuel efficiency and lower exhaust concentrations of carbon monoxide (CO) and hydrocarbons (THC), but higher PM concentrations than from spark ignition engines. Fuel-lean conditions (characterized by high air-to-fuel ratios) also provide an environment conducive to forming NOx through the thermal fixation of atmospheric nitrogen in the combustion process (Flagan and Seinfeld, 1988).

Reactions of NOx and volatile organic compounds (VOC) in the presence of sunlight lead to the formation of ground-level ozone (O_3), which can impact both ecosystem health and public health (EPA, 2005b). In order to protect the public and ecosystems from the adverse effects of ozone exposure, the Clean Air Act requires that the EPA set National Ambient Air Quality Standards (NAAQS), limiting ozone concentrations in outdoor air. From 1979 until 2004, the NAAQS for ozone was 0.12 ppmv, based on a 1-hour average of measured concentrations. An area was considered to be in violation of the NAAQS for ozone if ambient monitors detected concentrations higher than the standard four times in a 3-year period. In 1997, the EPA proposed changing the NAAQS for ozone to an 8-hour rolling average of 0.08 ppmv. Under the new standard, which was enforced beginning in 2004, an area is considered to be in violation of the NAAQS if the design value (defined as the annual fourth-highest 8-hour averaged daily peak concentration), averaged over three consecutive years, exceeds 0.08 ppmv at any ambient monitoring site. The EPA also established a new annual NAAQS for fine particulate matter (particles less than 2.5 micrometers in diameter or $PM_{2.5}$) of 15 ug/m^3 and a 24-hour average NAAQS of 65 ug/m^3 for similar reasons of protecting public and ecosystem health (EPA, 2004).

The State of Texas is currently grappling with some of the most challenging air quality planning issues in the United States. Four areas in Texas have historically been designated as non-attainment for ozone under the NAAQS for ozone with concentrations averaged over one hour: Dallas/Fort Worth, Houston/Galveston, Beaumont/Port Arthur, and El Paso. The State of Texas is also working to achieve compliance with the recently implemented NAAQS for ozone with concentrations averaged over 8 hours. Although Austin and San Antonio have been and are currently in compliance with the 1-hour average NAAQS for ozone, these areas have violated or are on the cusp of violating the 8-hour average NAAQS and were among the first of thirty-three areas in the United States to enter into an Early Action Compact with the EPA to voluntarily reduce emissions earlier than federal requirements for designated non-attainment areas. Although the State of Texas is in compliance with the current $PM_{2.5}$ standards, the EPA is considering revisions to the standard that could affect the state's future attainment status.

Achieving compliance with both the 1-hour and 8-hour NAAQS for ozone throughout eastern Texas will be a considerable challenge. Although peaks in 1-hour averaged ozone concentrations are most strongly influenced by local sources, 8-hour averaged ozone concentrations are influenced by emissions over much larger areas. Webb et al. (2005) at The University of Texas at Austin demonstrated that ozone formation in urban areas in eastern Texas is influenced by both local sources and regional transport from other urban areas within and outside of Texas.

Heavy-duty diesel engines comprise a significant fraction of the total NOx emission inventory from mobile sources in Texas urban areas, accounting, for example, for approximately 55 percent of total on-road mobile NOx emissions in the Houston area (TCEQ, 2004). The Texas Department of Transportation (TxDOT) operates the largest fleet in Texas and the seventh largest in the United States (Baker et al., TxDOT Project 0-4576-3). TxDOT owns and operates more than 17,000 pieces of major equipment, of which 10,000 are classified as motorized on-road units; 4,500 as off-road motorized units; and 2,500 as non-motorized units (such as trailers). Over 3,000 units are diesel powered. Characterization of emissions from on-road and non-road diesel engines during real-world driving conditions is important for TxDOT and the State of Texas in order to:

1. Characterize baseline emissions from heavy-duty diesel vehicles or equipment during different modes of operation within normal duty cycles.
2. Evaluate the effectiveness of emerging retrofit technologies and fuels/fuel additives during typical operations.
3. Understand how results from the new federal in-use testing program may affect current estimates of NOx emissions in ozone non-attainment areas.
4. Identify emission control strategies, such as changes in operating practices, which may avoid the costs of retrofits.

To satisfy the new in-use testing requirements, in September 2004, The University of Texas at Austin purchased a SEMTECH-D (Sensors EMission TECHnology) PEMS unit from Sensors, Inc. The purchase was jointly funded through the current TxDOT Project 0-5191 ($25K) and endowed funds from The University of Texas at Austin ($75K). The SEMTECH-D was selected among competing PEMS because it has been and is currently being deployed by the

EPA (Ensfield, 2002), California Air Resources Board, Caterpillar, Volvo, Cummins, and others. Because of the potential importance of identifying creditable reductions for a State Implementation Plan, UT placed a high priority on selecting an instrument that had been deployed and tested by the EPA from a company that had an extensive history of working with the EPA to advance the state of the science of PEMS technology. Sensors, Inc. was the only company that met these qualifications. UT is one of only a few universities worldwide to own and operate a SEMTECH-D for in-use characterization of emissions from diesel engines.

As part of Project 0-5191, UT conducted a small, technology demonstration project to measure exhaust emissions from single-axle and tandem-axle dump trucks during typical TxDOT operations. The primary objectives of this effort were to:

- Develop a protocol and baseline for estimating emissions from dump trucks under typical conditions in Texas. This baseline can then be used as the basis of comparison for future studies of emerging retrofit technologies and fuels/fuel additives.
- Characterize emissions during different modes of typical operations (idling, high-speed cruising, dumping, etc.).
- To the extent possible, compare the results of the study with other national or state-level emission inventories for heavy-duty diesel engines or in-use studies with PEMS.
- Assess preliminary implications for TxDOT emission reduction programs.

As will be described in more detail in the following sections, second-by-second *fuel-specific emission*s data (i.e., grams of pollutant/kilograms of fuel) for NOx, total hydrocarbons (THC), carbon monoxide (CO), and carbon dioxide (CO_2) during typical TxDOT operations were obtained from the PEMS during the technology demonstration project. In addition to several laboratory-based tests, a total of five field tests were conducted for project 0-5191, with three vehicles tested in May 2005 and two vehicles tested in November 2005. In August 2005, UT was able to purchase a Garmin International, Inc. global positioning system (GPS) receiver module for the PEMS. The GPS module provides second-by-second profiles of the route, elevation, and ground speed of the vehicle during testing, which greatly improved our ability to characterize modal emissions. UT's current PEMS system does not have an exhaust flow meter (additional cost of approximately $20K), and given the resources available for the study, other dataloggers (e.g., QuickCheck dataloggers) to collect vehicle speed, engine RPM, and engine load were not available. Consequently, instantaneous mass emissions (g/s), brake-specific mass emissions (g/bhp-hr), and cumulative distance-specific emissions (g/mi) were not obtainable. Nonetheless, a great deal of recent research by Harley and others, described in the following sections, has demonstrated the advantages of a fuel-based approach for estimating heavy- and light-duty vehicle emissions, including readily available tax records of fuel consumption and the lower variability of emission factors normalized to fuel consumption versus emission factors normalized to vehicle miles traveled (Dreher and Harley, 1998). It is also important to recognize that PEMS technology is continuing to evolve and will likely experience rapid advances over the next several years as federal regulations are phased in. A primary example of this evolution is the continuing development of sub-systems for PM measurement.

Following is a description of the Sensors, Inc. SEMTECH-D PEMS instrumentation along with the testing methodology and configuration used by the UT team. A summary of the results, comparisons to other fuel-specific emission inventories for heavy-duty diesel vehicles, and implications from the technology demonstration project are also presented and discussed.

2.2 Methodology

2.2.1 Fuel and Vehicle/Equipment Selection

As described earlier, the primary objectives of the pilot-scale study were to develop a protocol for estimating emissions from dump trucks under typical conditions in Texas and to characterize baseline emissions of NOx, CO, CO_2, and THC during different modes of typical operations (idling, high-speed cruising, dumping, etc.). The study could be used as a basis of comparison for future studies of emerging retrofit technologies and fuels/fuel additives. Because TxDOT is currently using (as is required by the State of Texas) Texas Low Emission Diesel (TXLED), it was selected as the fuel for the pilot study. The TXLED rule, which is enforceable under the Texas SIP for 110 counties in eastern Texas, requires that diesel fuel for both on-road and non-road use must contain less than 10 percent by volume of aromatic hydrocarbons and must have a cetane number of 48 or greater (TCEQ, 2006). An independent analysis of the fuel, characterizing such factors as its cetane number (engine test), percentage carbon and hydrogen (LECO), percentage nitrogen (Antek), percentage sulfur (XRF), aromatics content (FIA), aniline point, API gravity, and iodine number, could not be conducted with the resources of the pilot-scale study, but would be recommended for future studies. Although TxDOT obtains its TXLED from a single source, Valero, differences in fuel composition that could impact exhaust emissions are possible.

The vehicle selection process addressed several factors, including the fuel consumption of each vehicle/equipment class in the TxDOT fleet, inclusion in previous chassis or engine dynamometer-based emissions testing, and geographic location. Baker et al. (2004) found that approximately 40 percent of the diesel fuel used by on-road equipment in 2001 in the twelve major ozone non-attainment counties in Texas was by a combination of single-axle and tandem-axle dump trucks. Similarly, telescoping boom excavators and crawler and wheeled loaders together account for 49 percent of total diesel fuel consumption by TxDOT non-road vehicles (Baker et al., 2004). Because of the need to focus the pilot-scale study on a single vehicle/equipment class, dump trucks were selected for the study. In addition, several single-axle and tandem-axle dump trucks had undergone dynamometer-based testing by Matthews et al. (2005) during a study of PuriNOx and were accessible for the pilot-scale study in TxDOT's San Antonio district. The three vehicles selected for the pilot study are described in Table 2.1. All of the engines included in the pilot-scale study were EPA Tier 1 heavy-duty diesel engines. Applicable standards for heavy-duty (gross vehicle weight > 8500 lbs) compression ignition highway engines for model year 1998-2003 are 15.5 g/bhp-hr for CO, 1.3 g/bhp-hr for HC, 4.0 g/bhp-hr for NOx, and 0.10 g/bhp-hr for PM.

Table 2.1: Characteristics of the single-axle and tandem-axle dump trucks from the TxDOT San Antonio fleet used for the pilot-scale study

("NA" indicates that data was not available or could not be obtained.)

TXDOT ID	Model Year	Equipment	Engine Model	Engine Displacement (L)	Power Rating (hp @rpm)	Torque Rating @rpm)	Compression Ratio	Configuration
Single-Axle Dump Trucks								
15-4772G	1999	GMC C7500	Cat 3126B	7.2	195@2100	450@1440	NA	In-line 6 cylinder
Tandem-Axle Dump Trucks								
15-3512H	2000	Volvo	Cummins ISM305V	10.2	305 @2100	1350@2100	NA	In-line 6 cylinder
15-5184G	1999	International	Cat C10	10.3	305 to 335@2100	1050 to 1250@2100	16.00:1	In-line 6 cylinder

2.2.2 Portable Emissions Monitoring System

The SEMTECH-D manufactured by Sensors, Incorporated (http://www.sensors-inc.com) in Saline, Michigan was selected among competing PEMS because it has and is currently being deployed by the EPA, California Air Resources Board, Caterpillar, Volvo, Cummins, and others. Sensors, Inc. has an extensive history of working with the EPA to advance the state of the science of PEMS technology. The SEMTECH-D system has been commercially available since 2002 and, as described previously, is continuing to evolve as the federal regulations are phased-in. The SEMTECH-D analyzer is intended for on-vehicle monitoring of exhaust emissions from diesel-powered vehicles, agricultural equipment, and construction equipment, but it could also be applied in marine and mining applications and could be used concurrently with other emission testing systems in an engine test cell (Sensors, 2004). In an unrelated project, but as a demonstration of the wide-variety of potential applications of a PEMS, UT expects to work with Sensors to retrofit the SEMTECH-D system to be able to characterize emissions from natural gas compressors in the Victoria, Texas area within the next year.

Interested readers should refer to the SEMTECH-D User Manual for complete descriptions of the instrument architecture and operations (Sensors, 2004). The SEMTECH-D system at The University of Texas consists of several subsystems and modules, which are described in the following excerpts from the User Manual. Specifications for the emissions analyzer subsystems are provided in Appendix D and are reproduced from the User Manual.

1. **Emissions analyzer**

    - *Heated flame ionization detector (FID) for total hydrocarbon measurement.* The sample line, filter, stainless-steel FID chamber, and pump are heated to 191°C to prevent condensation of heavy hydrocarbons. The FID fuel (40/60 blend of hydrogen and helium) is housed within the PEMS itself and includes an electronic pressure sensor that is connected to the data acquisition system. Ignition is automated. One FID fuel bottle lasts approximately 8 hours. The user can select a measurement range of 100, 1,000, or 10,000 ppm. The heated FID analyzer specifications are shown in Table D1 of Appendix D.

- *Non-dispersive infrared (NDIR) CO and CO_2 analyzer.* Sensors, Inc has developed a proprietary Automotive Micro-Bench II (AMBII), NDIR analyzer for measuring CO and CO2. The AMBII analyzer has no moving parts and is immune to vibration. The exhaust sample is dried with a coalescing filter followed by a thermoelectric chiller prior to analysis. The specifications for the AMBII are shown in Table D2 of Appendix D.

- *Non-dispersive ultraviolet (NDUV) NO and NO_2 analyzer.* The NDUV analyzer measures NO and NO2 simultaneously and independently without a converter. Like the AMBII analyzer, the NDUV analyzer has no moving parts and is immune to vibration and shock. The exhaust sample is dried with a coalescing filter followed by a thermoelectric chiller prior to analysis. The performance of the Sensors, Inc NDUV analyzer is comparable to laboratory-grade chemiluminescent analyzers (Sensors, 2004). The specifications for the NDUV analyzer are given in Table D3 of Appendix D.

- *Electrochemical sensor for oxygen (O_2) measurement.* The exhaust sample travels through a flow adapter and an oxygen sensor, installed on the adapter, produces a signal proportional to the partial pressure of oxygen in the exhaust sample gas. The specifications for the O2 sensor are given in Table D4 of Appendix D.

2. **Ambient temperature, pressure, and relative humidity (RH) sensors.** The temperature and RH sensors are remote mounted and attached to the SEMTECH-D chassis through a cable. The pressure sensor is located inside the chassis. These sensors are required for calculation of the NOx humidity correction factors.

3. **Data logger, digital and analog input/output, and system control module.** The SEMTECH-D has embedded software and a graphical user interface (GUI) for instrument control, activity logs, and error reporting. The interface allows for real-time data display in pre-formatted data view screens and is configurable, providing on-road drive traces and dynamic charting. A basic data post-processor outputs second-by-second data for the following:
   - Date (mm/dd/yyyy) and time(hh:mm:ss..xxx)
   - Raw concentrations of CO(% and ppm), CO_2(ppm), THC(ppmC), NO(ppm), $NO_{2(}$ppm)
   - Dry to wet gas correction factor and concentrations of each pollutant with the factor applied
   - NOx humidity correction factor and NO/NO_2/NOx concentrations with the factor applied
   - Local ambient temperature (°C); relative humidity (%); absolute humidity (grains/lb dry air); and volumetric humidity (%)
   - Air/fuel ratio, stoichiometric air/fuel ratio, and lambda
   - Numerous instrument operating parameters including power supply (V DC), drain pump pressures (mbar), sample pump pressure (mbar), chiller temperature (°C), external line temperature (°C).
   - Fuel-specific emissions of each pollutant (grams pollutant/kilogram of fuel)

4. **Wireless communication module for remote monitoring and control using a personal computer** (a personal digital assistant, if available, could also be used).

5. **GPS module**. Garmin International, Inc. global positioning receiver module GPS 16-HVS tracks the route, elevation, and ground speed of the test vehicle. This is an optional module that UT was able to purchase in August 2005.

At the beginning of each day of sampling, a leak test was performed. The leak test through the entire sample path is automated using the instrument control screen in the SEMTECH-D software, once the user plugs the probe tip on the end of the sample line and initiates the test. The SEMTECH-D operates the pumps for 5 seconds to obtain a vacuum and then, after shutting the pumps off, monitors the vacuum pressure for 20 seconds (Sensors, 2004). The system indicates if the test is passed or if a failure has occurred (>10 percent decay in vacuum pressure).

Zero calibrations were performed following warm-up of the instrument for 60 minutes, at the beginning of each test, during each test, and at the conclusion of each test. Sensors, Inc. (2004) recommends performing a zero calibration after 60 minutes of data collection. Because of the nature of the TxDOT field operations, the sampling team attempted to follow this guidance but zero calibrations were conducted during the tests as operations would allow. Bottled zero air from Scott Gas Company was used to zero the NDUV, NDIR, and FID analyzers. The zero calibration is also automated using an instrument control screen after the user selects the gas channels (i.e., NO, NO_2, CO, CO_2, and THC) and the port for the zero air source. A purge delay of 30 seconds was used, which was the default for the instrument. A summary of the results of the zero calibration for each gas channel is provided.

A span calibration was performed at the beginning of each test. Two separate span calibrations were performed. The first span calibration was for the NO_2 gas channel. The NO_2 span gas (258 ppm) was obtained from Scott Gas Company. The second span calibration was for the CO, CO_2, NO, and THC gas channels (note that gas channels can be spanned individually or in combination). The span mix was obtained from Scott Gas Company and had a composition of 11.99 percent CO_2, 1205 ppm (0.1205%) CO, 1515 ppm NO, and 201.1 ppm THC as propane. The user inputs the bottle concentrations on the instrument "span" control screen and the port for the span gas source. The span gas verification is conducted and is passed if the measured concentration is within 10 percent of the bottle concentration. A purge delay of 30 seconds was used for the study, which was the default for the instrument. The span calibration is then initiated and, at its conclusion, a summary of the results for each gas channel is provided.

An audit was performed at the beginning and conclusion of each test in order to check the accuracy of the gas analyzers (Sensors, 2004). Similar to the span calibration, two separate audits were performed. The first check was for the NO_2 gas channel. The NO_2 audit gas (49.6 ppm) was obtained from Scott Gas Company. The second check was for the CO, CO_2, NO, and THC gas channels. The audit mix was obtained from Scott Gas Company and had a composition of 6.025 percent CO_2, 201.8 ppm (0.02018%) CO, 302.1 ppm NO, and 50.50 ppm THC as propane. The user inputs the bottle concentrations on the instrument "audit" control screen and the port for the audit gas source. The audit gas verification is conducted and is passed if the measured concentration is within specified limits (shown in Table D5) of the bottle concentration. A purge delay of 15 seconds was used for the study, which was the default for the instrument. The audit is then initiated and, at its conclusion, a summary of the results for each gas channel is provided.

2.2.3 On-Vehicle Testing Configuration

The SEMTECH-D weighs approximately 80 lbs. The testing configurations for the single-axle and tandem-axle dump trucks were similar except for the routing of the sampling line from the probe to the PEMS because the position of the exhaust pipes and the passenger-side window configurations were different between the two types of trucks. The testing configuration for the tandem-axle dump trucks is shown in Figure 2.1. The PEMS is placed on the passenger side of the seat in the cab of a truck on a platform designed by the UT researchers. UT researchers designed a platform for mounting a portable gasoline powered generator on the passenger-side of the truck frame to provide electrical power for the system. Backup electrical power is supplied by two batteries and an inverter that are wired into the power system and placed on the floor on the passenger-side of the cab. The inlet probe that collects the exhaust for analysis is inserted into the vehicle exhaust pipe. A heated sampling line that carries the exhaust sample to the instrument is routed through the wing window of the cab, along with the generator power cord and instrument water drain. A probe to measure engine inlet air temperature and humidity is tied to the front grill and routed through the wing window of the cab.

The testing configuration for the single-axle truck is shown in Figure 2.2. The exhaust is located on the bottom of the truck near the drive shaft; consequently, installation of the probe and routing of the sampling line is more complex than for the tandem-axle truck. The inlet probe that collected the exhaust for analysis was inserted into the vehicle exhaust pipe, and the heated sampling line that carries the sample to the instrument was tied to the frame of the vehicle so that it did not move or touch the drive shaft. The sampling line was routed next to the generator platform and through the cab window. The single-axle truck passenger-side does not have a wing-window, so the sampling line, power cord, instrument drain lines, and the cable to the temperature and relative humidity sensor had to be routed through the passenger-side cabin window, which remained open during the tests. As will be discussed in more detail below, this is a disadvantage in intense summer heat because it inhibits the full benefits of using the vehicles HVAC system to cool both the driver and the instrument.

While the sampling was occurring, UT researchers drove a *chase* vehicle (a Chevy Suburban) that closely followed the truck. Radio communication was maintained between the truck and the chase vehicle. Four researchers were in the chase vehicle, each with one of with the following duties: chase vehicle driver, remote monitoring of the PEMS using a laptop computer, video camera recording, event recording, and still photography. UT researchers developed an activity log filled in by the event recorder during each test. The log is shown in Appendix E and was used to supplement the PEMS data and video records during the data analysis. A second video camera was located behind the operator to record data from the test vehicle's tachometer. In a larger-scale testing program that would likely include data loggers to collect engine RPM and engine load, this second video camera would not be necessary.

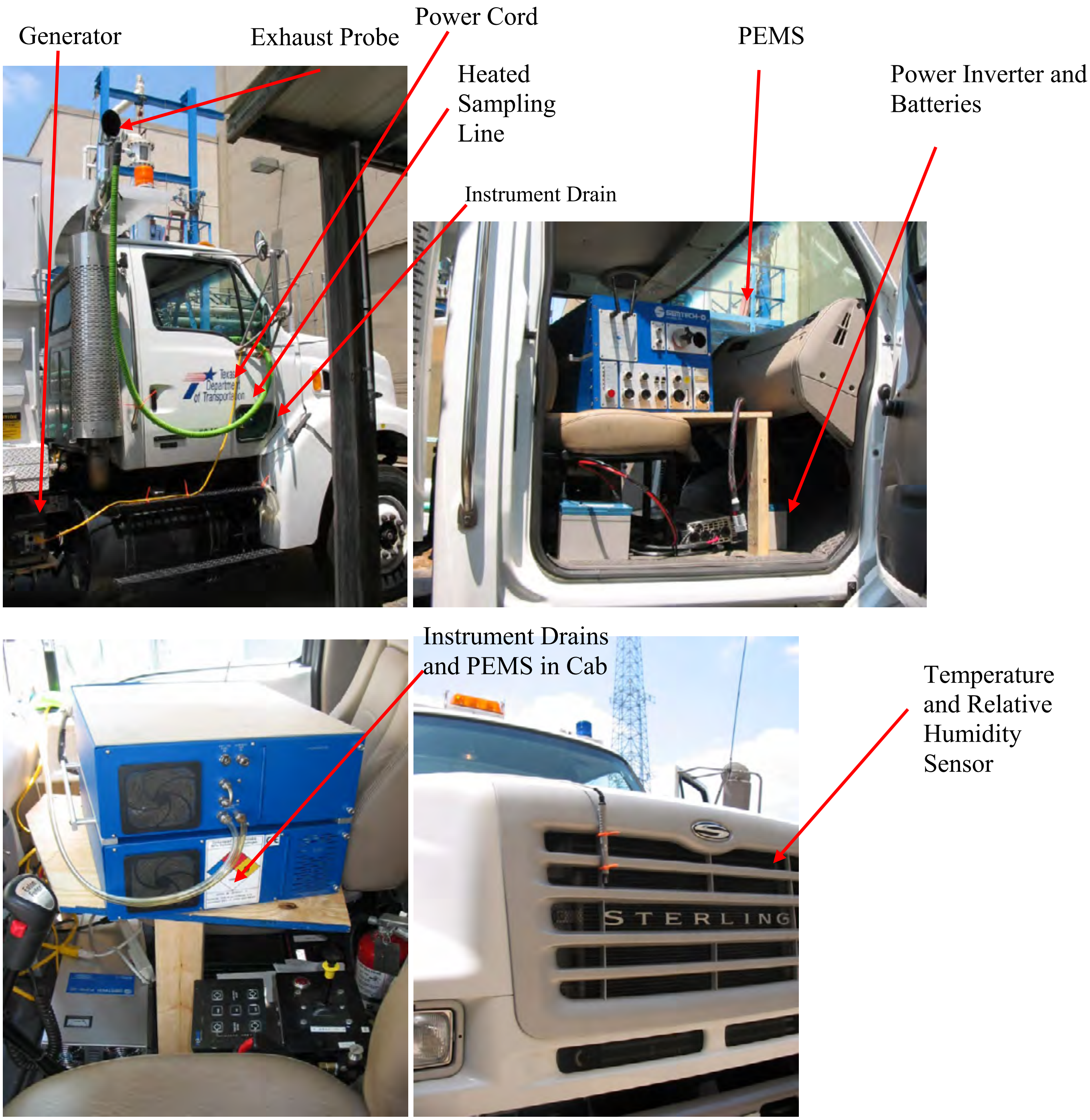


Figure 2.1: PEMS testing configuration on a tandem-axle heavy-duty diesel dump truck.

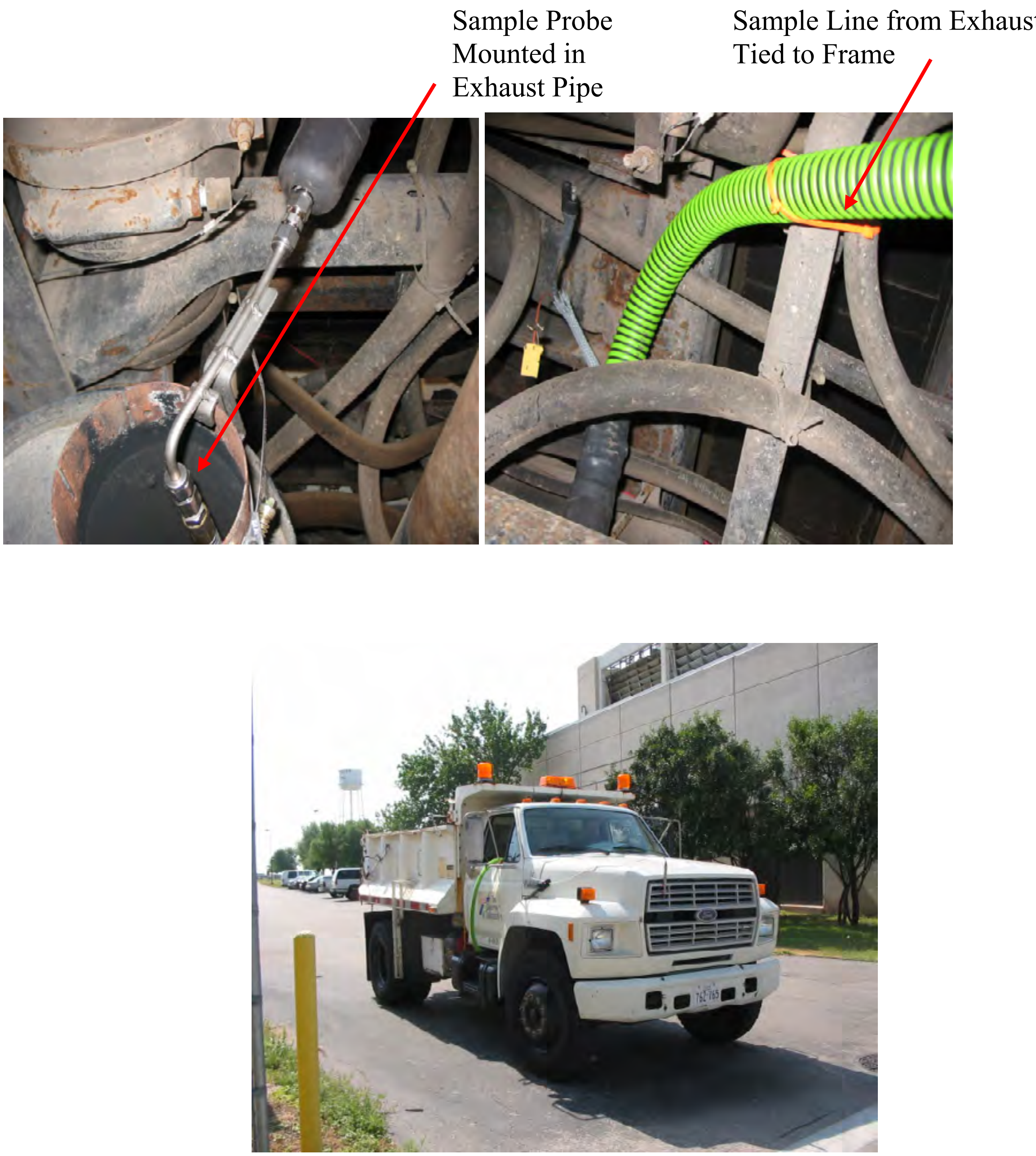


Figure 2.2: PEMS testing configuration on a single-axle heavy-duty diesel dump truck.

2.2.4 Study Design

All of the tests for the pilot-scale study were conducted at locations within TxDOT's San Antonio District given in Table 2.2. TxDOT chose the driver, route, and schedule/duty cycles for each test. For a larger-scale study, it is recommended that a combination of a controlled "roadeo"-type event, such as that conducted by Baker et al. (2004) for the PuriNOx study be conducted, along with collection of data during normal TxDOT operations that are not controlled by the research team. Typical activities for TxDOT dump trucks include extended periods of idling, travel to a site to load material into the bed, travel to another site to dump the material, and travel to and from the TxDOT office or maintenance yard. With the exception of the one test conducted in Pleasanton, Texas, the tests were conducted in the San Antonio metropolitan area. The routes in May 2005 consisted of a driving on urban highways, arterials, suburban, and rural roads. The vehicle speeds ranges from 0 mph to approximately 65 mph and included a mix of *stop and go*-type driving, steady cruising, and idling or dumping. The short haul between the load and dump site was approximately 15–20 miles; the *long* haul was approximately 30 miles. The test in Pleasanton, Texas in November 2005 consisted of brief periods of driving through the town (population 9,375 in 2005), extended periods of driving on rural highways, and brief periods of driving on a rural road to the load site. The vehicle speeds ranges from 0 mph to approximately 65 mph and primarily included steady cruising and idling with some light *stop and go* driving through the town of Pleasanton. On the first outgoing trip to the load site, the dump truck towed a front loader that was then unhitched and left at the load site; this was the only test during the pilot-scale study that included a towing segment. The test in San Antonio in November 2005 was similar to the route in Pleasanton. With the exception of the initial trip on urban highways and suburban arterials from the TxDOT District Office on Callaghan to the TxDOT office on Walzem Drive, the trip involved repeated cycles of loading at the Gibbs Sprawl Road site and dumping at the TxDOT office on Walzem Drive, driving through a suburban area with light *stop and go* traffic. The length of each haul was less than 10 miles. Vehicle speeds during the test ranged from 0 mph to approximately 55 mph.

Table 2.2: Pilot-scale study description.

Date	TxDOT Identif. No. (Ref. Table 1-1)	Coordination Site	Driver	General Description of Route and Duty Cycles	Total Mileage (miles)	GPS On-Board
5/24/2005	15-4772G (Single-Axle)	TxDOT District Office–Callaghan	Joel	A.M.: Highway driving through metropolitan San Antonio to reach load site; one short haul between load site and dump site; and idling during lunch P.M.: Two short hauls between load site and dump site; highway driving during rush-hour traffic to return to district office	A.M.: 67.3 P.M.: 107.4	No
5/25/2005	15-5184G	TxDOT District Office–Callaghan	Joel	A.M.: Highway driving through metropolitan San Antonio to reach load site; two *short* hauls between load site and dump site; and idling during lunch P.M.: Long haul and return to district office	A.M.: 111.8 P.M.: 82.4	No
5/26/2005	15-3512H	TxDOT District Office–Callaghan	Joel	Long haul; idling during lunch; one short haul; highway driving during rush-hour traffic to return to district office.	180.2	No
11/16/2005	15-4772G	TxDOT District Office–Callaghan and TxDOT Office–Walzem Drive	Jorge	Initial drive from TxDOT District office on urban highways and suburban arterials to TxDOT office on Walzem Road; seven cycles of travel between load site and dump site; return to TxDOT District office	71.5	Yes
11/30/2002	15-5184G	TxDOT Office–Pleasanton, Texas	Unknown	Brief drive through town towing front loader, driving on rural highways and briefly on rural road to load site, return to TxDOT office for dumping; repeat same route/duty cycle twice without towing front loader	117	Yes

2.2.5 Data Reduction and Analysis

As already described, the SEMTECH-D includes a basic data post-processor. UT developed a Microsoft Excel macro to obtain second-by-second traces of vehicle emissions and speed during each test, conduct a modal fuel-specific emissions analysis for each pollutant (i.e., CO, CO_2, NOx, and THC), and provide summary statistics for each mode, including average fuel-specific emissions, population standard deviation, median, minimum, maximum, 5th percentile, and 95th percentile. The macro is flexible and can be used to obtain other parameters such as air/fuel ratios and NOx/CO_2 ratios that may be of interest. It can be used in the field immediately following a test to obtain the desired traces and summary statistics.

It is important to note that because engine data and accurate estimates of fuel flow were not available for the pilot-scale study, only second-by-second fuel-specific emissions (Singer and Harley, 1996) were obtained for the pilot-scale study according to:

$$\text{Pfs (grams\_P/kilograms\_fuel)} = \frac{[P]}{[HC] + [CO] + [CO2] - [CO2]\ \text{ambient}} \times \frac{MWP}{MWfuel} \times 1000$$

where the fuel-specific emissions for pollutant P is the ratio of the mass of pollutant to the fuel burned (i.e., the ratio of measured concentration of pollutant (ppm) to the sum of the CO, CO2, and HC concentrations).

Although the results were extremely useful to assess the potential capabilities of PEMS testing and to develop protocols for field implementation, the limitations of the pilot-scale study should be noted and caution should be used in any attempt to extrapolate the results to the larger TxDOT fleet or to recommend emission control strategies. Nonetheless, the study provided indications of potentially important differences in emissions between modes of operation and the variability in emissions that can occur due to differences in engine conditions.

The data and event logs were reviewed to identify problems/sources of error and data reduction strategies. Sensors, Inc. recommends a fuel-specific drop-out rate of 0.5 percent CO_2 because of singularities that arise in the carbon balance of the combustion equation that influence calculations of the air/fuel ratio, dry-wet gas correction, and other parameters (Ensfield, 2006). By default, fuel-specific emissions are set to zero when CO_2 levels are below the 0.5 percent threshold in the SEMTECH-D software. Although the threshold can be changed, the 0.5 percent threshold was used for the pilot-scale study and records with CO_2 levels below this range were not included in the statistical summary.

Other data screening/reduction measures included replacement of negative emission values by zeros during the post-processing and assessment of unrealistic accelerations using the criteria of 10 mph that was also used by Frey and Kim (2005). Faults or warnings that arose during instrument calibration or vehicle testing were reviewed, and in some cases, described in the following section, led to an independent review of the data by Sensors, Inc.

One of the primary objectives of the pilot-scale study is to characterize emissions during different modes of typical operations. Frey and Kim (2005) conducted what is likely the largest PEMS study to date, including heavy-duty diesel dump trucks in the North Carolina Department of Transportation (NCDOT) fleet. This study was completed in Fall 2005. Frey and Kim's modal definitions were applied to the TxDOT pilot-scale study data in order to provide a basis of comparison with a different fleet and different PEMS instrument (Frey's group operates a

Montana system manufactured by Clean Air Technologies, Incorporated). These definitions, could be used only with the November 2005 tests that had the integrated GPS:

- Idle (speed=0, acceleration =0)
- Acceleration (mph/sec) = speed increases of 1 mph/s; Power Demand = speed (mph) x acceler (mph/s)
    - Low acceleration: Power Demand=20
    - Medium acceleration: (20<Power Demand=50)
    - High Acceleration: (Power Demand> 50)
- Low Cruise (speed < 30 mph)
- Medium Cruise (30 mph <= speed <45 mph)
- High Cruise (speed ≥ 45 mph)
- Deceleration (negative of acceleration)
- Dumping

The PEMS data for each test was segregated according to whether the vehicle was loaded, unloaded, or towing. Dumping had to be identified independently using the activity logs and video recordings. Summary statistics were then calculated separately for each mode.

Because the initial series of tests in May 2005 did not include the integrated GPS, video camera recordings were used to identify modes to the extent possible for each test. Because of the possibility for human error inherent in this approach, only the three cruise modes, an idling mode, and an "other" mode were used in the analysis. This allowed some comparison to data collected in November for modes such as idling and high cruise, which were easily identifiable.

2.3 Results and Discussion

2.3.1 Overview: Successes and Challenges

The pilot-scale study successfully demonstrated that the SEMTECH-D PEMS can be configured for and mounted on single-axle and tandem-axle dump trucks in the TxDOT fleet and can remain fully operational throughout typical, daily TxDOT duty cycles. Testing can be conducted for multiple days, allowing for routine maintenance and re-supply of calibration gases and FID fuel. The physical configuration of the instrumentation and power supplies worked very well, as did the chase vehicle activities and assignments. Researchers maintained radio contact with the TxDOT drivers, all of whom had considerable experience and were routine drivers of the trucks. Because our research team conducted the testing away from the laboratories at UT, the TxDOT maintenance crews and their equipment became important technical support as needs arose in the field.

Video records were useful, although not essential for data analysis if activity logs are maintained and an integrated GPS is available. The SEMTECH-D post-processor software is useful for converting the data from its *raw* form (.xml file) to a form that could be used with Microsoft Access or Excel or similar software. However, it was clearly not designed for rapid data analysis. Sensors did share basic macros they used for generating time series for pollutants, but, as described previously, UT felt that more comprehensive approaches for graphical and statistical analysis were needed. The UT macros run in MS Excel and can be used to generate all of the summary statistics described earlier as well as user-defined time series of single variables or a combination of variables immediately following a test. It is likely that as PEMS technology continues to evolve, the post-processing and data analysis software will also evolve.

In addition to the need to expand the measurement capabilities of the current UT PEMS system to include an exhaust flow meter and an integrated or external method of collecting engine data, several challenges were encountered that need to be considered in future test programs. As described previously, the sampling line, instrument drains, cable to the temperature and relative humidity sensors needed to be routed through main passenger-side window of the single-axle truck, which limited the effectiveness of the HVAC system, which was probably not functioning as well as expected even prior to the test. On May 24, 2005, during the first test of the single-axle truck, peak temperatures in San Antonio reached the mid-90s. During the afternoon, the instrument control screen began exhibiting warnings of high external/ambient temperatures (faults did not occur). Measured ambient temperatures in the afternoon were as high as 37° C (98.6° F). The instrument did not shut down and data collection per se was not affected. However, a high temperature is a concern for the NDUV NOx analyzer because it reduces the efficiency of the chiller. In addition to our own review, an independent review of the data was conducted by Sensors (Kalen and Ensfield, 2005), who thought that the data was not affected by the warnings. Sensors also indicated that they encountered similar warnings during vehicle testing with their instruments in Phoenix, and an enclosure to allow for cooling was under development. Similar problems were not encountered with either of the tandem-axle trucks, which had more robust HVAC systems and fully operational wing windows such that the main passenger side windows could remain closed. Given the need and importance of collecting data for non-road equipment during typical duty cycles in the future, it will be important to evaluate test conditions carefully. For example, certain types of equipment may not have space in the cabin to house the PEMS and could require mounting of the instrumentation outside of the cabin, which may allow greater airflow around the instrument but would also subject it more directly to extremes of temperature. Testing during the late fall through early spring in Texas would be more advisable than testing during the summer.

A generator was used as the main power supply to the instrument, which worked well during all of the tests as long as gasoline was supplied every few hours, and it did not place an additional load on the engine. However, in the future, given the potential for more complex testing configurations with different types of vehicles or equipment, it would be advisable to examine the effects of running the instrument off the vehicle's electrical system if it becomes difficult to safely mount a generator. The SEMTECH-D main power must be connected to 12 Vdc power source (Sensors, Inc. 2004). The team's experience is that the SEMTECH-D will draw as much as 70 amperes during its peak usage and approximately 30 amperes during routine operation.

2.3.2 TxDOT Duty Cycles

The results for the pilot study are summarized in Tables 2.3-2.7 and show percent time in mode and emissions for each of the vehicles. Note that the single-axle truck (15-4772G) and one of the tandem-axle trucks (15-5184G) were each tested twice, i.e., once in May 2005 and again in November 2005. As described previously, the results in May did not have an integrated GPS.

Duty cycles were quite similar between the single-axle truck and the two tandem-axle trucks. Idling was the most significant operating mode for the trucks tested, representing 20 percent-46 percent of the total fraction of operating time. Frey and Kim (2005) found similar (35 percent to 60 percent) results for dump trucks in the North Carolina Department of Transportation fleet. TxDOT does have an engine idling policy that limits idling time to five-minutes when the vehicle "is not in motion or not being used for its primary function (Noble, 2006) with exceptions for operation of the vehicles air conditioning system for employee health, for traffic conditions, for defrosting the windshield, for maintenance, for emergency purposes and for serving as the power source for another device." The goal of the TxDOT policy is to reduce both fuel consumption and emissions. Although it was beyond the scope of the pilot scale study, it would be beneficial to examine the effectiveness of the idling policy across TxDOT districts to determine if additional reductions could be achieved.

High speed cruising represented the second most significant operating mode for most of the vehicles, representing 12 percent–45 percent of the total fraction of operating time. The exception was the test conducted on November 16, 2005 for the single-axle truck (15-4772G), which primarily consisted of short hauls in a suburban area of San Antonio. In total, the cruise modes represented approximately 26 percent–50 percent of the total fraction of operating time. These results were higher than those recorded by Frey and Kim (2005) for NCDOT (20 to 30 percent). San Antonio is a large metropolitan area; and hauls conducted during the pilot-scale test often involved distances of 15 miles or greater on urban freeways or semi-rural highways with little traffic. Acceleration and deceleration modes (November tests only in Tables 2.6 and 2.7) comprised 4–7 percent and 17 percent–20 percent of the total operating time, respectively. Dumping represented from less than 1 percent to 3 percent of the total fraction of operating time.

Although a rigorous analysis of the engine rpm could not be conducted, the video recordings indicated that the single-axle truck (15-4772G) CAT 3126B engine, described in Table 2.1, idled at approximately 500 rpm and cruised at high speeds at 2000–2500 rpm. The tandem axle (15-5184G) Cummins ISM305V engine idled at approximately 500 rpm and cruised at high speeds at 1500–2000 rpm. The tandem axle (15-3512H) CAT C10 engine idled at 750 rpm and cruised at high speeds at 1500–2000 rpm.

2.3.3 Fuel-Specific Emission Profiles

Fuel-specific emission profiles indicate that characterizing idling versus other modes of operation is important for these types of vehicles. Not only does idling represent a significant fraction of the duty cycle, fuel-specific emissions for this mode of operation are consistently higher than other modes for all pollutants (although it is important to recognize that on a mass basis, idling may represent a smaller fraction of the total emissions). In their calculations of average emission rates on a per gallon basis (i.e., g_pollutant/gal of fuel consumed or kg of pollutant/gal of fuel consumed), Frey and Kim (2005) similarly found that idling is the most significant emission mode. Dumping occurs when the vehicle is idling or moving at very low speeds, and emissions for this operating mode were generally comparable to or slightly less than emissions during idling.

Following the November test of the single-axle truck (15-4772G), TxDOT notified our team that a problem existed with the fuel injection system of this vehicle, resulting in over-fueling of the engine. There was no visible evidence of a problem during the test, but this provided an interesting opportunity to compare these data with data collected earlier in the year when there was no known problem with this engine. Although there were significant differences in the ambient temperatures during the May and November tests that could also contribute to differences in emissions, average and median fuel-specific emissions of all pollutants were consistently greater by as much as a factor of two or higher during the November test of this truck (ref. Table 2.3 and Table 2.6). These results agree qualitatively with the type of problem reported by TxDOT. Higher emissions of CO and THC would be expected in a more fuel-rich mixture. NOx emissions may increase if the injection timing results in early heat release that increases the peak flame temperature (Flagan and Seinfeld, 1998). Agreement between the results for the May and November tests for the tandem-axle truck 15-5184G (ref. Table 2.4 and Table 2.7) was quite good for both CO_2 and NOx. Although weighted mean CO emissions for the two tests showed excellent agreement, CO emissions during idling were higher during the November test. Overall, these results suggested the utility of PEMS for understanding the impacts of engine operating conditions and maintenance and repair on exhaust emissions.

Median CO_2 emissions were similar between all non-idling modes regardless of the truck load. Median NOx emissions were reasonably consistent between non-idling modes (reference Tables 2.6 and 2.7) perhaps because NOx formation is largely dependent on the peak flame temperature and less dependent on the air/fuel or equivalence ratio (Flagan and Seinfeld, 1988). CO and THC emissions showed more variability between non-idling modes of operation; emissions differed by as much a factor of 2 or 3. Understanding the range of differences in emissions between modes of operation will be important for future PEMS test design and for mobile source emission model development.

Because the current UT PEMS system characterizes emissions on a fuel-specific basis, studies of fuel-based emission inventories were identified in order to provide a basis for comparison with results obtained from the current PEMS study, recognizing that almost all of these studies simply report an average fuel-specific emission factor and do not capture episodic emissions that would be obtainable with a PEMS. A summary of NOx emission factors is provided in Table 2.8. With the exception of the results of Kean et al. (2000) and Baker et al. (2004), most of the studies include results for on-road heavy-duty diesel trucks that may or may not have the same engine types as those included in the pilot scale study. Nonetheless, they provide a useful basis for comparison. Weighted median NOx emission factors for the single-axle truck with the CAT 3126B engine were 41.88 g NOx as NO_2/kg TXLED and 90.69 g NOx as NO_2/kg TXLED for the May and November tests, respectively. Assuming that the fuel injection problem led to higher NOx emissions in the November test that were not representative of typical operating conditions, the result for the May test is in excellent agreement with the value reported by Baker et al. (2004) for the same engine type on a chassis dynamometer and is well within the range of values reported across all of the studies. Weighted median NOx emission factor for the tandem-axle dump truck (15-5184G) with the CAT C10 engine were 28.71 g NOx as NO_2/kg TXLED and 22.91 g NOx as NO_2/kg TXLED for the May and November tests, respectively. The agreement between these values and the value reported by Baker et al. (2004) for the same engine type is quite good. The weighted median NOx emission factor for the tandem-axle truck (15-3512H) with the Cummins ISM305V engine was 37.30 g NOx as NO_2/kg TXLED, which was well within the range of values reported across all of the studies.

2.4 Conclusions and Recommendations

Although earlier emissions testing programs have been conducted primarily in laboratory settings using engine or chassis dynamometers, new federal rules now require measurement of exhaust emissions from on-road and, in the future, non-road heavy-duty diesel engines during real-world driving conditions using PEMS. This pilot study demonstrated the successful deployment of the Sensors, Inc. SEMTECH-D PEMS on single-axle and tandem-axle dump trucks, which account for approximately 40 percent of the diesel fuel used by on-road equipment in TxDOT fleet in the twelve major ozone non-attainment counties in Texas (Baker et al., 2004). Exhaust emissions were measured during typical TxDOT duty cycles, and a modal emissions analysis was conducted. Idling accounted for the most significant fraction (20 percent–46 percent) of the duty cycle and had the highest average and median fuel-specific emission factors for all pollutants. Although emissions during this mode of operation may represent a smaller fraction of the total emissions on a mass basis, TxDOT should continue to examine the idling practices of its dump trucks with respect to the impacts on both emissions and fuel consumption.

Differences in emissions between non-idling modes of operation varied by pollutant. CO_2 and NOx emissions were reasonably consistent between non-idling modes; CO and THC emissions exhibited greater variability with differences of a factor of two or three in some cases. The range of NOx emission factors measured in this study showed very good agreement with emission factors measured through chassis dynamometer testing of the same engine types by Baker et al. (2004), and were well within the range of values reported in other studies. TxDOT should continue to characterize baseline emissions from other on-road and non-road equipment besides dump trucks during typical operations. Future PEMS-based testing programs offer a significant advantage not only because emissions can be characterized under real-world conditions, but also because PEMS testing is considerably less expensive than dynamometer-based testing. New fuels and fuel additives as well as new after-market emission reduction technologies will be emerging from the Texas Emission Reduction Program (TERP), the New Technology Research and Development (NTRD) Program, and similar state or national-scale incentive programs. The pilot-scale testing program under TxDOT Project 0-5191 focused only on characterization of baseline emissions from dump trucks as a demonstration of the PEMS technology; strategies for achieving emissions reductions have not been evaluated. Emission reduction technologies and/or fuels/fuel additives should be selected for in-use evaluation on TxDOT equipment. Inter-comparison of results study with other national (EPA) or state-level emission inventories for heavy-duty diesel engines should be conducted.

Table 2.3: Percent time in mode and summary of fuel-specific emissions (g_pollutant/kg/fuel) for single-axle truck 15-4772G on May 24, 2005.

Note that the load and/or cruise mode could not be obtained for some data because video records were not available; thus, the percent time in the modes may sum to less than 100%.

Pollutant	Load	Cruise Mode	Count	Time Fraction (%)	Average	Population Standard Deviation	Median	Minimum	Maximum	5th Percentile	95th Percentile
CO_2	Loaded	Idle	2529	15	3223.84	9.99	3222.58	3160.56	3299.94	3209.85	3238.15
	Loaded	Low Cruise	512	3	3204.77	33.06	3193.16	3137.22	3372.17	3175.96	3269.95
	Loaded	Med Cruise	579	3	3205.92	38.17	3195.52	3132.58	3423.92	3171.01	3278.59
	Loaded	High Cruise	3423	20	3200.52	20.22	3196.88	3138.43	3419.04	3189.70	3220.50
	Loaded	Other	700	4	3201.52	35.03	3193.40	3127.12	3409.20	3162.84	3268.53
	Unloaded	Idle	3009	17	3230.99	13.54	3231.68	3185.43	3296.72	3201.78	3248.48
	Unloaded	Low Cruise	332	2	3209.09	27.95	3201.76	3139.51	3354.31	3180.10	3261.82
	Unloaded	Med Cruise	281	2	3203.75	28.50	3197.11	3128.10	3362.13	3179.77	3250.08
	Unloaded	High Cruise	3696	21	3200.19	15.94	3198.37	3126.98	3437.54	3190.94	3212.55
	Unloaded	Other	756	4	3208.23	36.41	3197.32	3127.06	3427.91	3171.63	3279.52
		Dump	155	1	3218.55	10.86	3221.05	3189.24	3242.23	3199.41	3234.25
	All Data		17259	100	3212.02	24.58	3201.92	3116.01	3437.54	3187.41	3247.54
CO	Loaded	Idle	2529	15	20.50	5.25	19.96	4.81	66.18	12.38	28.53
	Loaded	Low Cruise	512	3	17.56	9.96	16.89	0.00	88.90	4.80	33.36
	Loaded	Med Cruise	579	3	9.25	9.99	5.47	0.00	57.90	0.00	32.22
	Loaded	High Cruise	3423	20	6.60	5.29	5.46	0.00	73.66	2.76	15.40
	Loaded	Other	700	4	12.25	11.03	8.71	0.00	89.31	1.96	33.35
	Unloaded	Idle	3009	17	16.15	5.35	13.57	8.53	41.76	10.46	24.96

Pollutant	Load	Cruise Mode	Count	Time Fraction (%)	Average	Population Standard Deviation	Median	Minimum	Maximum	5th Percentile	95th Percentile
	Unloaded	Low Cruise	332	2	17.81	8.00	16.48	0.00	60.53	7.20	32.02
	Unloaded	Med Cruise	281	2	10.18	7.84	7.76	0.00	52.03	3.47	25.25
	Unloaded	High Cruise	3696	21	7.13	5.28	5.97	0.00	135.15	3.21	14.85
	Unloaded	Other	756	4	13.36	8.84	12.08	0.00	64.39	2.22	29.20
		Dump	155	1	16.82	4.67	16.50	8.50	25.96	9.97	23.57
	All Data		17259	100	12.31	8.27	10.92	0.00	135.15	3.20	25.98
NOx	Loaded	Idle	2529	15	52.11	7.43	54.95	20.03	77.02	35.24	58.54
	Loaded	Low Cruise	512	3	43.36	13.18	45.42	11.91	78.14	19.46	61.98
	Loaded	Med Cruise	579	3	28.89	14.18	23.82	10.06	97.73	13.31	54.23
	Loaded	High Cruise	3423	20	26.33	11.50	22.13	9.62	90.04	13.74	48.22
	Loaded	Other	700	4	31.31	14.37	28.10	9.32	120.93	14.43	53.56
	Unloaded	Idle	3009	17	49.91	9.72	55.01	28.56	81.05	31.80	59.57
	Unloaded	Low Cruise	332	2	36.32	10.88	34.17	16.23	82.22	21.30	56.49
	Unloaded	Med Cruise	281	2	36.38	15.86	35.16	10.41	83.51	15.13	62.09
	Unloaded	High Cruise	3696	21	34.12	15.28	34.53	11.84	104.10	14.31	54.73
	Unloaded	Other	756	4	36.83	14.28	37.96	10.39	117.03	14.86	57.83
		Dump	155	1	47.81	9.66	51.28	27.65	60.14	30.70	58.75
	All Data		17259	100	39.48	15.78	41.88	9.32	120.93	14.79	58.38
	Loaded	Idle	2529	15	4.76	1.27	5.25	0.50	12.54	2.45	6.26
	Loaded	Low Cruise	512	3	3.14	2.84	2.36	0.36	21.93	0.58	8.65
	Loaded	Med Cruise	579	3	1.54	1.70	0.96	0.32	12.41	0.43	5.06
	Loaded	High Cruise	3423	20	1.15	1.13	0.90	0.36	19.69	0.48	2.42

Pollutant	Load	Cruise Mode	Count	Time Fraction (%)	Average	Population Standard Deviation	Median	Minimum	Maximum	5th Percentile	95th Percentile
THC	Loaded	Other	700	4	1.72	1.90	0.99	0.30	13.00	0.36	5.64
	Unloaded	Idle	3009	17	3.91	1.60	3.40	1.57	8.33	2.03	6.92
	Unloaded	Low Cruise	332	2	3.50	2.78	2.83	0.38	16.51	0.75	8.45
	Unloaded	Med Cruise	281	2	1.29	1.26	0.88	0.30	10.40	0.37	3.97
	Unloaded	High Cruise	3696	21	0.99	0.92	0.78	0.27	16.04	0.43	2.04
	Unloaded	Other	756	4	2.13	1.95	1.33	0.28	10.75	0.39	6.40
		Dump	155	1	3.11	0.83	3.06	1.60	5.80	2.02	4.62
	All Data		17259	100	2.53	2.11	1.61	0.27	21.93	0.48	6.16

Table 2.4: Percent time in mode and summary of fuel-specific emissions (g_pollutant/kg/fuel) for tandem axle truck 15-5184G on May 25, 2005.

Note that the load and/or cruise mode could not be obtained for some data because video records were not available; thus, the percent time in the modes may sum to less than 100%.

Pollutant	Load	Cruise Mode	Count	Time Fraction (%)	Average	Population Standard Deviation	Median	Minimum	Maximum	5th Percentile	95th Percentile
CO2	Loaded	Idle	2998	13	3228.52	14.35	3229.08	2938.10	3364.52	3219.54	3241.97
	Loaded	Low Cruise	490	2	3201.15	41.35	3195.26	2930.56	3418.03	3161.43	3256.03
	Loaded	Med Cruise	277	1	3191.18	196.42	3192.02	0.00	3408.54	3163.15	3291.08
	Loaded	High Cruise	5241	23	3193.74	19.31	3190.77	3092.35	3412.39	3183.95	3213.35
	Loaded	Other	772	3	3207.33	48.59	3192.97	3003.18	3426.36	3152.17	3305.42
	Unloaded	Idle	5355	24	3222.19	17.44	3223.90	2790.53	3380.87	3190.63	3238.14
	Unloaded	Low Cruise	199	1	3208.61	35.77	3201.10	3071.71	3357.24	3164.12	3267.35
	Unloaded	Med Cruise	346	2	3201.92	39.65	3190.64	3132.13	3423.41	3159.18	3290.52
	Unloaded	High Cruise	3106	14	3193.88	17.81	3191.32	3119.43	3420.46	3183.62	3211.21
	Unloaded	Other	685	3	3199.24	41.08	3191.43	2960.60	3402.40	3149.09	3277.56
	Unloaded	Dump	178	1	3228.96	14.26	3227.99	3199.38	3357.31	3207.52	3236.12
	All Data		22395	100	3209.11	34.58	3204.28	0.00	3426.36	3182.34	3240.02
CO	Loaded	Idle	2998	13	17.91	6.49	17.74	0.00	179.42	14.14	21.03
	Loaded	Low Cruise	490	2	15.44	15.96	12.92	0.00	186.75	3.37	30.59
	Loaded	Med Cruise	277	1	11.70	10.92	8.33	0.00	56.62	0.00	36.69
	Loaded	High Cruise	5241	23	8.45	7.11	7.06	0.00	150.79	2.81	20.68
	Loaded	Other	772	3	15.19	14.79	12.09	0.00	143.48	0.00	42.82
	Unloaded	Idle	5355	24	18.00	5.88	18.30	0.00	272.76	10.07	22.72
	Unloaded	Low Cruise	199	1	17.68	11.11	15.19	0.00	91.62	6.30	39.71
	Unloaded	Med Cruise	346	2	14.77	14.20	10.92	0.00	137.93	0.02	37.63
	Unloaded	High Cruise	3106	14	8.86	6.30	7.44	0.00	98.75	3.42	19.19

	Unloaded	Other	685	3	15.67	17.56	10.99	0.00	169.90	1.31	42.40
	Unloaded	Dump	178	1	15.50	1.97	15.05	3.27	27.33	13.48	18.55
	All Data		22395	100	13.72	9.22	14.59	0.00	272.76	3.34	23.62
NOx	Loaded	Idle	2998	13	62.07	7.48	64.83	9.39	125.98	49.94	68.50
	Loaded	Low Cruise	490	2	27.99	15.25	22.61	6.07	78.29	11.58	55.48
	Loaded	Med Cruise	277	1	20.00	7.80	18.22	0.00	61.83	12.06	32.10
	Loaded	High Cruise	5241	23	19.30	6.15	17.84	8.07	70.85	14.09	31.44
	Loaded	Other	772	3	23.36	15.12	17.62	7.19	92.16	11.03	61.14
	Unloaded	Idle	5355	24	56.43	14.70	64.23	6.98	91.89	18.55	67.03
	Unloaded	Low Cruise	199	1	36.79	15.73	37.33	8.35	69.93	12.52	65.31
	Unloaded	Med Cruise	346	2	24.64	15.22	19.34	8.28	98.75	11.94	57.15
	Unloaded	High Cruise	3106	14	19.54	6.29	17.61	7.68	77.42	13.84	30.71
	Unloaded	Other	685	3	24.57	14.69	19.73	7.03	105.84	11.33	53.27
	Unloaded	Dump	178	1	64.29	8.58	66.62	33.82	84.09	38.55	68.74
	All Data		22395	100	38.09	21.73	28.71	0.00	125.98	13.95	67.08
THC	Loaded	Idle	2998	13	3.37	0.48	3.30	0.62	11.05	2.91	4.13
	Loaded	Low Cruise	490	2	2.57	1.96	2.03	0.41	16.02	0.70	5.97
	Loaded	Med Cruise	277	1	2.07	2.25	1.31	0.00	15.09	0.36	6.65
	Loaded	High Cruise	5241	23	1.40	1.65	0.96	0.31	19.33	0.47	4.24
	Loaded	Other	772	3	2.37	2.08	1.54	0.32	11.98	0.46	7.00
	Unloaded	Idle	5355	24	3.70	1.00	3.66	0.58	15.66	1.85	4.90
	Unloaded	Low Cruise	199	1	3.68	2.47	2.86	0.50	12.43	0.90	8.86
	Unloaded	Med Cruise	346	2	2.55	2.39	1.62	0.34	14.78	0.55	7.13
	Unloaded	High Cruise	3106	14	1.52	1.28	1.19	0.25	16.79	0.61	3.59
	Unloaded	Other	685	3	2.43	2.13	1.65	0.29	14.58	0.50	6.85
	Unloaded	Dump	178	1	3.37	0.71	3.23	2.24	9.06	3.03	3.89
	All Data		22395	100	2.56	1.70	2.77	0.00	19.33	0.56	4.76

Table 2.5: Percent time in mode and summary of fuel-specific emissions (g_pollutant/kg/fuel) for tandem axle truck 15-3512H on May 26, 2005.

Note that the load and/or cruise mode could not be obtained for some data because video records were not available; thus, the percent time in the modes may sum to less than 100%.

Pollutant	Load	Cruise Mode	Count	Time Fraction (%)	Average	Population Standard Deviation	Median	Minimum	Maximum	5 Percentile	95 Percentile
CO_2	Loaded	Idle	1162	7	3221.07	18.93	3221.29	3175.03	3414.52	3193.63	3232.41
	Loaded	Low Cruise	500	3	3206.44	27.77	3198.87	3119.44	3374.13	3181.67	3253.74
	Loaded	Med Cruise	320	2	3202.37	26.88	3193.47	3168.66	3399.58	3185.94	3243.53
	Loaded	High Cruise	5254	33	3197.16	14.83	3195.10	3148.01	3389.53	3190.61	3206.06
	Loaded	Other	631	4	3204.71	25.12	3195.17	3158.07	3379.73	3180.75	3241.68
	Unloaded	Idle	1134	7	3226.42	40.60	3221.46	3164.92	3392.87	3186.43	3328.15
	Unloaded	Low Cruise	216	1	3210.38	21.93	3216.52	3157.68	3357.94	3180.32	3229.97
	Unloaded	Med Cruise	279	2	3203.73	26.26	3196.81	3142.99	3377.80	3181.34	3243.18
	Unloaded	High Cruise	1993	12	3200.39	17.87	3196.49	3168.48	3414.82	3191.76	3223.30
	Unloaded	Other	441	3	3207.75	31.17	3197.82	3147.44	3390.07	3180.71	3254.79
		Dump	72	<1	3212.77	3.95	3213.97	3199.82	3218.63	3205.90	3216.79
	All Data		15946	100	3206.43	26.39	3197.15	1851.07	3414.82	3188.89	3232.33
	Loaded	Idle	1162	7	14.03	3.89	14.21	0.00	44.27	5.47	17.88
	Loaded	Low Cruise	500	3	10.47	8.85	10.07	0.00	126.72	1.41	24.71
	Loaded	Med Cruise	320	2	7.37	9.33	3.07	0.00	80.59	2.04	24.86

CO	Loaded	High Cruise	5254	33	5.64	5.65	3.59	0.00	76.78	2.19	16.52
	Loaded	Other	631	4	8.79	7.53	5.90	0.00	48.76	1.49	20.93
	Unloaded	Idle	1134	7	17.48	6.60	16.59	0.00	52.85	10.38	28.66
	Unloaded	Low Cruise	216	1	12.39	5.88	14.79	0.00	25.84	1.39	20.09
	Unloaded	Med Cruise	279	2	7.51	6.25	5.50	0.00	46.31	0.31	19.37
	Unloaded	High Cruise	1993	12	6.33	5.63	4.40	0.00	59.51	1.86	16.96
	Unloaded	Other	441	3	9.13	7.87	6.57	0.00	51.74	0.63	23.03
		Dump	72	<1	13.86	1.82	13.58	9.14	17.55	11.18	16.55
	All Data		15946	100	9.36	9.98	6.82	0.00	820.95	2.10	21.54
	Load	**Cruise Mode**	**Count**	**Time Fraction (%)**	**Average**	**Population Standard Deviation**	**Median**	**Minimum**	**Maximum**	**5 Percentile**	**95 Percentile**
NOx	Loaded	Idle	1162	7	43.74	8.74	45.67	9.00	95.72	19.52	51.71
	Loaded	Low Cruise	500	3	31.86	12.91	29.73	8.02	89.34	15.64	49.91
	Loaded	Med Cruise	320	2	29.52	10.89	27.54	9.84	78.72	16.40	45.37
	Loaded	High Cruise	5254	33	35.20	6.14	36.21	8.11	69.45	24.92	42.93
	Loaded	Other	631	4	29.79	11.52	27.11	8.08	71.31	15.42	46.80
	Unloaded	Idle	1134	7	53.29	11.65	50.81	11.32	141.36	39.68	73.17
	Unloaded	Low Cruise	216	1	37.31	9.06	41.93	12.31	57.25	19.41	47.29
	Unloaded	Med Cruise	279	2	27.46	9.51	26.14	10.49	62.19	15.14	44.89
	Unloaded	High Cruise	1993	12	28.53	6.95	28.26	8.33	86.70	18.44	38.77
	Unloaded	Other	441	3	27.87	9.85	25.53	12.44	61.06	15.23	45.82

		Dump	72	<1	46.01	1.41	46.26	41.48	48.20	43.25	48.00
	All Data		15946	100	36.60	11.19	37.30	8.02	141.36	18.26	51.56
THC	Loaded	Idle	1162	7	6.01	1.85	6.45	0.79	13.74	1.72	7.66
	Loaded	Low Cruise	500	3	3.77	3.15	3.09	0.64	25.35	0.94	9.30
	Loaded	Med Cruise	320	2	2.35	2.69	1.19	0.75	24.37	0.93	7.22
	Loaded	High Cruise	5254	33	2.11	2.42	1.34	0.52	35.08	1.01	5.77
	Loaded	Other	631	4	2.87	2.58	1.51	0.62	20.78	0.84	6.88
	Unloaded	Idle	1134	7	5.16	1.69	5.22	1.06	11.78	2.39	7.92
	Unloaded	Low Cruise	216	1	4.90	2.36	5.28	0.87	13.18	1.30	7.49
	Unloaded	Med Cruise	279	2	2.83	2.63	1.70	0.73	19.81	0.91	8.17
	Unloaded	High Cruise	1993	12	2.54	2.21	1.80	0.61	25.31	1.17	6.26
	Unloaded	Other	441	3	3.66	3.38	2.08	0.66	21.51	0.96	10.98
		Dump	72	<1	4.87	0.62	5.05	3.09	5.76	3.81	5.63
	All Data		15946	100	3.45	2.77	2.20	0.52	35.08	1.02	7.40

Table 2.6: Percent time in mode and summary of fuel-specific emissions (g_pollutant/kg/fuel) for single-axle truck 15-4772G on November 16, 2005.

Poll.	Load	Cruise Mode	Cnt.	Time Fraction (%)	Average	Population Standard Deviation	Median	Minimum	Maximum	5 Percentile	95 Percentile
CO_2	Loaded	Idle	3336	28	3277.94	44.52	3268.64	3141.49	3365.19	3208.70	3345.06
	Loaded	Low Accel.	93	1	3203.05	38.95	3197.82	3129.76	3372.40	3157.44	3269.90
	Loaded	Med Accel.	193	2	3196.93	28.54	3193.10	3118.92	3336.99	3157.72	3255.95
	Loaded	High Accel.	22	0	3194.61	44.74	3188.29	3140.43	3390.01	3165.84	3209.72
	Loaded	Decel.	671	6	3209.69	40.24	3199.27	3074.17	3394.96	3156.98	3278.75
	Loaded	Low Cruise	323	3	3205.61	39.64	3195.00	3123.33	3373.56	3159.70	3286.18
	Loaded	Med Cruise	370	3	3193.07	15.49	3192.99	3134.89	3322.10	3172.03	3209.70
	Loaded	High Cruise	418	4	3202.23	23.78	3196.76	3173.91	3432.86	3186.61	3238.90
	Unloaded	Idle	2081	18	3272.18	27.03	3275.55	2769.12	3333.31	3240.36	3306.39
	Unloaded	Low Accel.	159	1	3217.20	43.87	3204.77	3146.75	3378.92	3168.09	3303.77
	Unloaded	Med Accel.	204	2	3203.05	43.47	3194.89	3131.38	3407.56	3154.28	3312.03
	Unloaded	High Accel.	211	2	3201.81	34.15	3196.57	3133.40	3318.74	3152.59	3277.21
	Unloaded	Decel.	1344	11	3217.64	47.95	3199.97	3042.91	3418.88	3163.89	3309.35
	Unloaded	Low Cruise	574	5	3207.89	35.82	3199.62	3132.17	3378.87	3158.32	3270.90
	Unloaded	Med Cruise	356	3	3202.45	33.86	3197.21	3135.46	3424.52	3172.61	3260.88
	Unloaded	High Cruise	1054	9	3198.23	23.78	3193.13	3137.53	3416.82	3181.46	3224.17
	Dump	Dump	405	3	3220.92	34.45	3223.73	3127.44	3313.47	3167.77	3273.64
	Any Loading	Idle	5417	46	3275.72	38.85	3273.92	2769.12	3365.19	3212.64	3341.08
	Any Loading	Low Accel.	252	2	3211.98	42.68	3199.68	3129.76	3378.92	3160.07	3295.30
	Any Loading	Med Accel.	397	3	3200.08	37.10	3193.46	3118.92	3407.56	3155.95	3274.02
	Any Loading	High Accel.	233	2	3201.13	35.35	3195.06	3133.40	3390.01	3152.62	3276.36
	Any Loading	Decel.	2015	17	3215.00	45.68	3199.70	3042.91	3418.88	3160.25	3303.94
	Any Loading	Low Cruise	897	8	3207.07	37.26	3197.85	3123.33	3378.87	3158.75	3276.24

Poll.	Load	Cruise Mode	Cnt.	Time Fraction (%)	Average	Population Standard Deviation	Median	Minimum	Maximum	5 Percentile	95 Percentile
	Any Loading	Med Cruise	726	6	3197.67	26.58	3194.43	3134.89	3424.52	3172.13	3231.78
	Any Loading	High Cruise	1472	12	3199.37	23.85	3194.23	3137.53	3432.86	3183.03	3225.78
	Any Loading	Dump	405	3	3220.92	34.45	3223.73	3127.44	3313.47	3167.77	3273.64
	All Data		1181 4	100	3238.59	51.17	3234.40	2769.12	3432.86	3173.33	3335.44
CO	Loaded	Idle	3336	28	42.11	29.97	52.65	0.00	90.58	0.00	80.10
	Loaded	Low Accel.	93	1	22.12	17.72	19.33	0.00	77.04	0.00	50.08
	Loaded	Med Accel.	193	2	12.30	12.47	8.87	0.00	63.14	0.00	40.85
	Loaded	High Accel.	22	0	14.18	11.19	10.93	0.00	46.48	2.25	34.62
	Loaded	Decel.	671	6	35.71	26.33	32.30	0.00	148.06	0.36	83.27
	Loaded	Low Cruise	323	3	32.52	22.21	29.10	0.00	133.86	3.06	72.23
	Loaded	Med Cruise	370	3	8.92	9.12	7.74	0.00	105.00	0.00	23.26
	Loaded	High Cruise	418	4	9.29	6.71	8.98	0.00	60.73	0.00	19.68
	Unloaded	Idle	2081	18	48.45	20.64	51.43	0.00	330.67	2.39	74.11
	Unloaded	Low Accel.	159	1	19.96	14.82	18.88	0.00	77.35	0.00	43.07
	Unloaded	Med Accel.	204	2	19.21	17.47	13.85	0.00	98.03	0.00	54.79
	Unloaded	High Accel.	211	2	16.13	16.07	12.03	0.00	82.35	0.00	44.90
	Unloaded	Decel.	1344	11	29.11	23.27	23.01	0.00	197.20	0.00	74.60
	Unloaded	Low Cruise	574	5	27.62	17.43	25.98	0.00	88.68	2.15	62.38
	Unloaded	Med Cruise	356	3	16.47	14.96	11.65	0.00	103.61	1.99	43.08
	Unloaded	High Cruise	1054	9	17.30	13.27	16.22	0.00	136.88	0.00	37.54
	Dump	Dump	405	3	41.73	15.91	40.44	6.10	83.00	15.93	74.37
	Any Loading	Idle	5417	46	44.55	26.95	51.45	0.00	330.67	0.00	79.16
	Any Loading	Low Accel.	252	2	20.75	15.99	19.20	0.00	77.35	0.00	47.44
	Any Loading	Med Accel.	397	3	15.85	15.63	10.85	0.00	98.03	0.00	48.29
	Any Loading	High Accel.	233	2	15.95	15.68	11.84	0.00	82.35	0.00	44.89

Poll.	Load	Cruise Mode	Cnt.	Time Fraction (%)	Average	Population Standard Deviation	Median	Minimum	Maximum	5 Percentile	95 Percentile
	Any Loading	Decel.	2015	17	31.31	24.53	25.11	0.00	197.20	0.00	78.04
	Any Loading	Low Cruise	897	8	29.38	19.43	27.01	0.00	133.86	2.65	65.86
	Any Loading	Med Cruise	726	6	12.62	12.90	10.09	0.00	105.00	0.00	34.57
	Any Loading	High Cruise	1472	12	15.03	12.32	12.67	0.00	136.88	0.00	33.06
	Any Loading	Dump	405	3	41.73	15.91	40.44	6.10	83.00	15.93	74.37
	All Data		11814	100	33.36	25.89	27.71	0.00	330.67	0.00	76.88
NOx	Loaded	Idle	3336	28	109.46	13.60	108.90	43.99	151.01	88.69	136.54
	Loaded	Low Accel.	93	1	63.61	24.57	61.77	24.02	156.96	31.32	104.79
	Loaded	Med Accel.	193	2	61.71	16.98	59.14	21.48	146.18	38.78	89.30
	Loaded	High Accel.	22	0	61.22	9.43	64.33	35.14	81.23	44.88	70.84
	Loaded	Decel.	671	6	78.25	25.22	72.51	10.61	256.34	43.75	122.16
	Loaded	Low Cruise	323	3	73.19	23.35	69.62	26.40	200.98	42.68	111.25
	Loaded	Med Cruise	370	3	65.98	10.60	64.82	28.02	151.33	52.40	79.49
	Loaded	High Cruise	418	4	65.42	8.07	65.00	35.65	161.67	54.97	75.57
	Unloaded	Idle	2081	18	111.26	16.65	117.94	35.97	158.36	79.98	130.02
	Unloaded	Low Accel.	159	1	69.36	26.71	63.11	21.37	224.02	38.14	113.57
	Unloaded	Med Accel.	204	2	62.65	25.24	56.03	21.05	211.45	34.30	105.13
	Unloaded	High Accel.	211	2	59.49	20.52	57.46	17.49	165.30	30.15	99.50
	Unloaded	Decel.	1344	11	76.86	24.56	70.49	15.44	305.68	47.12	118.45
	Unloaded	Low Cruise	574	5	71.81	20.71	69.53	15.89	198.36	44.09	105.37
	Unloaded	Med Cruise	356	3	67.56	30.19	62.65	19.45	384.98	46.85	97.59
	Unloaded	High Cruise	1054	9	66.40	11.36	65.93	26.69	199.64	53.21	78.21
	Dump	Dump	405	3	84.44	19.68	85.24	31.45	138.56	52.73	118.11
	Any Loading	Idle	5417	46	110.15	14.88	110.58	35.97	158.36	84.06	134.84
	Any Loading	Low Accel.	252	2	67.24	26.09	62.69	21.37	224.02	33.67	111.64

Poll.	Load	Cruise Mode	Cnt.	Time Fraction (%)	Average	Population Standard Deviation	Median	Minimum	Maximum	5 Percentile	95 Percentile
	Any Loading	Med Accel.	397	3	62.19	21.63	57.98	21.05	211.45	37.54	102.51
	Any Loading	High Accel.	233	2	59.65	19.75	58.05	17.49	165.30	30.70	97.50
	Any Loading	Decel.	2015	17	77.32	24.79	70.97	10.61	305.68	45.95	119.85
	Any Loading	Low Cruise	897	8	72.31	21.71	69.57	15.89	200.98	43.24	108.80
	Any Loading	Med Cruise	726	6	66.75	22.47	63.87	19.45	384.98	47.76	86.08
	Any Loading	High Cruise	1472	12	66.13	10.54	65.63	26.69	199.64	53.72	77.28
	Any Loading	Dump	405	3	84.44	19.68	85.24	31.45	138.56	52.73	118.11
	All Data		1181 4	100	89.12	27.12	90.69	10.61	384.98	50.67	128.85
THC	Loaded	Idle	3336	28	8.10	2.02	8.30	0.81	13.85	5.05	11.05
	Loaded	Low Accel.	93	1	2.08	1.45	1.74	0.37	8.71	0.58	4.61
	Loaded	Med Accel.	193	2	0.82	0.64	0.58	0.36	3.93	0.38	1.93
	Loaded	High Accel.	22	0	0.71	0.72	0.45	0.37	3.78	0.38	1.35
	Loaded	Decel.	671	6	4.15	4.05	3.07	0.37	23.01	0.44	12.39
	Loaded	Low Cruise	323	3	3.56	3.08	2.83	0.37	17.65	0.44	9.31
	Loaded	Med Cruise	370	3	0.61	0.45	0.53	0.35	6.77	0.38	1.05
	Loaded	High Cruise	418	4	0.85	0.94	0.66	0.40	11.11	0.43	1.72
	Unloaded	Idle	2081	18	6.15	1.54	6.15	0.76	15.45	3.84	8.73
	Unloaded	Low Accel.	159	1	2.21	1.69	1.74	0.40	11.52	0.64	5.09
	Unloaded	Med Accel.	204	2	1.40	1.49	0.79	0.33	11.62	0.38	4.39
	Unloaded	High Accel.	211	2	1.08	1.00	0.78	0.33	8.41	0.40	2.73
	Unloaded	Decel.	1344	11	3.09	2.91	1.87	0.33	16.27	0.53	8.88
	Unloaded	Low Cruise	574	5	2.72	1.87	2.46	0.34	15.98	0.51	6.00
	Unloaded	Med Cruise	356	3	1.46	1.69	0.85	0.33	11.97	0.38	4.82
	Unloaded	High Cruise	1054	9	1.03	0.87	0.76	0.39	9.22	0.53	2.54
	Dump	Dump	405	3	4.60	2.17	4.26	0.87	13.49	1.79	8.66

Poll.	Load	Cruise Mode	Cnt.	Time Fraction (%)	Average	Population Standard Deviation	Median	Minimum	Maximum	5 Percentile	95 Percentile
	Any Loading	Idle	5417	46	7.35	2.08	6.78	0.76	15.45	4.46	10.51
	Any Loading	Low Accel.	252	2	2.17	1.60	1.74	0.37	11.52	0.62	4.89
	Any Loading	Med Accel.	397	3	1.12	1.19	0.66	0.33	11.62	0.38	3.23
	Any Loading	High Accel.	233	2	1.04	0.99	0.75	0.33	8.41	0.39	2.72
	Any Loading	Decel.	2015	17	3.45	3.37	2.15	0.33	23.01	0.49	9.96
	Any Loading	Low Cruise	897	8	3.02	2.41	2.57	0.34	17.65	0.47	7.29
	Any Loading	Med Cruise	726	6	1.03	1.30	0.61	0.33	11.97	0.38	3.42
	Any Loading	High Cruise	1472	12	0.98	0.89	0.73	0.39	11.11	0.48	2.32
	Any Loading	Dump	405	3	4.60	2.17	4.26	0.87	13.49	1.79	8.66
	All Data		1181 4	100	4.63	3.46	4.87	0.33	23.01	0.48	10.08

Table 2.7: Percent time in mode and summary of fuel-specific emissions (g_pollutant/kg/fuel) for tandem-axle truck 15-5184G on November 30, 2005.

Poll.	Load	Cruise Mode	Count	Time (%)	Average	Pop. Std. Dev.	Median	Minimum	Maximum	5th Percentile	95th Percentile
CO_2	Loaded	Idle	3347	28	3237.54	8.73	3238.48	3152.46	3254.13	3222.53	3249.42
	Loaded	Low Accel.	85	1	3194.55	33.45	3188.36	3148.20	3327.42	3158.73	3265.47
	Loaded	Med Accel.	156	1	3205.41	41.39	3192.43	3129.33	3378.35	3153.60	3289.05
	Loaded	High Accel.	50	0	3193.95	6.95	3191.47	3188.56	3225.08	3190.32	3209.64
	Loaded	Decel.	1096	9	3199.33	33.98	3189.26	2997.67	3389.10	3166.71	3259.27
	Loaded	Low Cruise	280	2	3203.01	38.17	3193.86	3134.16	3371.16	3155.99	3275.00
	Loaded	Med Cruise	177	1	3198.31	33.61	3190.90	3126.48	3363.22	3163.50	3273.78
	Loaded	High Cruise	1938	16	3191.95	11.67	3190.36	3143.96	3345.54	3187.44	3199.25
	Unloaded	Idle	654	5	3239.66	10.18	3244.73	3182.57	3278.37	3230.01	3248.51
	Unloaded	Low Accel.	55	0	3200.09	36.97	3192.00	3158.05	3384.06	3164.22	3262.11
	Unloaded	Med Accel.	67	1	3198.74	42.80	3189.88	3137.09	3347.50	3147.57	3271.62
	Unloaded	High Accel.	95	1	3201.31	34.73	3191.15	3131.44	3331.22	3155.23	3265.77
	Unloaded	Decel.	777	6	3197.53	26.69	3188.44	3082.98	3336.47	3177.91	3254.49
	Unloaded	Low Cruise	199	2	3198.30	25.83	3193.19	3135.68	3341.95	3164.84	3244.85
	Unloaded	Med Cruise	77	1	3207.84	41.50	3191.72	3161.17	3353.70	3169.74	3325.36
	Unloaded	High Cruise	1269	11	3189.75	7.67	3189.01	3154.91	3380.10	3186.85	3192.19
	Tow	Idle	162	1	3198.67	25.81	3188.58	3148.85	3237.25	3162.85	3230.43
	Tow	Low Accel.	28	0	3186.13	24.65	3179.32	3144.63	3251.98	3154.80	3237.49
	Tow	Med Accel.	57	0	3200.43	33.44	3194.19	3116.32	3296.67	3149.96	3257.15
	Tow	Decel.	464	4	3202.47	32.77	3194.33	3011.65	3356.25	3182.14	3254.65
	Tow	Low Cruise	124	1	3202.07	32.65	3193.29	3145.83	3366.46	3169.65	3262.58
	Tow	Med Cruise	82	1	3206.36	43.24	3195.12	3112.14	3391.52	3173.27	3276.48
	Tow	High Cruise	602	5	3195.02	9.46	3194.34	3149.34	3336.68	3192.25	3195.96

Poll.	Load	Cruise Mode	Count	Time (%)	Average	Pop. Std. Dev.	Median	Minimum	Maximum	5th Percentile	95th Percentile
	Dump	Dump	133	1	3220.69	30.60	3216.72	3181.15	3345.99	3185.16	3279.10
	Any Loading	Idle	4163	35	3236.36	12.71	3238.04	3148.85	3278.37	3220.99	3248.91
	Any Loading	Low Accel.	168	1	3194.96	33.71	3187.94	3144.63	3384.06	3160.00	3261.19
	Any Loading	Med Accel.	280	2	3202.80	40.37	3193.42	3116.32	3378.35	3152.53	3281.80
	Any Loading	High Accel.	145	1	3198.77	28.62	3191.37	3131.44	3331.22	3163.26	3257.76
	Any Loading	Decel.	2337	20	3199.35	31.54	3189.64	2997.67	3389.10	3171.10	3256.77
	Any Loading	Low Cruise	603	5	3201.26	33.47	3193.40	3134.16	3371.16	3159.30	3258.13
	Any Loading	Med Cruise	336	3	3202.46	38.28	3192.31	3112.14	3391.52	3164.17	3300.31
	Any Loading	High Cruise	3809	32	3191.70	10.30	3190.25	3143.96	3380.10	3187.20	3195.69
	Any Loading	Dump	133	1	3220.69	30.60	3216.72	3181.15	3345.99	3185.16	3279.10
	All Data		11974	100	3210.22	28.96	3194.44	2997.67	3391.52	3181.12	3248.81
CO	Loaded	Idle	3347	28	30.46	6.85	31.90	8.60	40.73	15.86	38.79
	Loaded	Low Accel.	85	1	18.12	13.47	15.46	1.55	84.27	3.97	42.75
	Loaded	Med Accel.	156	1	13.05	14.82	5.35	0.00	74.09	1.43	40.42
	Loaded	High Accel.	50	0	7.53	13.98	4.65	2.17	98.47	3.37	15.54
	Loaded	Decel.	1096	9	21.23	18.64	14.82	0.00	211.17	5.55	53.77
	Loaded	Low Cruise	280	2	17.99	11.81	16.14	0.33	102.12	3.59	38.54
	Loaded	Med Cruise	177	1	11.99	10.23	8.51	0.00	56.73	3.47	33.15
	Loaded	High Cruise	1938	16	8.75	5.94	7.70	0.00	72.54	4.02	18.17
	Unloaded	Idle	654	5	31.76	6.14	29.80	12.82	85.50	27.55	36.85
	Unloaded	Low Accel.	55	0	17.68	10.54	14.89	0.47	56.00	5.83	38.22
	Unloaded	Med Accel.	67	1	18.45	16.01	14.57	1.14	85.36	2.72	42.29
	Unloaded	High Accel.	95	1	12.22	16.31	5.33	0.00	87.87	1.04	49.29
	Unloaded	Decel.	777	6	16.82	13.52	10.18	2.86	100.46	6.83	42.78
	Unloaded	Low Cruise	199	2	22.26	13.13	21.00	1.32	72.09	4.88	42.42
	Unloaded	Med Cruise	77	1	17.33	12.21	12.97	3.58	79.52	4.58	37.98

Poll.	Load	Cruise Mode	Count	Time (%)	Average	Pop. Std. Dev.	Median	Minimum	Maximum	5th Percentile	95th Percentile
	Unloaded	High Cruise	1269	11	8.79	2.51	8.92	0.71	43.16	4.86	11.67
	Tow	Idle	162	1	27.53	7.47	24.93	11.63	46.07	17.70	39.61
	Tow	Low Accel.	28	0	19.02	10.11	17.94	0.00	52.50	5.59	33.88
	Tow	Med Accel.	57	0	10.17	18.26	3.48	0.00	93.69	0.00	46.71
	Tow	Decel.	464	4	12.41	15.22	6.28	0.00	137.77	2.43	38.77
	Tow	Low Cruise	124	1	13.64	9.92	12.14	0.00	50.02	0.33	28.48
	Tow	Med Cruise	82	1	6.95	10.06	2.77	0.00	59.82	1.57	28.47
	Tow	High Cruise	602	5	4.78	3.37	4.12	0.00	55.79	2.38	7.40
	Dump	Dump	133	1	27.75	8.40	27.21	4.18	58.41	15.56	42.06
	Any Loading	Idle	4163	35	30.55	6.81	31.73	8.60	85.50	16.05	38.44
	Any Loading	Low Accel.	168	1	18.13	12.06	15.74	0.00	84.27	4.64	38.81
	Any Loading	Med Accel.	280	2	13.75	16.12	5.48	0.00	93.69	1.02	42.63
	Any Loading	High Accel.	145	1	10.60	15.70	5.01	0.00	98.47	1.60	46.49
	Any Loading	Decel.	2337	20	18.01	16.77	10.83	0.00	211.17	3.48	47.90
	Any Loading	Low Cruise	603	5	18.51	12.31	16.68	0.00	102.12	2.85	39.69
	Any Loading	Med Cruise	336	3	11.98	11.26	8.66	0.00	79.52	2.28	35.74
	Any Loading	High Cruise	3809	32	8.14	4.89	7.77	0.00	72.54	3.35	13.98
	Any Loading	Dump	133	1	27.75	8.40	27.21	4.18	58.41	15.56	42.06
	All Data		11974	100	19.01	13.77	14.49	0.00	211.17	3.65	38.10
	Loaded	Idle	3347	28	62.21	5.57	63.99	22.44	73.16	50.12	67.16
	Loaded	Low Accel.	85	1	19.17	9.00	16.78	9.02	51.46	11.13	40.59
	Loaded	Med Accel.	156	1	18.65	6.61	17.98	7.68	49.13	11.01	28.70
	Loaded	High Accel.	50	0	20.92	4.46	20.72	11.67	37.37	13.14	27.11
	Loaded	Decel.	1096	9	27.39	15.94	19.71	4.00	106.71	14.61	62.55
	Loaded	Low Cruise	280	2	25.00	13.95	20.10	7.59	73.36	10.87	57.35
	Loaded	Med Cruise	177	1	18.55	5.18	17.45	10.75	44.75	12.85	24.26

Poll.	Load	Cruise Mode	Count	Time (%)	Average	Pop. Std. Dev.	Median	Minimum	Maximum	5th Percentile	95th Percentile
NOx	Loaded	High Cruise	1938	16	18.60	4.54	16.92	12.69	51.33	14.77	27.75
	Unloaded	Idle	654	5	56.49	6.78	52.68	25.52	78.03	50.10	65.08
	Unloaded	Low Accel.	55	0	20.22	8.06	19.76	6.99	49.39	10.08	31.79
	Unloaded	Med Accel.	67	1	18.25	6.94	16.59	8.02	44.33	11.18	30.12
	Unloaded	High Accel.	95	1	21.68	8.10	19.43	8.74	48.65	10.87	33.81
	Unloaded	Decel.	777	6	24.35	14.98	17.19	10.74	100.94	14.05	60.12
	Unloaded	Low Cruise	199	2	24.60	11.88	22.36	8.26	60.63	10.91	50.29
	Unloaded	Med Cruise	77	1	22.15	11.57	18.54	12.98	84.51	14.29	46.83
	Unloaded	High Cruise	1269	11	16.11	3.02	14.85	8.34	46.13	14.24	22.58
	Tow	Idle	162	1	57.90	8.08	57.43	30.07	94.86	48.01	71.78
	Tow	Low Accel.	28	0	20.97	11.68	17.40	9.89	63.99	11.24	45.59
	Tow	Med Accel.	57	0	18.86	7.04	17.67	8.17	46.71	11.41	33.71
	Tow	Decel.	464	4	28.47	17.42	21.25	11.06	94.46	14.63	68.13
	Tow	Low Cruise	124	1	28.21	16.57	21.08	7.72	68.04	9.80	59.91
	Tow	Med Cruise	82	1	22.32	5.71	21.35	10.96	55.99	15.72	29.85
	Tow	High Cruise	602	5	18.77	4.05	18.93	9.48	50.78	14.44	24.88
	Dump	Dump	133	1	39.41	13.16	40.48	15.93	72.21	19.62	58.37
	Any Loading	Idle	4163	35	61.14	6.28	63.61	22.44	94.86	50.09	67.15
	Any Loading	Low Accel.	168	1	19.81	9.24	17.66	6.99	63.99	10.62	40.50
	Any Loading	Med Accel.	280	2	18.60	6.78	17.59	7.68	49.13	11.12	31.08
	Any Loading	High Accel.	145	1	21.42	7.07	20.30	8.74	48.65	11.70	33.43
	Any Loading	Decel.	2337	20	26.59	16.02	19.71	4.00	106.71	14.30	63.35
	Any Loading	Low Cruise	603	5	25.53	13.98	21.20	7.59	73.36	10.80	53.79
	Any Loading	Med Cruise	336	3	20.30	7.49	19.71	10.75	84.51	13.11	29.43
	Any Loading	High Cruise	3809	32	17.80	4.19	15.87	8.34	51.33	14.40	24.87
	Any Loading	Dump	133	1	39.41	13.16	40.48	15.93	72.21	19.62	58.37

Poll.	Load	Cruise Mode	Count	Time (%)	Average	Pop. Std. Dev.	Median	Minimum	Maximum	5th Percentile	95th Percentile
	All Data		11974	100	35.37	21.30	22.91	4.00	106.71	14.38	66.41
THC	Loaded	Idle	3347	28	3.86	0.76	3.79	0.71	5.94	2.34	5.31
	Loaded	Low Accel.	85	1	1.97	2.01	1.24	0.42	11.34	0.65	6.02
	Loaded	Med Accel.	156	1	1.72	1.61	0.99	0.35	8.25	0.42	5.24
	Loaded	High Accel.	50	0	0.73	0.96	0.50	0.35	6.77	0.37	1.60
	Loaded	Decel.	1096	9	2.55	2.43	1.49	0.25	15.81	0.48	7.20
	Loaded	Low Cruise	280	2	2.34	1.82	1.80	0.35	9.59	0.45	5.89
	Loaded	Med Cruise	177	1	1.65	1.81	1.00	0.33	11.34	0.38	5.13
	Loaded	High Cruise	1938	16	1.09	1.16	0.89	0.26	16.10	0.40	2.55
	Unloaded	Idle	654	5	4.45	0.62	4.52	1.23	7.31	3.75	5.09
	Unloaded	Low Accel.	55	0	2.33	1.54	1.73	0.86	7.77	1.08	5.52
	Unloaded	Med Accel.	67	1	2.00	1.91	1.31	0.27	9.05	0.43	6.80
	Unloaded	High Accel.	95	1	1.28	1.39	0.61	0.27	8.04	0.30	3.86
	Unloaded	Decel.	777	6	2.06	2.05	1.17	0.32	16.56	0.59	5.86
	Unloaded	Low Cruise	199	2	3.11	2.48	2.22	0.40	12.83	0.54	7.62
	Unloaded	Med Cruise	77	1	2.83	2.55	1.88	0.27	13.30	0.33	7.78
	Unloaded	High Cruise	1269	11	1.07	0.43	1.09	0.32	7.30	0.49	1.50
	Tow	Idle	162	1	2.86	0.69	2.90	1.06	4.07	1.75	4.02
	Tow	Low Accel.	28	0	1.63	1.05	1.27	0.37	4.71	0.65	4.09
	Tow	Med Accel.	57	0	1.10	0.94	0.67	0.36	3.78	0.40	3.36
	Tow	Decel.	464	4	1.53	1.58	0.86	0.29	11.91	0.37	4.23
	Tow	Low Cruise	124	1	1.82	1.28	1.50	0.32	6.54	0.40	4.15
	Tow	Med Cruise	82	1	1.30	1.95	0.50	0.31	11.12	0.33	5.24
	Tow	High Cruise	602	5	0.73	0.44	0.54	0.30	6.28	0.40	1.22
	Dump	Dump	133	1	4.59	1.55	4.55	1.54	11.01	2.23	7.79
	Any Loading	Idle	4163	35	3.92	0.79	3.84	0.71	7.31	2.34	5.25

Poll.	Load	Cruise Mode	Count	Time (%)	Average	Pop. Std. Dev.	Median	Minimum	Maximum	5th Percentile	95th Percentile
	Any Loading	Low Accel.	168	1	2.03	1.75	1.39	0.37	11.34	0.66	5.59
	Any Loading	Med Accel.	280	2	1.66	1.61	0.97	0.27	9.05	0.41	4.47
	Any Loading	High Accel.	145	1	1.09	1.28	0.55	0.27	8.04	0.31	3.78
	Any Loading	Decel.	2337	20	2.19	2.19	1.20	0.25	16.56	0.44	6.55
	Any Loading	Low Cruise	603	5	2.49	2.03	1.89	0.32	12.83	0.45	6.52
	Any Loading	Med Cruise	336	3	1.84	2.11	1.03	0.27	13.30	0.35	6.79
	Any Loading	High Cruise	3809	32	1.02	0.89	0.94	0.26	16.10	0.42	1.84
	Any Loading	Dump	133	1	4.59	1.55	4.55	1.54	11.01	2.23	7.79
	All Data		11974	100	2.42	1.84	1.68	0.25	16.56	0.45	5.26

Table 2.8: Comparison of NOx emission factors for heavy-duty diesel trucks.
Emission factors for off-road equipment from Kean, Sawyer, and Harley (2000) are also reported.

Study	**Year**	**Description**	**NOx Emission Factor (g NOx as NO2 / kg No. 2 Diesel Fuel)**
Yanowitz et al. (1999)	1976-1997	Review of U.S. Chassis Dynamometer Data	35-38
Atkinson et al. (1996)	1995	Chassis Dynamometer in West Virginia	46
Pierson et al. (1996)	1992	Tunnel Study in Tuscarora, Pennsylvania	39±3
Pierson et al. (1996)	1992	Tunnel Study in Baltimore, Maryland	37±4 (uphill) 34±2 (downhill)
Rogak et al. (1997)	1995	Tunnel Study in Vancouver, BC, Canada	48±17
Kirchstetter et al. (1999)	1997	Caldecott Tunnel Study Oakland, CA	42±5
Countess et al. (1998)	1997	Remote Sensing in California	31±0.2
Countess et al. (1999)	1998	Remote Sensing in Colorado	53
Kean, Sawyer, and Harley (2000)	2000	U.S. EPA NONROAD Model	48±6 (off-road equipment fleet average) 46 (off-road construction and mining equipment)
Baker et al. (2004)	2003	Chassis Dynamometer	45.83 (TxDOT single-axle dump truck with CAT 3126B engine) 19.38 (TxDOT single-axle dump truck with Int. T44E engine)
Baker et al. (2004)	2003	Chassis Dynamometer	16.97 (TxDOT tandem-axle dump truck with CAT C10 engine)

2.5 References for Part 2

Atkinson, C.M., N.N. Clark, and D.W. Lyons (1996) "An Estimation of the Comparative Contribution of Heavy-Duty Diesel Buses and Trucks to Mobile Source Emissions," in *Sixth CRC On-Road Vehicle Emissions Workshop*, San Diego, CA, 1996, Coordinating Research Council: Atlanta, GA.

Baker, R., T. DeFries, DK Ezekoye, M. Hall, S. Kishan, R. Macemehl, R. Matthews, J. Prozzi, and H. Wheat (2004), *TxDOT Emulsified Diesel Final Report* (Contract No. 0-4576), submitted to the Texas Department of Transportation, Report No. FHWA/TX-04/4576-3.

Countess, R, L. Cohen, S.J. Countess, G.A. Bishop, and D.H. Stedman (1998), "Remote Sensing of Heavy-Duty Truck Exhaust," in *Eighth CRC On-Road Vehicle Emissions Workshop*, San Diego, CA, 1998, Coordinating Research Council: Atlanta, GA.

Countess, R, L. Cohen, S.J. Countess, G.A. Bishop, and D.H. Stedman (1999), "Remote Sensing of Heavy-Duty Trucks Revisited," in *Ninth CRC On-Road Vehicle Emissions Workshop*, San Diego, CA, 1999, Coordinating Research Council: Atlanta, GA.

Dreher, D.B. and R.A. Harley (1998), "A Fuel-Based Inventory for Heavy-Duty Diesel Truck Emissions," *Journal of the Air and Waste Management Association*, 48:352-358.

Ensfield, C. (2002), *On-Road Emissions Testing of 18 Tier 1 Passenger Cars and 17 Diesel-Powered Public Transport Buses*, submitted to the United States Environmental Protection Agency, EPA420-R-02-030.

Ensfield, C., personal communication, July 26, 2006.

Flagan, R.C. and J.H. Seinfeld (1988), *Fundamentals of Air Pollution Engineering*, Prentice-Hall, Englewood Cliffs, NJ.

Frey, H.C. and K. Kim (2005), *Operational Evaluation of Emissions and Fuel Use of B20 Versus Diesel Fueled Dump Trucks*, Research Project No. 2004-18, FHWA/NC/2005-07, submitted to the U.S. Department of Transportation, September 30, 2005.

Kean, A.J., R.F. Sawyer, and R.A. Harley (2000), "A Fuel-Based Assessment of Off-Road Diesel Engine Emissions," *Journal of the Air and Waste Management Association*, 50:1929-1939.

Kirchstetter, T.W., R.A. Harley, N.M. Kreisberg, M.R. Stolzenburg, and S.V. Hering (1999), "On-Road Measurement of Fine Particle and Nitrogen Oxide Emissions from Light- and Heavy-Duty Motor Vehicles," Atmospheric Environment 33:2955-2968.

Matthews, R, personal communication, February 23, 2005.

National Research Council (2000), *Modeling Mobile Source Emissions*, National Academy Press, Washington, D.C.

Noble, D.F., "Memorandum: TCEQ Engine Idling Law," submitted to Texas Department of Transportation District Engineers and Division/Office Directors, April 20, 2006 (obtained from D. Lewis, April 22, 2006).

Pierson, W. R., A. W. Gertler, N. F. Robinson, J. C. Sagebiel, B. Zielinska, G. A. Bishop, D. H. Stedman, R. B. Zweidinger, and W. D. Ray (1996), "Real-world automotive emissions—summary of recent tunnel studies in the Fort McHenry and Tuscarora Mountain tunnels," *Atmospheric Environment*, 30:2233-2256.

Rogak, S.N., U. Pott, T. Dann, and D. Wang (1997), "Gaseous emissions from vehicles in a traffic tunnel in Vancouver, BC." *Journal of Air and Waste Management Association*, 48:604.

Sensors, Incorporated (2004), *On-Vehicle Diesel Emission Analyzer, SEMTECH-D User's Manual*, Document: 9510-064, Revision 3.4.

Singer, B.C. and D.A. Harley (1996), "A Fuel-Based Motor Vehicle Emission Inventory," *Journal of the Air and Waste Management Association*, 46(6):581-593.

Texas Commission on Environmental Quality (2004), "Summary of Development and Processing of Onroad Mobile Source Inventories Used for Photochemical Modeling Efforts in Texas," State Implementation Plan, Appendix F1, http://www.tnrcc.state.tx.us/oprd/sips/june2004hgb_EDrec.html. (accessed September 3, 2005).

Texas Commission on Environmental Quality (accessed 2006), Texas Low Emissions Diesel (TXLED) Program (http://www.tceq.state.tx.us/implementation/air/sip/cleandiesel.html#Intro)

United States Environmental Protection Agency (2004), *Air Quality Criteria for Particulate Matter*, Volume II of III, EPA/600/P-99/002bF, October 2004 (see Chapter 8 for a comprehensive summary of epidemiologic studies of human health effects associated with fine particulate matter exposure).

United States Environmental Protection Agency (2005), *Final Rule on In-Use Testing Program for Heavy-Duty Diesel Engines and Vehicles*, EPA420-F-05-021.

United States Environmental Protection Agency (2005b), *Air Quality Criteria for Ozone and Related Photochemical Oxidants*, Volume II of III, EPA/600/R-05/004bA, January 2005 (see Chapter 7 for a comprehensive summary of epidemiologic studies of human health effects associated with ambient ozone exposure).

Webb, A, C. Durrenberger, G. McGaughey, D. Allen, and E. McDonald-Buller (2005), "Comparison of APCA and Zero-Out Photochemical Modeling Approaches for Transport Analyses," in preparation for submission to *Atmospheric Environment*.

Yanowitz, J., R.L. McCormick, and M.S. Graboski (1999), "Emissions from On-Road Heavy-Duty Diesel Vehicles: A Review of Data from Dynamometer, Tunnel, Remote Sensing, and Idling Studies," in Eighth CRC On-Road Vehicle Emissions Workshop, San Diego, CA, 1999, Coordinating Research Council: Atlanta, GA.

Appendix A: Mobile Source Emission Reduction Strategies

Introduction

The following is a summary of various mobile source emission control strategies, along with a review of methodologies for their evaluation. All are relevant for combating ozone formation, with some far more practical and effective than others.

Mobile Source Emissions Reduction Strategies

To overcome the non-attainment designation, an area can implement various TCMs, VMEPs or TERMs:

> "TCM refers to those projects or programs specifically contained within an area's SIP (State Implementation Plan) that are legally bound and enforced. Voluntary Mobile Source Emissions Reduction Programs (VMEP) are those projects in the SIP that are voluntary and defined under strict EPA guidance. For all other projects and programs, where emissions credits are taken during conformity to meet the area's Motor Vehicle Emissions Budget (MVEB) and not contained within the SIP, Transportation Emissions Reduction Measure (TERM) is used. The whole collection of these three categories is referred to as Mobile Source Emissions Reduction Strategies." (FHWA 2003, 13-7)

Mobile source emission reduction strategies help reduce emissions from transportation sources by reducing VMT and/or altering flow dynamics (e.g., speeds). Table A.1 (from TRB Special Report 264) shows a variety of TCMs that could be used to reduce mobile source emissions.

Table A.1 Mobile source control strategies and their potential impacts

Pollution Control Strategy	Potential Impacts	
	Travel Response	Emission Reduction
CMAQ-eligible		
Transit improvements	Yes	Yes
Traffic flow improvements	Yes	Yes
Ridesharing programs	Yes	Yes
Travel demand management programs	Yes	Yes
Telecommute/telework programs	Yes	Yes
Bicycle and pedestrian improvements	Yes	Yes
Vehicle inspection and maintenance programs	No	Yes
Conventional- and alternative-fuel vehicle programs[a]	No	Yes
Pricing measures[b]	Yes	Yes
Non-CMAQ-eligible		
New-vehicle emission standards	No	Yes
Clean conventional and alternative fuels	No	Yes
Vehicle scrappage programs	No	Yes
Remote sensing	No	Yes

[a] The purchase of publicly owned alternative-fuel vehicles and related fueling facilities and the incremental cost of upgrading privately owned vehicle fleets to alternative fuels are the only CMAQ-eligible expenditures in this category (FHWA 1999, 13).

[b] Some pricing strategies are not CMAQ-eligible.

Source: TRB 2002 (The CMAQ Program: Assessing 10 Years of Experience, Table 4-1)

Following is a detailed list of mobile source control strategies that could be implemented within most of the categories shown in Table A.1. The effect of each strategy is detailed in the Texas Transportation Institute report *The Texas Guide to Accepted Mobile Source Emission Reduction Strategies* (TxDOT 2003).

Traffic flow improvements

Note: Though these do not reduce travel, they may reduce emissions by reducing congestion.

Traffic signalization

Traffic operations (e.g., ramp metering, road widening)

Enforcement and incident management (e.g., roving police and service vehicles and incident management teams)

Intelligent Transportation Systems (ITS)

HOV facilities

Reversing lanes (more lanes in peak direction)

Ridesharing

Regional rideshare

Vanpool programs

Information technology for transit and ridesharing

Work-site based strategies

Staggered work hours
Compressed work weeks
Flextime arrangements (allow employees to select their arrival and departure times.).
Tele-work/Tele-commuting
On-site facility amenities provision (to minimize lunch trips and errand running)
Monetary incentives (by employers) for alternative mode use (e.g., carpooling)

Alternate modes

Non-motorized (bike/pedestrian) mode facility support
Public education and promotion of alternative modes

New transit facilities

Light rail transit investment
Rapid bus transit investment
Commuter rail investment

Other transit improvements

Shuttles, feeder buses, para-transit
Service upgrades (e.g., higher frequency and newer buses)
Commuter or light rail-road grade separation
Designated bus lanes
Bus priority signalization

Parking management

Park-and-ride lots
Parking supply management (e.g., limiting total available parking)
Parking demand management (e.g., pricing)
Parking restrictions (e.g., area-wide parking caps)
Work-site parking management

Vehicle and Fuel measures

Alternative-fuel buses
Alternative-fuel vehicle programs
Inspection and maintenance (I/M) programs
Limits on extended vehicle idling (especially for medium- and heavy-duty trucks)
Accelerated vehicle retirement (vehicle scrappage programs for high emitters)
Vehicle purchase incentives (e.g., for hybrid technology) and re-powering

Pricing measures

- Modal subsidies and vouchers
- Transit fare adjustments
- Gasoline tax increases
- Road pricing (flat-rate tolling)
- Congestion pricing (e.g., HOT lanes, area wide or cordon pricing)
- Distance-based taxes (VMT fees)

Land Use Planning

- Rail or bus-based transit-oriented development (TOD) (e.g., condos and retail near transit stations)
- Traditional neighborhood design (TND) (e.g., narrower streets, wider sidewalks, greater street connectivity)
- Downtown revitalization (e.g., providing high density housing and improving walk/bike facilities)
- Access management (e.g., fewer driveway cuts and more pedestrian friendly frontage)
- Jobs-housing balance programs (to shorten work trips)
- Mixed-land use development (e.g., housing and retail, to shorten shop trips)
- Infill development (to raise densities and avoid peripheral locations with their longer trips)

Evaluation of Emission Reduction Strategies

Traffic flow improvement projects are most commonly used for emission credits, because these address congestion delays as well, and are thus very popular with the public. In contrast, trip reduction ordinances are the least popular and thus uncommon. Strategy selection depends on a region's needs and characteristics, available funding, and program guidelines. Typically, larger areas implement the widest range of techniques and can fund the more expensive programs.

> "Projects are typically dependent on funding sources like the CMAQ program, or the project's relation to the SIP. For example, the CMAQ program is intended to improve air quality. However, because CMAQ funds must be spent in non-attainment or maintenance areas, certain projects are ineligible for such funding. Legislation prohibits vehicle retirement programs and highway capacity expansion projects. FHWA policy excludes highway maintenance and reconstruction projects because they preserve existing levels of service and are unlikely to further air quality improvements." (FHWA 2003, Ch 13, p.8)

Evaluation of all these strategies can be achieved via large-area sketch planning tools, "post-processors," and micro simulation of traffic flow. Sketch-planning tools are simple spreadsheets or databases that require the user to input all data and regional travel characteristics. "Post-processors, on the other hand, interface with data output from travel demand forecasting models" (FHWA 2003, 13-10). Finally, micro simulation models can be used to model intersection or corridor performance through signal timing or other design changes. Dynamic traffic assignment models are currently being developed (e.g., DYNASMART and VISTA) to model entire networks in this way.

As an example, the following section describes a particular sketch-planning tool in some detail.

Guidelines for Computing Emission Reductions from Different Strategies

This section summarizes guidelines for computing emission reductions from different strategies, as described in the Center for Clean Air Policy's *Transportation Emissions Guidebook* (CCAP 2005). It provides several *rules of thumb* to calculate emissions reductions from the implementation of specific transportation and land use policies.

The first part of this Guidebook, titled "Land Use, Transit and Travel Demand Management," focuses on the mobile source emissions impacts of travel demand and land use policies. It consists of three parts: a series of policy briefs (offering both qualitative descriptions and quantitative analysis), an emissions calculator (a spreadsheet tool to quantify the order of magnitude for potential VMT deductions and their associated emission benefits), and a technical appendix. The following summarizes all these.

Background

The main factors influencing transportation emissions are vehicle technology, fuel characteristics, and vehicle miles traveled (VMT). Though there has been tremendous improvement in the vehicle technology and fuel quality, mobile-source emissions remain high due to dramatic increases in VMT. Land use has a key role to play; for example, urban sprawl leads to excessive automobile use to reach distant destinations, as well as low population densities, which make public transportation infeasible. There is a move towards smarter growth (in, e.g., Portland, OR; Arlington, VA; and Denver, CO) with an objective to have "compact built forms that are typically more walkable and less reliant on automobile use for daily transportation needs" (CCAP 2005, pg 7). For smarter growth, policies at both the regional and neighborhood levels need to be implemented.

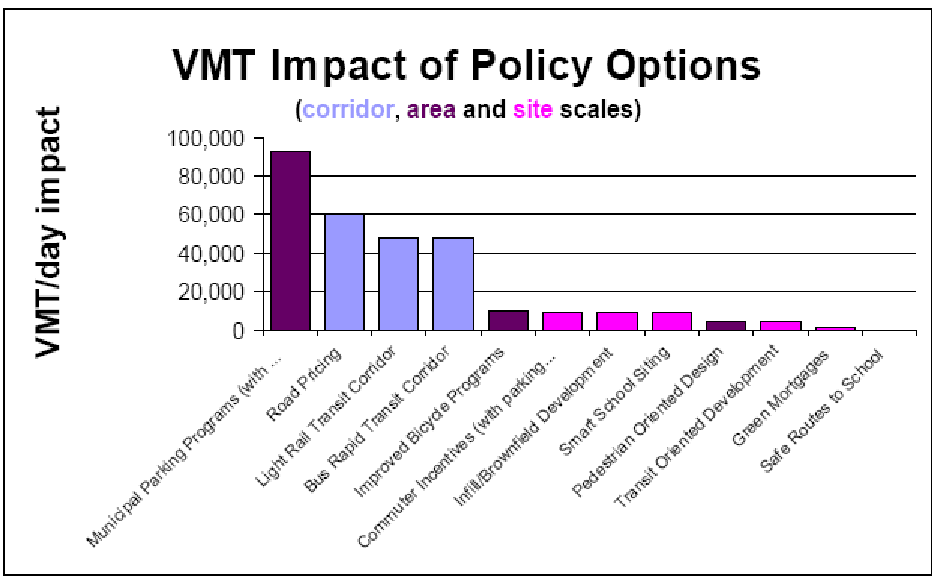


Figure A.1 Impacts of Various Site, Corridor and Area Level Strategies

Figure A.1 shows the impacts of various site, corridor and area-level policies on daily VMT (using guidebook defaults [CCAP 2005]). The implementation of "small scale projects in a region are not enough to curb growing rates of automobile use and subsequent transportation emissions" (CCAP 2005, pg 8). Thus, several of these policies have to be implemented in tandem in order to reduce VMT (and thus emissions) effectively. Moreover, CCAP concludes that a local balance of employment, housing, recreational, and educational facilities also is required. The emission reductions estimates relating to each of these policies (individually) are discussed in the next section.

Policy Briefs

Land Use

Transit Oriented Development (TOD)

TOD provides accessible transit alternatives and local employment and shopping opportunities. It reduces VMT principally by affecting mode split (a move from car to transit and walk/bike). Site-level VMT reductions are estimated to range from 20 to 30 percent.

Infill/Brownfield Development

Infill/brownfield development guides development away from green fields and the city edge to underutilized sites within the city. It reduces VMT by changing mode split and trip length. Site-level VMT reduction estimates: 15-50 percent.

Pedestrian-Oriented Design

Pedestrian-oriented design creates a walkable urban environment. It reduces VMT for short trips. Site-level VMT reduction: 1-10 percent.

Smart School Siting

A smart school siting policy preserves existing schools with pedestrian and bicycle access and constructs new schools within established communities. It reduces VMT by impacting mode split and trip length. Site-level VMT reduction: 15-50 percent.

Permitting and Zoning Reform

Permitting and zoning reform includes a variety of statutes, local codes and ordinances that facilitate smart growth principles. No associated policy quantification is available, though such effects could be quite significant (e.g., Oregon's urban growth boundary, and Seattle's parking caps).

Transportation Alternatives

Transit Service Improvement

Transit service improvement increases ridership. It reduces VMT by changing mode split. For example, a 1 percent transit frequency improvement is estimated to increase transit ridership by 0.5 percent.

Light Rail Transit (LRT)

LRT produces minimal air/noise pollution (locally). It reduces VMT by impacting mode split. Corridor-level VMT reduction estimate: 1-2 percent.

Bus Rapid Transit (BRT)

BRT enhances transit level of service and makes use of low-emission technologies. It reduces VMT via a shift in mode split. Corridor-level VMT reduction: 1-2 percent.

Bike Infrastructure

Bike infrastructure provides a safe bicycling environment and more accessible facilities, thus increasing cycling (a non-polluting form of transportation). It reduces VMT for short trips. Area-level VMT reduction: 1-5 percent.

Fiscal Tools and Incentives

Targeted Infrastructure Funding

By allocating state and federal funding to existing urban and suburban areas, targeted infrastructure funding could avoid urban sprawl and direct growth inward. No associated VMT estimates are available; however, some examples include Atlanta, GA's Livable Centers Initiative (LCI) and the Transportation for Livable Communities Program (TLC), both of which support mixed land use.

Road Pricing

Variable road pricing can help balance supply of and demand for scarce road space. It thereby increases average speed and travel time reliability while encouraging route and possibly mode shift. It reduces VMT by impacting mode split, number of trips taken and emission rates. Area-level VMT reductions are estimated to range from 1-3 percent (without taking into account the effect of trip length reduction which would further reduce VMT). In congested regions, the VMT effects could be much more striking, particularly with network-wide pricing. For example, Gulipalli and Kockelman (2006) predict a 7 percent reduction in VMT with low levels of marginal-cost pricing of freeways only, based on generous link-performance functions. In the longer term and with more realistic travel time performance functions, the predicted VMT reductions would be much higher. With toll rates averaging 5¢/mile or more, the reductions would be even steeper.

Commuter Incentives

Commuter incentives provide benefits to employees and employers using alternatives to commuting solo. These reduce VMT by impacting mode split and the number of trips taken in the case of telecommuting. Employer VMT reductions are estimated to range significantly, depending on incentives (or SOV-restrictions) involved; CCAP estimates anywhere from 5 to 25 percent for employer-based VMT.

Pay-As-You-Drive Insurance

Pay-as-you-drive insurance is thought to reduce VMT by moving the fixed costs of car ownership into a VMT-dependent cost. By increasing the marginal cost of trip-making, it may reduce VMT up to 10 percent. However, given that it also reduces the fixed costs of auto ownership and use, it may increase trip-making for some populations.

Green Mortgages

"Location Efficient Mortgages (LEM), Energy Efficient Mortgages, and Smart Commute are initiatives that provide discounted mortgages to people who chose to buy a home in compact, energy efficient, mixed-use communities serviced by public transportation" (CCAP 2005, pg 78). However, stand-alone green mortgages do not guarantee VMT reductions. These are most effective when used to encourage transit-oriented development and/or infill/brownfield development. Like infill/brownfield development, these reduce VMT by changing mode split and trip length. Per household VMT deductions are estimated to be 15-50 percent.

State and Local Programs

Comprehensive Smart Growth

Comprehensive smart growth applies multiple strategies in a coordinated fashion to address the impact of growth. It reduces VMT through changes in mode split, number of trips and trip length. Regional VMT reductions are on the order of 3-20 percent.

Public Participation in Planning

Public participation improves the effectiveness of smart growth principles. No associated policy quantification is available in the literature.

Open Space Programming

Open space preservation improves air quality through maintaining the natural features of open space. It directs growth into established communities. No associated policy quantification is available.

Municipal Parking Programs

Supply restrictions and pricing of parking reduce VMT by impacting mode split and number of trips taken. Site-level VMT reductions may be 15-30 percent.

Safe Routes to School Programs

Sate routes to school programs encourage walking and biking to school by creating safer pedestrian environments. These are felt to reduce VMT via mode choices, with site-level VMT reductions of 0-5 percent.

Guidebook Emissions Calculator

The CCAP Guidebook's emission calculator allows users to specify mode splits, numbers of trips, average trip lengths, emission factors, etc. in order to estimate the impact of policies and compare different scenarios. Users are advised to compare the results against the default values, which are based on the latest literature.

Inputs include VMT per day at site, area, corridor, regional and state scales, automobile average commute distances (by automobile), and gasoline prices. For almost all policies[1], a spreadsheet can be constructed to estimate VMT and emissions reductions. In each spreadsheet, mode splits and fuel economy (miles per gallon, for CO_2 emissions per gallon) need to be

[1] Policy exceptions are Permitting & Zoning Reform, Targeted Infrastructure Funding, Public Participation in Planning and Open Space Programming.

identified for both the base case and policy implementation case. In addition, emission factors (in grams per VMT) need to be specified. Table A.2 shows the default emission factors used in all calculations.

Table A.2 Default Emission Factors (gm/VMT)

NOx	1.544
PM-10	0.072
PM-2.5	0.052
SO2	0.085
CO	23.394
VOC	3.060
NH3	0.091
CO2	392.6
CH4	0.084
N20	0.028

The basic formula for calculating VMT reductions is as follows:

$$VMT\ reduction = (T_{BC} \times TL_{BC} \times MS_{BC}) - (T_P \times TL_P \times MS_P)$$

where T is the number of trips, TL is average trip length, and MS is the fraction of automobile trips (i.e., mode split). The subscripts donate base case (BC) and policy application case (P).

The basic formula for calculating emissions reductions is

$$Emission\ reduction = VMT\ reduction \times Emission\ Factor$$

The *Policy Comparison Matrix* offers a snapshot of VMT and emissions reductions and is incorporated in the Calculator. The default policy comparison matrix is shown in Table A.3. A similar matrix with user data and results is also given in the Calculator.

The Guidebook's *technical appendix* discusses the importance of accounting for land-use in travel demand models, as well as some limitations of present models in predicting:

- Local travel (i.e., intra-zonal trips)
- Impacts of mixed-use development on VMT (accounting for non-motorized trips)
- Local impacts (such as traffic calming)
- Long-term induced travel (from long-run location changes).

It also points towards some other sketch planning tools, like the Smart Growth Index (SGI[2]), Community Viz[3], and Planning for Community, Energy, Economic, and Environmental Sustainability ($PLACE^3S$[4]), which help anticipate the localized impacts of various policies. There is a discussion of emission calculators like the TravelMatters[5], Climate Calculator[6], and COMMUTER[7] model. Finally, a regional scenario modeling called the MetroQUEST[8] is discussed.

Limitations

The CCAP Guidebook provides a simplistic procedure for estimating VMT and emissions reductions. It is based on rules of thumb and not on any behavioral model. "This calculation is not meant to give an exact estimate of the VMT reductions from the policy measures; rather it presents an order of magnitude sense of potential of VMT reductions." (CCAP 2005) Additionally, this guidebook cannot estimate the composite impact of a variety of policies that in reality may be implemented together.

[2] http://www.epa.gov/smartgrowth/topics/sg_index.htm
[3] http://www.communityviz.com/
[4] http://www.sustainable.doe.gov/articles/place3s.shtml
[5] http://www.travelmatters.org/
[6] http://safeclimate.net/calculator/
[7] http://www.epa.gov/otaq/transp/traqmodl.htm#commuter
[8] http://www.envisiontools.com/questsite/downloads/MetroQUEST_Product_Description.pdf

Table A.3 CCAP Policy Comparison Matrix

Policy		Scale	VMT Rule of Thumb (%)
Land Use			
1.1	Transit Oriented Development	Site	20-30%
1.2	Infill/Brownfield Development	Site	15-50%
1.3	Pedestrian Oriented Design	Area	1-10%
1.4	Smart School Siting	Site	15-50%
1.5	Permitting/Zoning Reform	Area	NQ
Transportation Alternatives			
2.1	Improved Transit Service	Regional	0.5% per 1% improvement in transit frequency
2.2	Light Rail Transit Corridor	Corridor	1-2%
2.3	Bus Rapid Transit Corridor	Corridor	1-2%
2.4	Bicycle Initiatives	Area	1-5%
Fiscal Tools & Incentives			
3.1	Targeted Infrastructure Spending	Regional	part of 4.1
3.2	Road Pricing	Corridor	1-3%
3.3	Commuter Incentives (with parking pricing)	Site	5-25%
3.4	Pay-As-You-Drive Insurance (5% penetration rate)	State	up to 10% per driver
3.5	Green Mortgages	100 Households	15-50% per HH
State & Local Programs			
4.1a	Limited Smart Growth	Regional	3-20%
4.1b	Comprehensive Smart Growth	Regional	
4.1c	Aggressive Smart Growth	Regional	
4.2	Public Participation	Regional	NQ
4.3	Open Space Preservation	Site	NQ
4.4	Municipal Parking Programs (with parking pricing)	Area	15-30%
4.5	Safe Routes to School	Site	0-5%

Note: Detailed table available at http://www.ccap.org/guidebook/policycomparisonmatrix

References for Appendix A

FHWA (2003) "Estimating Regional Mobile Source Emissions," U.S. Department of Transportation, Federal Highway Administration, FHWA-NHI-04-120, October 2003.

Greg Dierkers, Erin Silsbe, Shayna Stott, Steve Winkelman & Mac Wubben (2005) *CCAP Transportation Emissions Guidebook*, Part One. Accessed from www.ccap.org/guidebook on September 5, 2005.

Gulipalli, P., and Kockelman, K. (2006) "Credit-Based Congestion Pricing: A Dallas-Fort Worth Application," Presented at the 85th Annual Meeting of the Transportation Research Board and under consideration for publication in *Transport Policy*.

TxDOT (2003) "The Texas Guide to Accepted Mobile Source Emission Reduction Strategies," Texas Transportation Institute, Texas Department of Transportation, August 2003. Accessed from http://moser.tamu.edu/Reference/index.html on Nov 20, 2004.

TRB (2002) "The Congestion Mitigation and Air Quality Improvement Program: Assessing 10 Years of Experience," Special Report 264. The National Academies, Transportation Research Board: Washington, D.C. 2002. Accessed from http://trb.org/publications/sr/sr264.pdf on November 15, 2004.

U.S. EPA (1994) "Methodologies for Estimating Emission and Travel Activity Effects of TCMs," Office of Air Quality Planning and Standards and Office of Mobile Sources, July 1994. Accessed from http://www.epa.gov/air/oaqps/ on October 5, 2004.

U.S. EPA (2003) *The Green Book*, Office of Air Quality Planning and Standards, Accessed from http://www.epa.gov/oar/oaqps/greenbk/ on October 10, 2004.

Appendix B: Details of Travel Demand Modeling for DFW CBCP Scenario

Introduction

Predictive travel demand model results for a strategy of congestion pricing in the Dallas-Ft. Worth (DFW) region are discussed at some length, along with the importance of appropriate models for trip departure times (as these can be substantially impacted by congestion pricing) and quantification of AADT estimator errors (because traffic volumes are a key input to regional models of ozone formation and air quality).

The following section describes the estimation of emission reductions (due to congestion pricing) using the outputs of a behaviorally based, detailed model of travel demand.

Summary of VMT Results from Tolling Studies for the Dallas-Forth Worth and Austin Regions

Using an enhanced four-step travel demand model (where destination and mode choices were nested and full-feedback of travel times to these choices was permitted), Gulipalli and Kockelman (2006) compared the status quo VMT predictions for Dallas-Ft. Worth (DFW) to those in the context of two special scenarios: Marginal cost pricing (MCP[9]) of freeways, and MCP of all roads. Ultimately, they found MCP on freeways to result in tolls varying from 0.006 to 3.3¢/mile and a decrease of total system VMT of about 7 percent. The total system VMT decrease for the MCP-on-all-roads scenario was also found to be 7 percent with tolls up to 5.066¢/mile. In the short run, VMT was predicted to decrease by 7 percent and 6 percent for the MCP-on-freeways and MCP-on-all-roads scenarios, respectively. The average trip length was predicted to decrease from 9.63 to 9.09 miles (5.6 percent reduction) for the MCP-on-freeways scenario in the short run. Freeway VMT is predicted to fall by over 12 percent for both the MCP scenarios (in the short and long runs).

Though the VMT reductions are small, volume-to-capacity ratios over 1.0 all but disappeared, as travelers avoided congested links, where tolls were highest. The link performance functions in that application were too gentle (in terms of travel time as a function of demand); more realistic performance assumptions would have produced higher toll rates and greater VMT (and emissions) reductions. MOBILE6 emission rates, as a function of vehicle speed, were computed for four pollutants (HC, CO, NOx, and CO2) and particulate matter (PM2.5 and PM10). The particulate matter included sulfates, carbon, sulfur dioxide, ammonia, brake wear, and tire wear. This, in combination with link-specific speed and flow information, was used to compute total daily estimates by emission type for the three scenarios. The emissions estimates fell by about 7 percent for the MCP-on-freeways scenario and by about 8 percent for MCP-on-all-roads scenario.

Gupta, Kalmanje, and Kockelman (2006) examined a scenario of a flat 20¢/mile toll on all roads in Austin (including soon-to-be-added toll roads), which is roughly equivalent to a $4 increase in gas prices. They estimated a 24.8 percent reduction in total system VMT. Based on

[9] MCP means that the cost of delay imposed by the last (marginal) user is charged as the toll. Thus, on each link, if a new vehicle adds 0.1 second of travel time to all 2,000 vehicles in that 1-hour interval, all users will be asked to pay 200 seconds worth of delay (0.056 hours, or roughly $0.50).

these two studies, it may be reasonable to model changes in VMT up to 25 percent, under various scenarios.

Spatial Distribution of VMT Changes under Congestion Pricing

Introduction

The spatial distribution of VMT changes that are due to different time- or corridor-based policies can have a significant impact on the spatial distribution of emissions, and ozone formation. This section discusses one such application, for the case of MCP of all roadways in the DFW region.

Link-level VMT values, before and after congestion-based tolling, were aggregated to square grid cells of 4 km size (approximately 2.5 miles by 2.5 miles). The changes in total VMT and percentage changes in VMT (by cell) following a policy of MCP on all roads (in the short term, where work locations are held fixed, but other trip destinations are flexible) are plotted for each of the five time periods (figures B.1 through B.5):

T0: 9:00 p.m. to 6:00 a.m. (night off-peak)

T1: 6:00 a.m. to 9:00 a.m. (AM peak)

T2: 9:00 a.m. to 3:30 p.m. (day time off-peak)

T3: 3:30 p.m. to 7:00 p.m. (PM peak)

T4: 7:00 p.m. to 9:00 p.m. (late PM)

Table B.1 provides summary statistics for the various VMT values, as aggregated over the region's 957 grid cells.

Table B.1 Descriptive Statistics for Grid-Cell VMT at Different Times of Day (T0 through T4) Before Pricing (status quo [SQ]) and After Pricing (short term [ST])

VARIABLE	MINIMUM	MAXIMUM	MEAN	STD_DEV
Grid.cell ID	1	957.00	479.00	276.41
Grid cell area (sq. mi.)	6.3747	6.46	6.42	0.02
Length of network in grid cell (miles)	0.0	155.6	14.8	16.6
VMT_T0 SQ	0	284872	10684	22711
VMT_T1 SQ	0	647519	27958	55219
VMT_T2 SQ	0	1091649	40338	86670
VMT_T3 SQ	0	906102	40131	78863
VMT_T4 SQ	0	274024	10821	22446
VMT_TO ST	0	287197	10769	22884
VMT_T1 ST	0	542525	26262	48840
VMT_T2 ST	0	970634	38903	80558

VARIABLE	MINIMUM	MAXIMUM	MEAN	STD_DEV
VMT_T3 ST	0	720854	35649	65963
VMT_T4 ST	0	242105	10398	20754
VMT_change_T0	-13	2325	84	187
VMT_change_T1	-104994	10851	-1696	7283
VMT_change_T2	-121015	12408	-1435	7690
VMT_change_T3	-185248	8128	-4482	13733
VMT_change_T4	-31920	4948	-423	2170
%VMT_change_T0	-0.76	2.80	0.62	0.39
%VMT_change_T1	-39.6	589.6	13.48	40.35
%VMT_change_T2	-25.2	1542.3	5.78	78.92
%VMT_change_T3	-60.2	427.0	7.25	32.48
%VMT_change_T4	-18.8	1656.0	5.97	84.74

Note: Only 770 cells (rather than 957) contain coded roadways and thus exhibit %VMT changes.

The following sections describe the spatial disaggregation of changes in VMT (and %VMT) over the five times of day.

Spatial disaggregation of VMT changes

Figures B.1 through B.5 show how marginal-cost pricing of congestion triggers changes in VMT across the DFW region. During the AM peak, there is a predicted increase in VMT near the region's periphery (i.e., in areas of low population and network density), as traffic avoids the region's more congested (and thus more heavily tolled) roads and locations. Overall, VMT is reduced, and as expected, the reductions are greatest in central locations.

During the daytime off-peak period (9:00 a.m. to 3:30 p.m.), VMT increases occur over a larger central area than in the AM peak period. The VMT reductions follow a pattern similar to the AM peak, but are less pronounced.

During the PM peak (3:30 to 7:00 p.m.) both the area and magnitude of VMT reduction is greater than that in the AM peak (76,000 VMT reduction overall, versus 35,000). The VMT increases appear more uniform, though lower in magnitude when compared to the region's PM peak areas of VMT reductions.

During the late PM period (7:00 to 9:00 p.m.), predicted VMT shifts are gentler than those exhibited during the daytime periods, but they are more significant than those during the overnight period (9:00 p.m. to 6:00 a.m.). The largest VMT reductions are found centrally.

During the nighttime, VMT reductions are predicted only at the region's periphery, where there is little traffic and few roads. The increase in VMT is fairly uniform in the outer doughnut shaped region and increases towards the center (high network density) of the region.

In this study, the time periods chosen to analyze the VMT changes are discrete (i.e., fixed, multi-hour windows), and the travel demand model relies on fixed percentages for trip timing (e.g., 39.6 percent of home-based work trips are assumed to travel during the AM peak). While such assumptions are the norm in travel forecasting, they certainly limit our appreciation of time-of-day-based policies, such as congestion pricing. In reality, people often shift their departure times, in order to avoid traffic or tolls. The following section describes the development of continuous departure time models to address this issue.

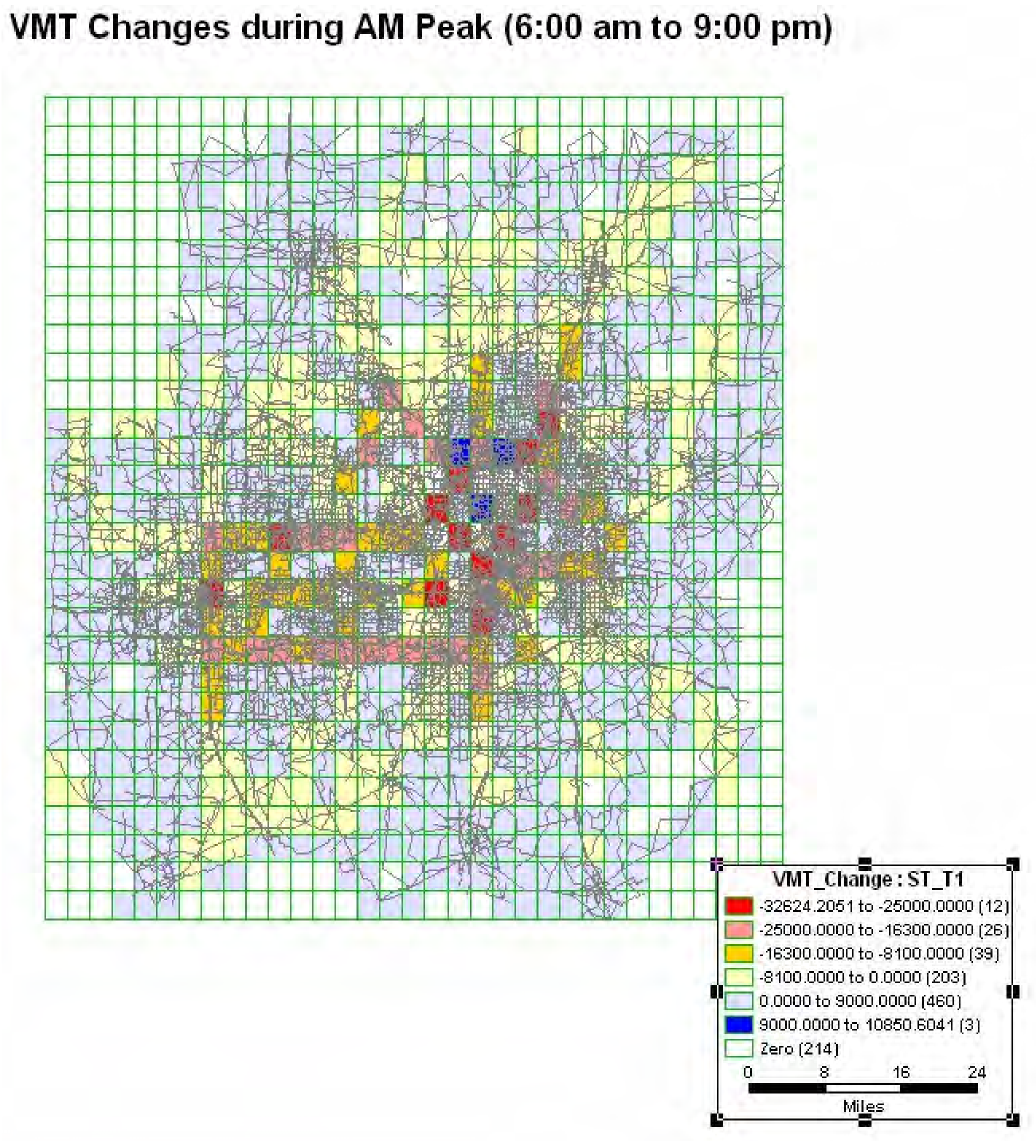


Figure B.1 VMT Changes during AM Peak Period

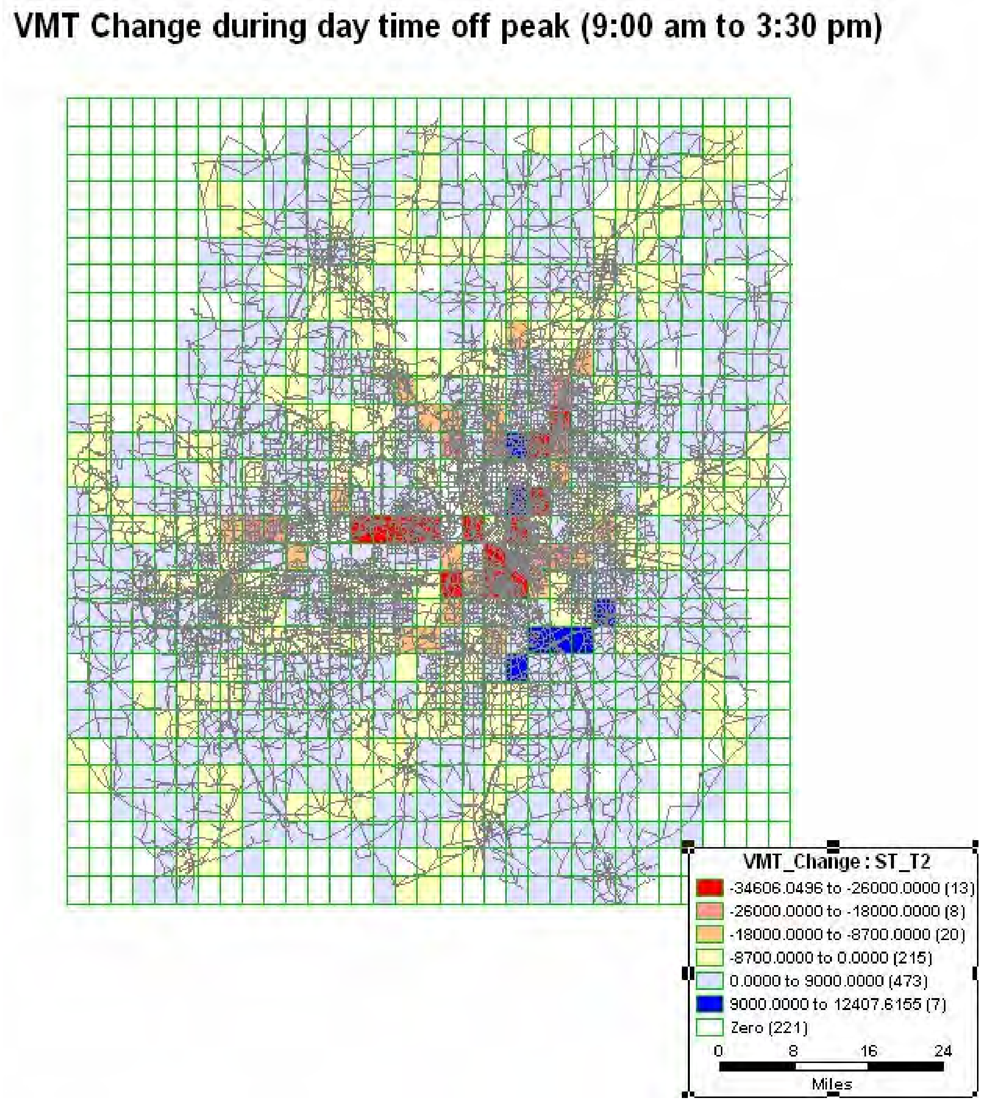


Figure B.2 VMT Changes during Day Time Off-Peak

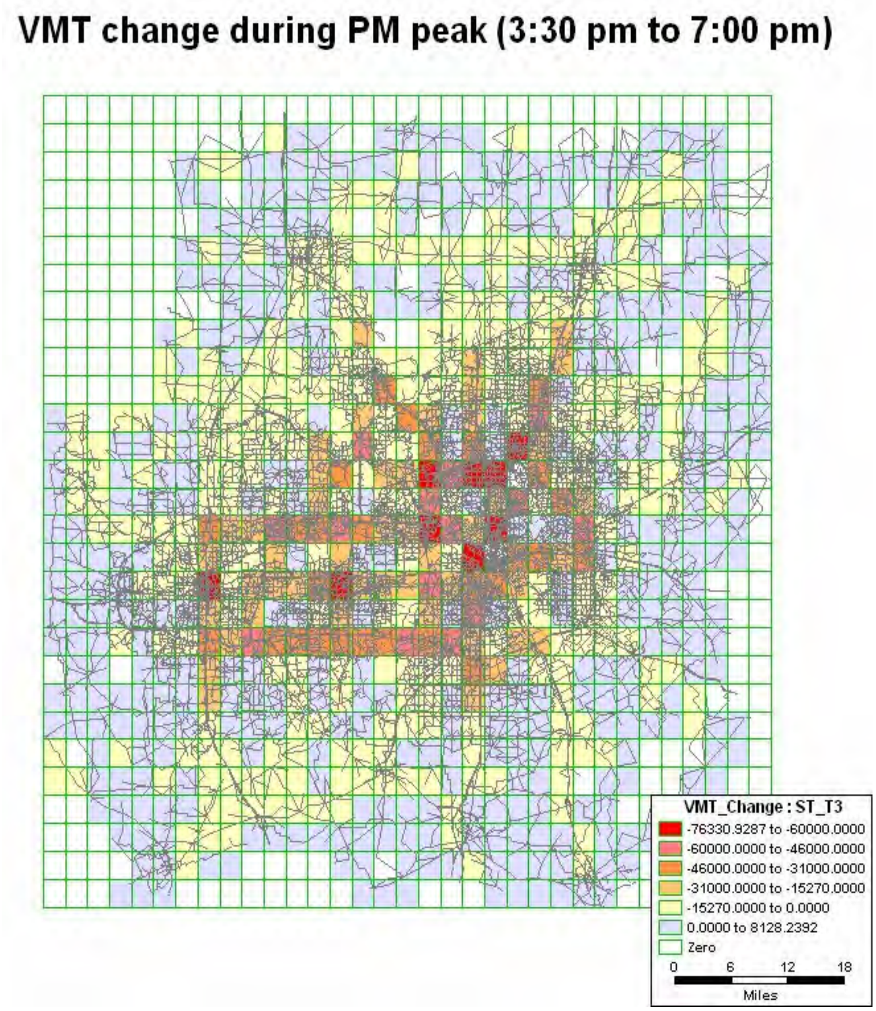


Figure B.3 VMT Changes during PM Peak

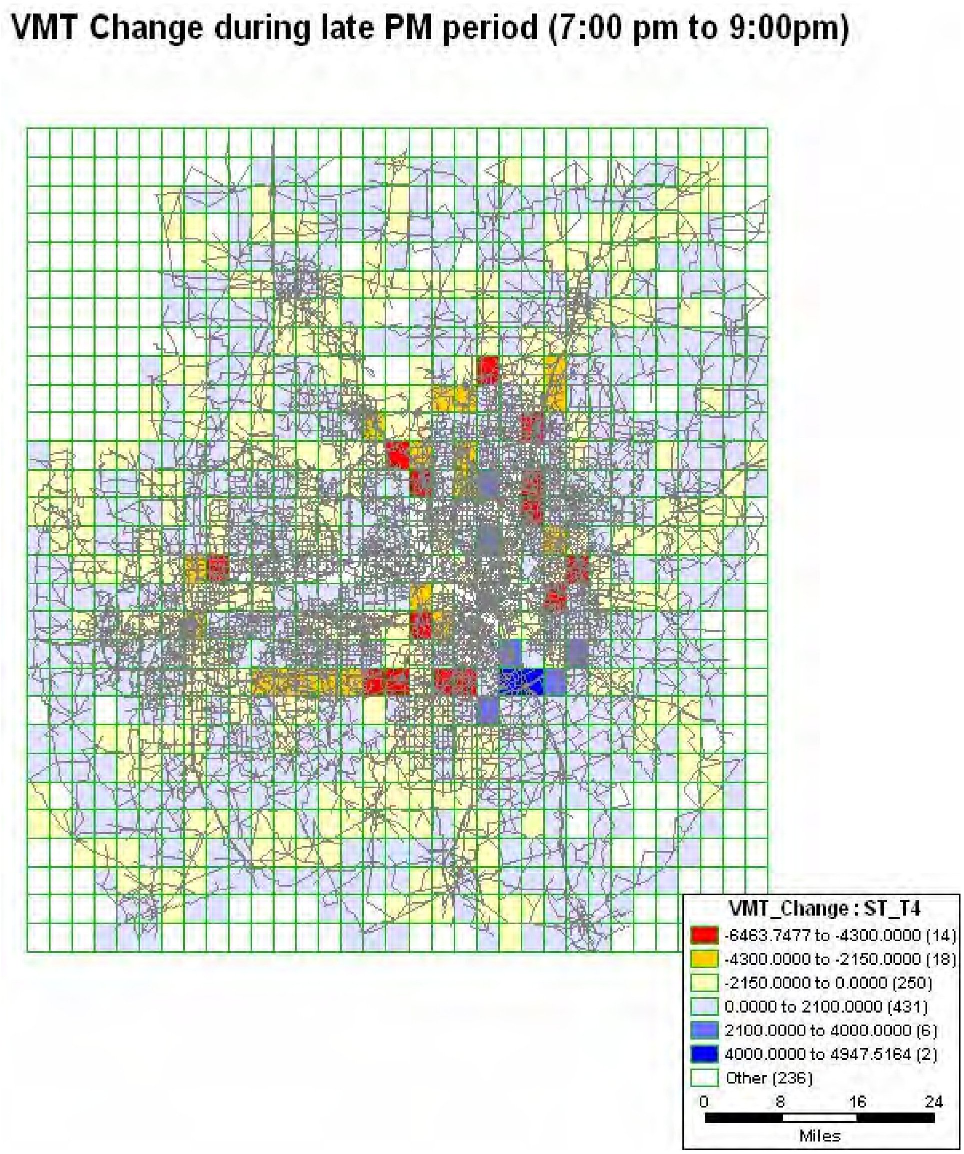


Figure B.4 VMT Changes during Late PM Period

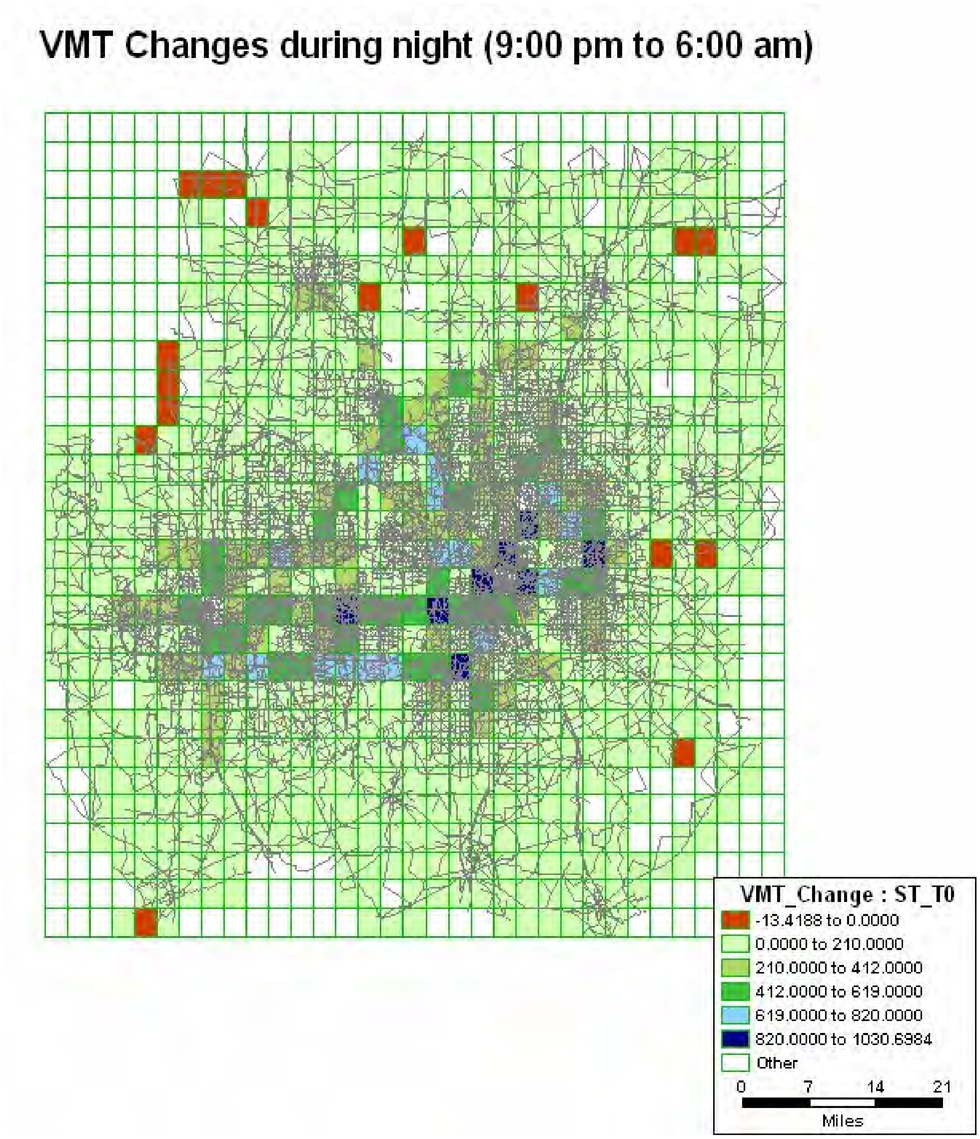


Figure B.5 VMT Changes during Night Time

Continuous Departure Time Models

Duration models, in which time is treated as a continuous variable, offer several advantages over discrete alternatives. They predict trip departure times on a continuous scale, thus enhancing the inputs to, and outputs of, models of traffic and emissions. Such model predictions influence policies targeting congestion management and air quality. In addition, continuous-time models allow for results that avoid problems of temporal aggregation and period association, providing more fluid estimates of choice and illuminating finer adjustments in traveler behavior, while offering the necessary inputs for dynamic traffic assignment models.

Continuous departure time models were estimated using Bayesian techniques and Austin, Texas' 1996 Travel Survey data, to predict departure times for travelers engaged in various trip types. The models for trip types exhibiting single departure time peaks across the sample data, such as the home-to-work, work-to-home and non-home-based (NHB) trips, were estimated using accelerated failure time specification (AFT) with different distributional assumptions (lognormal, standard Weibull, and Weibull with unobserved heterogeneity (UH) models). In contrast, the home-based non-work (HBNW) trip type displays multiple departure time peaks during the course of a day and therefore was estimated using a mixture of normals specification. These formulations are presented in Section B-1. Tables B.2 through B.5 summarize the estimation result. Marginal effects of each of the variables (on departure times for home to work, work to home and NHB trips) are shown in Table B.6. Plots of predicted and actual departure time distributions are shown in Figures B.6 through B.9, illustrating the estimated models' goodness of fit.

A variety of demographic and trip-related variables were found to be highly statistically significant in all estimated models. In the ***home-to-work*** models, the attributes of greatest practical significance (in terms of their effect on departure times) were found to be (in order of importance): (a) Hispanic ethnicity (resulting in a 10%[10] earlier departure time than the base ethnicity of Asian), (b) employment status (with full-time employees departing 8 percent earlier than part-time employees), (c) trip attributes (external trips leaving 6.4 percent later [after controlling for trip distance]), and (d) flexible work hours (leaving 6.1 percent later in the day than those without flexible work hours). In the ***work–to-home*** lognormal model, the most practically relevant attributes were found to be (a) race (Hispanic), (b) external trips, (c) day of the week (Friday), and (d) mode (shared ride). Under the Weibull models for ***work-to-home***, the most practically relevant attributes were found to be (a) mode, (b) external trips, (c) race, and (d) job type.

Model comparisons reveal that individuals tend to depart earlier *from* work on Fridays, though no day-of-week effects were found in home-to-work trips (i.e., departures from home). However, there is some evidence here that individuals leave later for work in the summertime (though there is no such effect found here for work-to-home trips). Interestingly, the presence of children appears to have little effect on departure time choice in home-to-work trips, but an earlier departure time for parents (or those living in households with children) is evident in the work-to-home trips. Combining the effects from the two HBW models, it is reasonable to conclude that individuals with higher incomes, Caucasians and Hispanics, full-time workers, and those commuting solo tend to work the longest days. In contrast, those enjoying flexible work schedules and those working at offices tend to experience more compressed workdays (though their lunch breaks may also be shorter).

The ***NHB departure time*** model results indicate that a work trip purpose, the presence of kids, traveler age and employment status are the most statistically and practically significant variables. Most results are intuitive: for example, those in households with children present and those taking NHB trips either to or from work tend to make those trips earlier in the day. In addition, males tend to make NHB trips earlier in the day, summertime NHB trips tend to occur earlier too, but later in springtime and later on Fridays.

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[10] 10% earlier at a particular time of day means that the group leaves 10 percent of the time (in minutes from midnight) earlier than the other group. For example, if we need to compare the departure time of Hispanics to that of Asians at 7 a.m., Hispanics would leave about 42 minutes earlier (10% of 7x60) compared to Asians. The percentage increase/decrease in expected departure time for a unit change in *X is* quantified using the values $100*(e^{\beta}-1)$ and $100*(e^{-\beta/\alpha}-1)$ for the lognormal, and Weibull models, respectively. For indicator variables, these equations give the percentage increase (lognormal model) or decrease (Weibull models) in the expected departure time for those exhibiting such characteristics (X=1), relative to others (X=0).

The bi-modal model results for ***HBNW trips*** indicate that the most important determinants of departure time are the presence of children, employment status, mode of travel and travel cost. The directional effects of each of the variables and their comparison for AM and PM peaks are accomplished by focusing on coefficient signs. For example, retired individuals tend to take HBNW trips later in the AM period (β_{AM} = +0.0574) but earlier in the PM period (β_{PM} = -0.0673). Interestingly such trips are taken later in the AM period in spring and later in the PM during summer.

Overall, the Weibull model with UH was found to perform best for both home-to-work and work-to-home trips, in terms of goodness of fit and predictive (aggregate) distributions (Figure B.6 and B.7). However, recognition of unobserved heterogeneity in the home-to-work departure time model improved model fit much more than in the work-to-home application. The lognormal model performed best in fitting the NHB trip data, and the normal mixture model did better in terms of predicting the modes of the HBNW departure time distribution. The empirical analyses provided intuitively appealing results, allowing for behavioral understanding of departure time patterns across user groups, as well as generalized travel costs, recognizing both time and money. These models with enhanced level of service data (travel times and cost at various times of day) could be used understand the impacts of various emission control strategies such as congestion pricing.

AADT Error Estimation

AADT is a key variable in many models and policy decisions, producing VMT estimates for analyses of crash rates, evaluation of infrastructure management needs, air quality compliance and validation of travel demand model predictions. Differences in protocol, from state to state and site to site, shape the uncertainty or error in the resulting AADT estimates. It is very important that analysts, including designers, planners and policymakers, have a sense of the magnitude of these errors, in order to appreciate the reliability of their results, their designs and their policies. By attaching uncertainty information to AADT estimates (e.g., via the use of confidence intervals), more accurate results can be communicated and more robust decisions made.

To quantify the uncertainty in AADT, the relative magnitudes of errors in AADT estimates due to short-term sampling (i.e., day-to-day random variations in traffic counts), reliance on other sites' factors, misclassification, and spatial approximation were studied using Minnesota, Florida, Austin, and Southern California data sets. This section provides a brief summary of the study. For detailed discussion on this topic the reader is referred to Gadda et al. (2006), as well as Section B-2. The results obtained here suggest that sample counts should not be taken over the weekends (since there is a higher probability of error in AADT estimates). Rural sites and facilities with many lanes also require greater care in Minnesota, though those with higher counts in Florida tend to prove more predictable overall. Proper site classification is key, and tendencies may vary by state. These analyses of ATR data can be performed by any agency, to assess whether certain roadway types or times of year require greater sampling caution. Fine clustering, based on functional class, lane count, and multiple area types, may prove very useful. Finally, spatial errors appear to increase dramatically beyond 0.5 miles (from the count site) in urban areas and 1 mile in rural areas. Evidently, extrapolation between count stations is fraught with high degree of potential misprediction.

If misprediction can be so severe in these cases (consistent with the Austin TDM evidence), analysts should be highly skeptical of counts one or more miles away when seeking to estimate VMT, crash rates, emissions and other variables. Perhaps a combination of upstream and downstream counts will assist the prediction, as well as evidence from cross-street counts, to obtain a sense of whether traffic is being added or removed from the facility of interest. Alternatively, far more frequent SPTC spacings may be necessary, to ensure extrapolation does not exceed 0.5 miles, except in locations where traffic loads are known to be highly stable over space.

Conclusions

Spatial analysis of VMT changes in DFW due to congestion pricing produces several interesting results, and these serve as important inputs for modeling ozone formation in space. Moreover, the continuous departure time model specification and estimation results pursued under this research project should help provide more dynamic VMT data over the course of a 24-hour day, allowing for more robust temporal calculations of emissions and ozone formation, as well as human exposure. Finally, the AADT error analyses suggest that that one-day counts result in an average base-level error of 10 percent (due to day-of-week and seasonal variations), and that such errors increase rapidly when count volumes are extrapolated over space.

Section B-1: Continuous Departure Time Models

B-1.1 Introduction

Data that represent an interval of time are called duration data. Departure times (generally) mark the end of an activity's duration. Our interest lies in understanding how the covariates of an individual affect the distribution of these times. This requires assuming a base start time in order to compute the duration of activities that precede a driver's departure. The choice of this time point "origin" is often problematic in continuous time models (Allison 1995), leading to somewhat different results for different origin choices. In ambiguous cases, this is dealt with by choosing the most intuitive origin. Here, the origin has been chosen as midnight, i.e., all the durations are calculated with respect to midnight. For example, an 8:00 a.m. departure time implies 8-hour (480-minute) event duration.

Parametric duration models using distributions like the exponential, lognormal and Weibull have been popular in the time-to-event/time-to-failure and survival analysis literature (see, e.g., Wang (1996)). This chapter describes the parametric AFT formulation of such models using the lognormal and Weibull distributions (as described in Kalbfleisch and Prentice (1980)). In addition, the Weibull-based model is extended to include unobserved heterogeneity among individuals, and a normal mixture specification is described for modeling bi-modal behaviors.

B-1.2 Accelerated Failure Time Specification

Let the natural log of duration t (of an activity that occurs before taking a trip) be related to the covariates through a linear model,

$$\log(t) = \beta X + \sigma w \qquad (1)$$

where X is the set of covariates, β is a vector of parameters to be estimated, σ is the standard deviation of the transformed t value, and w is a random variable having a specified distribution.

Eq (1) is the most generic form of an AFT model. It not only provides for an easier interpretation in terms of $\log(t)$ but also specifies that the effect of the co-variable as multiplicative on t rather than on the hazard function (as in the case of PH model). Different AFT models can be developed by varying the distribution of w. For example, if w is assumed to be a standard normal, it leads to a lognormal AFT model, and therefore a Weibull distribution. If w is assumed to have an extreme value distribution, it also results in a Weibull distribution. These are described below.

Lognormal Model

When w is assumed to have a standard normal distribution the density of t is log-normal, and is given by

$$f(t|\mu,\tau) = \sqrt{\frac{\tau}{2\pi}}\frac{1}{t}\exp\left(-\frac{\tau}{2}(\log t-\mu)^2\right); t>0$$

where $\mu = \beta X$ and $\tau = 1/\sigma$, from Eq (1).

If T is defined as the duration during which an individual i does not take a trip (as measured relative to some base starting time, like midnight of the evening before), then the distribution $F(t)$ provides the probability that the duration for which an individual does not take a trip is less than a certain duration t. This is the same as the probability of taking a trip before a duration t elapses. The associated density $f(t)$ then offers the trip's departure time probabilities over the course of the day Moreover, the probability that a person takes a trip between times t_1 and t_2 can be obtained by integrating $f(t)$ from t_1 to t_2. Under this definition the likelihood of a trip starting at time t (relative to the base start time) for an individual i can be written as follows:

$$f(t|X_i,\beta,\tau) = \sqrt{\frac{\tau}{2\pi}}\frac{1}{t}\exp\left(-\frac{\tau}{2}(\log t-X_i\beta)^2\right)$$

Assuming all reported trips (across respondents) are independent of one another, the joint likelihood for n trips is:

$$\ell(t|xi,\beta,\tau) = \prod_{i=1}^{n}\sqrt{\frac{\tau}{2\pi}}\frac{1}{t}\exp\left(-\frac{\tau}{2}(\log t-X_i\beta)^2\right)$$

Weibull Model

If we let w have an extreme value distribution, the duration T before a respondent's trip would have a Weibull density (Kalbfleisch and Prentice [1980], pg 32). Letting the parameters of the Weibull density be α and λ, we have,

$$f(t|\lambda,\alpha) = \alpha t^{\alpha-1}\lambda\exp(\lambda t^{\alpha}).$$

where $\alpha = 1/\sigma$, $\lambda = \exp(X\beta^*)$ (thus ensuring non-negativity of the hazard rate) and $\beta^* = -\beta/\sigma$. *X* is a set of covariates and *β** is a vector of parameters to be estimated. *X, β* and *σ* are as in Equation (1).

It follows that

$$f(t|X,\alpha,\beta^*) = \alpha t^{\alpha-1}\exp(X\beta)\exp(-t^{\alpha}\exp(X\beta^*))$$

The likelihood of a trip starting at time *t* from the designated starting time (taken to be midnight here) for an individual *i* can be written as follows:

$$f(t|X_i,\alpha,\beta^*) = \alpha t^{\alpha-1}\exp(X_i\beta)\exp(-t^{\alpha}\exp(X_i\beta^*)).$$

Assuming that all trips are independent of one another (which may not be the case for members of the same household), the joint likelihood for *n* trips is:

$$\ell(t|xi,\alpha,\beta^*) = \prod_{i=1}^{n}\alpha t^{\alpha-1}\exp(X_i\beta^*)\exp(-t^{\alpha}\exp(X_i\beta^*))$$

Weibull Model with Unobserved Heterogeneity (UH)

One way to accommodate UH is via a multiplicative error term v_i in each respondent's hazard function, as follows:

$$h(t,X_i) = v_i\alpha t^{\alpha-1}\exp(X_i\beta^*)$$

Then, the density and likelihood functions are as follows:

$$f(t|X_i,\alpha,\beta) = v_i\alpha t^{\alpha-1}\exp(X_i\beta^*)\exp(-t^{\alpha}v_i\exp(X_i\beta^*))$$

$$\ell(t|xi,\alpha,\beta) = \prod_{i=1}^{n}v_i\alpha t^{\alpha-1}\exp(X_i\beta^*)\exp(-t^{\alpha}v_i\exp(X_i\beta^*))$$

To ensure non-negativity, vi is assumed to be gamma distributed here, with a mean of 1 and an unknown variance δ (to be estimated).

B-1.3 Normal Mixture Model

A mixture of normals provides a relatively flexible model for estimation of densities in a Bayesian framework (Roeder and Wasserman, 1997). Such models help capture any multimodality existing in the data. Consider, for example, a set of observations $y_1, y_2, \ldots\ldots, \ldots, y_n$ to be modeled through a normal mixture distribution (as a mixture of *k* normals:

$$f = \sum_{i=1}^{k} p_i N(\mu_i, \sigma_i^2)$$

where p_i is the probability of y_i being in group *i* (of the *k* groups), so that $\sum_{i=1}^{k} p_i = 1$.

Here, we assume a lognormal density for duration *t*, which makes the distribution of $y = \ln(t)$ normal. Moreover, the (aggregate) home-based non-work (HBNW trip data appear to be potentially bimodal, so we examine a mixture of two normal distributions, so that each observation y_i is presumed to come from one of two groups. In this way, the model can be formulated as follows:

$$f(y|\mu_1, \mu_2, \sigma_1^2, \sigma_2^2) = pN(\mu_1, \sigma_1^2) + (1-p)N(\mu_2, \sigma_2^2)$$

Robert (1996) suggested a re-parameterization of this model, in order to avoid *all* the data going into one component of the mixture; i.e.,

This assumes the following: $\mu_2 = \mu_1 + \theta,\ \theta > 0$.

Assuming $\mu_1 = \beta_1 X_i$, $\mu_2 = \beta_2 X_i$, $\tau_1 = 1/\sigma^2{}_1$, and $\tau_2 = 1/\sigma^2{}_2$, then:

$$f(y|X_{i,}\beta_1, \beta_2, \tau_1, \tau_2) = p\sqrt{\frac{\tau_1}{2\pi}}\exp\left(-\frac{\tau_1}{2}(y - X_i\beta_1)^2\right) + (1-p)\sqrt{\frac{\tau_2}{2\pi}}\exp\left(-\frac{\tau_2}{2}(y - X_i\beta_2)^2\right)$$

Thus, the likelihood for *n* (independent) departures will be,

$$\ell(t|xi, \beta_1, \beta_2, \tau_1, \tau_2) = \prod_{i=1}^{n}\left(p\sqrt{\frac{\tau_1}{2\pi}}\exp\left(-\frac{\tau_1}{2}(y - X_i\beta_1)^2\right) + (1-p)\sqrt{\frac{\tau_2}{2\pi}}\exp\left(-\frac{\tau_2}{2}(y - X_i\beta_2)^2\right)\right)$$

Table B.2 Final Model Results for Home-to-Work Trips

Attribute	Variable	Lognormal		Weibull		Weibull with UH	
		beta	t-stat	beta	t-stat	beta	t-stat
	Alpha(α)			2.9970	58.638	7.8840	6.116
	Constant(b0)	6.5310	143.161	-20.3000	-50.347	-50.2800	-6.368
Household Attributes	Income (divided by 10000)	-0.0030	-1.436	0.0211	2.762		
	Kids					0.1671	1.156
Individual attributes	Age (divided by 10)	-0.2402	-4.008	0.8344	3.943	1.4590	3.349
	Student	0.0360	1.618	-0.0807	-1.014	-0.1482	-0.940
	African-American	-0.0505	-1.728			0.5225	1.810
	Hispanic	-0.1046	-2.982	0.2572	2.492	0.6259	2.560
	Caucasian	-0.0505	-1.728	0.1285	1.664	0.3086	1.478
Employment attributes	Full-time	-0.0802	-3.751	0.2809	4.029	0.4715	3.295
	Flex Work	0.0594	4.235	-0.1835	-3.571	-0.3723	-3.664
	Retail	0.0376	1.726	-0.1632	-2.315	-0.1950	-1.224
	Industry	-0.0313	-1.461			0.2596	1.905
	Education	-0.0313	-1.461	0.1605	2.441		
	Office	0.0223	1.078			-0.2250	-1.648
	Government	-0.0499	-2.108	0.1605	2.441	0.2596	1.905
Trip attributes	Drive alone	-0.0420	-2.109	0.2357	3.243	0.2860	1.144
	Shared Ride					0.2170	0.741
	External	0.0622	0.928	-0.2299	-0.968		
	Cost	-0.0174	-8.649	0.0640	9.863	0.0988	6.339
Season	Summer	0.0365	0.978	-0.1644	-1.223		
	τ (inverse of S.D)	12.6700	28.973	NA	NA	NA	NA
	σ (S.D of v_i)	NA	NA	NA	NA	1.2850	8.169
Number of observations		1717		1717		1717	
DIC (Deviance Information Criterion)		21849.1		22559.6		19976.1	

Table B.3 Final Model Results for Work-to-Home Trips

Attribute	Variable	Lognormal		Weibull		Weibull with UH	
		beta	t-stat	beta	t-stat	beta	t-stat
	Alpha(α)	-	-	6.1480	17.831	6.2240	18.030
	constant(b0)	6.7680	96.493	-43.0700	-17.580	-43.6500	-17.948
Household Attributes	Income (divided by 10000)	0.0055	1.816	-	-	-	-
	Kids	-0.0184	-0.656	0.0727	0.960	0.0748	0.986
Individual attributes	Age (divided by 10)	-0.0776	-0.931	1.1720	5.093	1.1790	5.275
	Student	0.0388	1.232	-0.0978	-1.118	-0.0888	-1.013
	African-American	-	-	-0.2001	-1.253	-0.2068	-1.339
	Hispanic	0.0884	2.159	-0.1216	-1.022	-0.1547	-1.151
	Caucasian	0.0592	1.915	-0.1216	-1.022	-0.1261	-1.121
Employment attributes	Full-time	0.0185	0.681	0.0847	1.101	0.0923	1.254
	Flex Work	-0.0129	-0.654	0.0497	0.912	0.0498	0.915
	Retail	-	-	-0.1430	-1.906	-0.1443	-1.949
	Industry	-0.0437	-1.377	0.1783	2.609	0.1541	1.771
	Office	-0.0237	-1.066	-	-	-	-
	Government	-0.0237	-1.066	0.1783	2.609	0.2063	2.387
Trip attributes	Drive alone	0.0302	0.614	-0.3705	-2.786	-0.3390	-2.598
	Shared Ride	0.0421	0.786	-0.3705	-2.786	-0.3390	-2.598
	External	0.0779	0.787	-0.6625	-2.389	-0.6690	-2.420
	Cost	0.0032	1.170	0.0312	3.748	0.0319	3.885
Day of week	Friday	-0.0565	-2.169	0.1221	1.705	0.1226	1.694
Season	Summer	-	-	-	-		
	τ (inverse of S.D)	7.4550	26.894	NA	NA	NA	NA
	σ (S.D of v_i)	NA	NA	NA	NA	0.0506	1.660
Number of observations		1472		1472		1472	
DIC(Deviance Information Criterion)		21439.8		19667.6		19682.3	

Table B.4 Final Model Results for NHB Trips

Variable	Attribute	Lognormal		Weibull		Weibull with UH	
		beta	t-stat	beta	t-stat	beta	t-stat
	Alpha(α)			4.4410	55.932	4.4030	56.096
	constant(b0)	6.7630	244.948	-30.7000	-54.433	-30.4600	-53.495
Household	Income (divided by 10000)			0.0098	2.428	0.0099	2.464
Attributes	Kids	-0.0548	-4.121	0.2449	6.106	0.2406	5.874
Individual	Age (divided by 10)	-1.8120	-5.106	1.0620	10.993	1.0540	10.780
Attributes	Male	-0.0193	-2.010	0.0770	2.636	0.0765	2.632
	Hispanic	-0.0647	-2.651			0.0547	0.970
	Caucasian	-0.0272	-1.471	0.0308	0.774	0.0547	0.970
	Full-time	0.0716	5.332	-0.2872	-8.049	-0.2881	-7.919
Employment	Part-time	0.0524	2.691	-0.1001	-1.784	-0.1034	-1.782
Attributes	Retired	0.0314	1.228				
Trip	work trip	-0.0957	-8.696	0.5270	14.255	0.5220	14.021
Attributes	Shared Ride	0.0323	3.122	-0.1724	-5.247	-0.1746	-5.313
	Cost			-0.0117	-1.973	-0.0117	-1.963
Day of week	Friday	0.0292	2.418	-0.1335	-3.554	-0.1327	-3.479
Season	Summer	-0.0582	-1.954				
	Spring	0.0205	1.268	-0.0845	-1.878	-0.0860	-1.960
	τ (inverse of S.D)	9.3700	48.751	NA	NA	NA	NA
	σ (S.D of v_i)	NA	NA	NA	NA	0.0383	1.818
Number of observations		1456		1456		1456	
DIC (Deviance Information Criterion)		67943.6		65934.9		65935.8	

Table B.5 Normal Mixture Model Results for HBNW Trips

Variable	Attribute	AM Peak		PM Peak	
		Beta1	t-stat	Beta2	t-stat
	Constant(b0)	6.202	94.34134	6.894	416.3043
Household attributes	Income (divided by 10000)			-0.0018	-2.4552
	Kids			-0.03472	-5.00649
Individual attributes	Age (divided by 100)	0.1909	2.536203	-0.09104	-3.84947
	Student			0.01357	1.592162
	Hispanic	-0.07154	-1.81851	-0.00959	-0.90738
	Caucasian			-0.01056	-1.23249
Employment attributes	Full-time	0.07171	2.302087	0.08576	8.706599
	Part time	0.1297	3.782444	0.05601	5.119744
	Retired	0.05743	1.440431	-0.06729	-3.40364
	Retail	-0.08453	-2.14326		
	Industry	0.05343	1.200135		
	Education	0.06427	1.113479	0.02036	1.444996
	Office	-0.05817	-1.63124		
	Government	0.05204	1.191665	0.01302	1.203327
Trip attributes	Drive alone	0.05448	1.6914	0.08308	8.421693
	Shared Ride	0.05637	1.912144	0.1113	13.06338
	Cost	0.006153	1.494172	-0.00465	-3.68013
Season	Spring	0.04648	1.682839		
	Summer			0.03339	2.614722
Number of observations		7325			

Table B.6 Marginal Effects of the Variables on Departure Time for HBW Trips (Expressed as Percentages)

	Home-to-work trips			Work-to-home trips			NHB trips		
Variable (X)	Log-normal	Wei-bull	Wei-bull (UH)	Log-normal	Wei-bull	Wei-bull (UH)	Log-normal	Wei-bull	Wei-bull (UH)
Age (divided by 10)	-2.373	-2.746	-2.373	-2.746	-0.773	-0.773	-16.573	-2.363	-2.365
Income (divided by 10000)	-0.297	-0.703	-0.297	-0.703	0.555	0.555	0	-0.22	-0.225
Children	0	0	0	0	-1.822	-1.822	-5.333	-5.365	-5.318
Male	0	0	0	0	0	0	-1.911	-1.719	-1.722
Student	3.670	2.730	3.670	2.730	3.956	3.956	0	0	0
African American	-4.927	0.000	-4.927	0.000	0	0	0	0	0
Hispanic	-9.932	-8.224	-9.932	-8.224	9.247	9.247	-6.265	0	-1.235
Caucasian	-4.927	-4.197	-4.927	-4.197	6.094	6.094	-2.683	-0.691	-1.235
Full-time	-7.703	-8.947	-7.703	-8.947	1.862	1.862	7.423	6.681	6.762
Part-time	0	0	0	0	0	0	5.38	2.28	2.376
Retired	0	0	0	0	0	0	3.19	0	0
Flexible work-hours	6.117	6.314	6.117	6.314	-1.280	-1.280	0	0	0
Work trip	0	0	0	0	0	0	-9.126	-11.19	-11.18
Retail	3.826	5.596	3.826	5.596	0	0	0	0	0
Industry	-3.085	0	-3.085	0	-4.274	-4.274	0	0	0
Educational institutions	-3.085	-5.214	-3.085	-5.214	0	0	0	0	0
Office	2.255	0	2.255	0	-2.337	-2.337	0	0	0
Government	-4.868	-5.214	-4.868	-5.214	-2.337	-2.337	0	0	0
Education	0	0	0	0	0	0	0	0	0
Drive alone	-4.110	-7.563	-4.110	-7.563	3.069	3.069	0	0	0
Shared ride	0	0	0	0	4.296	4.296	3.283	3.958	4.045
External	6.415	7.973	6.415	7.973	8.103	8.103	0	0	0
Trip cost ($)	-1.727	-2.114	-1.727	-2.114	0.325	0.325	0	0.264	0.266
Friday	0	0	0	0	-5.492	-5.492	2.963	3.052	3.06
Spring							2.071	1.921	1.972
Summer	3.717	5.639	3.717	5.639	0	0	-5.654	0	0

Units of the values in the table: % change in departure time per unit change in X

Note: Zero values indicate that the variable was not statistically significant and was removed from the final models or was not included in the model.

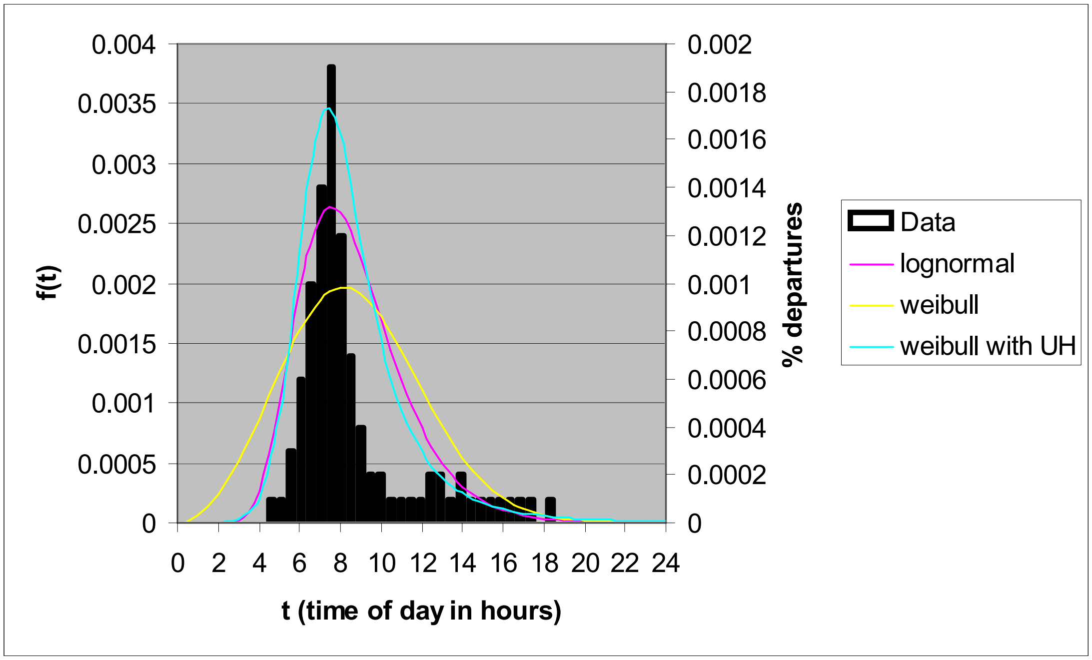

Figure B.6 Comparison of Different Model Predictions for Home-to-Work Trips

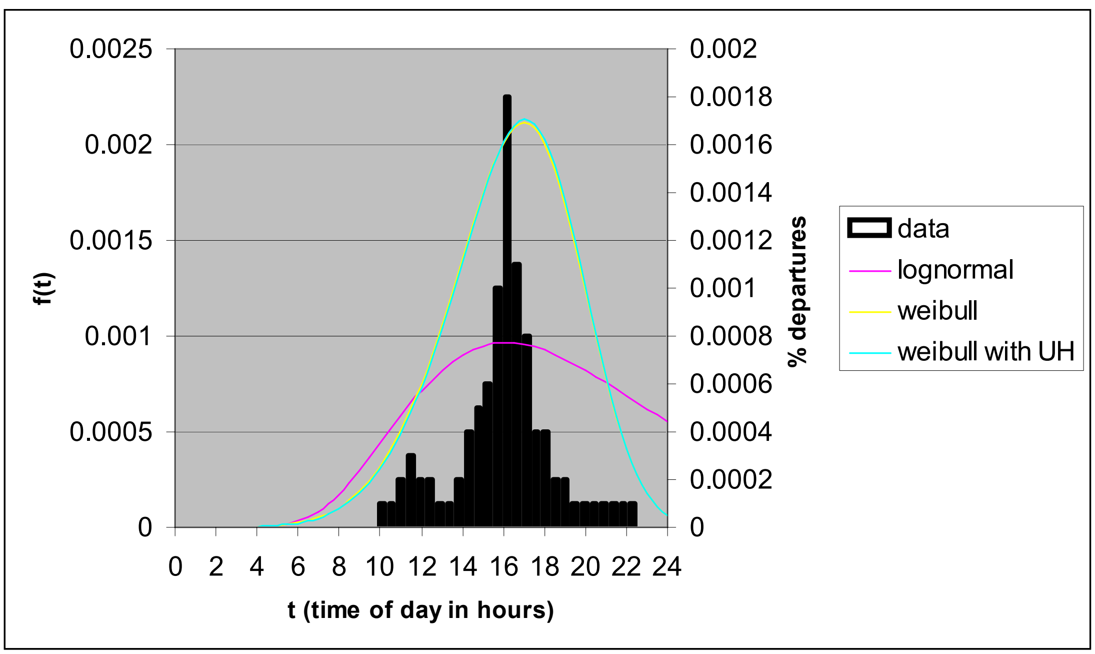

Figure B.7 Comparison of Different Model Predictions for Work-to-Home Trips.

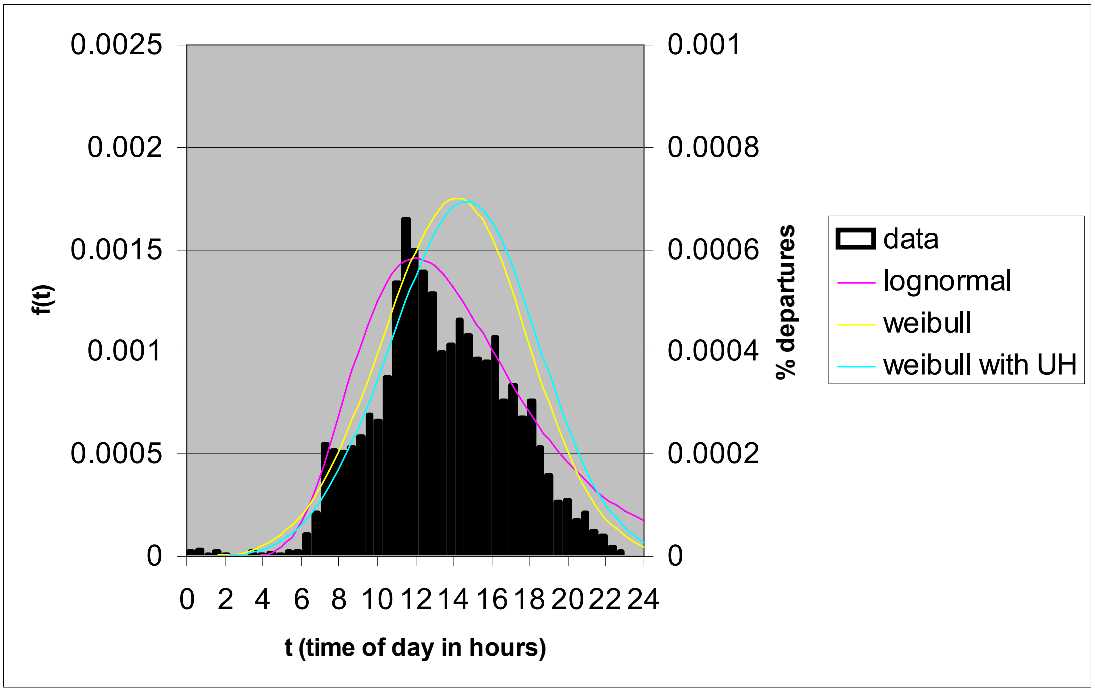

Figure B.8 Comparison of Different Model Predictions for NHB Trips.

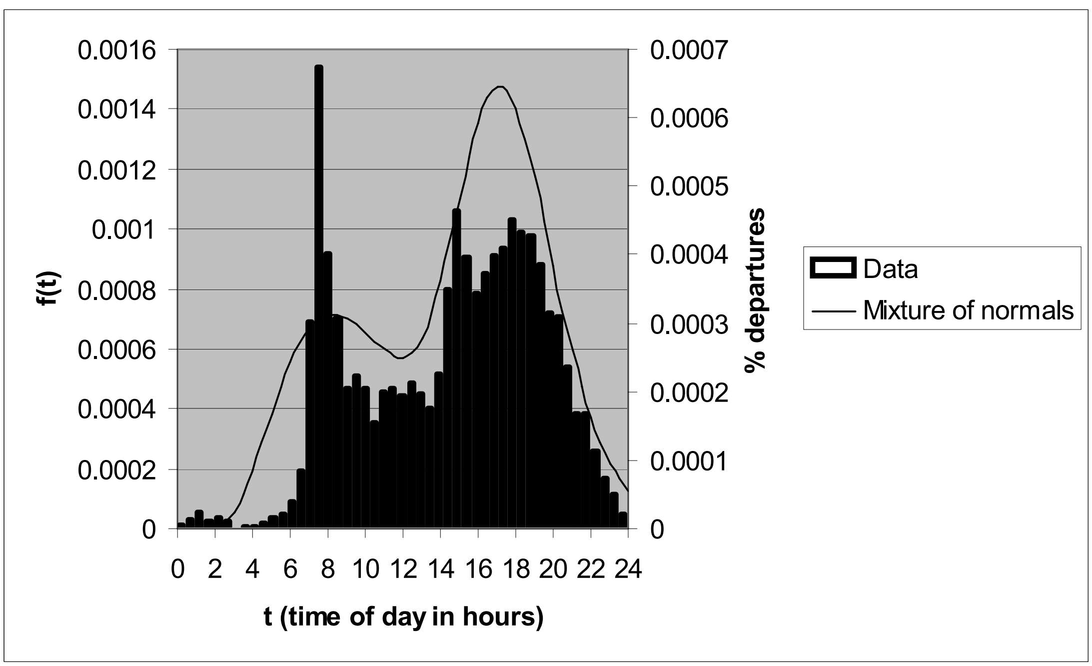

Figure B.9 Mixture Model Predictions for HBNW Trips.

Section B-2: AADT Error Estimation

B-2.1 Methodology

In this section, the methods used to estimate and compare different types of error are described.

Sampling Errors and Factoring Errors

Day of week (DOW) and month of year (MOY) factors were created based on individual-site as well as grouped-site data. A year's AADT was estimated from each day's short-term count using a variation of the *Traffic Monitoring Guide*'s (FHWA 2001) standard formula:

$$AADT_{est,i} = VOL_i * M_i * D_i * A_i * G_i \qquad (1)$$

where AADTest,i is the estimate of annual average daily traffic count (vehicles per day) at location i, VOLi is the actual 24-hour axle volume, Mi is the applicable "seasonal" (MOY) factor (which may come from a group assignment), Di is the applicable DOW factor for factor group h, Ai is an axle-correction factor for location i, and Gi is a traffic growth factor for factor group h (for inter-sample years [and not applicable here]).

Eq. (1) can be modified as necessary, depending on the conditions used to take the short duration counts. In this study, vehicle counts (rather than axle counts) were given and analysis was done for the same year's count, so axle-correction and traffic growth factors were not required. Moreover, every ATR site had (virtually) a full-year's data, so month-of-year and day-of-week factors could be created expressly and precisely for each location. In this way, Eq. (1) becomes the following:

$$AADT_{est,i} = VOL_i * M_i * D_i \qquad (2)$$

The two relevant factors for ATR site *i*, M_i and D_i, were calculated as follows:

$$M_i = AADT_i / MADT_i \quad \text{and} \quad D_i = AADT_i / DADT_i$$

where $AADT_i$ is the true *AADT* (an average of all 365 days' counts), $MADT_i$ is the average daily traffic for the applicable month in question, at location *i*, and *DADT* is the average daily traffic for the applicable day in question (e.g., all Mondays in the year, or all Fridays in the year), at that location. In this way, if a particular month of the year, or day of the week, has unusually low or high counts (e.g., January and Sunday exhibit less-than-AADT traffic levels, typically), it will have a monthly or daily factor that corrects for this bias, raising or lowering the day's count to better reflect an annual (AADT) estimate. As noted, factors were created in two distinct ways: (1) using a site's own data for a set of idealized factors (resulting in estimates of pure sampling error), (2) relying on other, similar sites' data for these factors (resulting in estimates of factoring errors). For the latter approach, group membership was determined on the basis of area type (urban versus rural), functional class (freeway versus arterial, and, in the case of Florida, collector], and, in the case of Minnesota, number of lanes (two to four lanes, versus five or more).

Error Measurement

Because both actual and estimated AADT values were available for all ATR sites, percentage errors in AADT estimation were calculated as follows:

$$\%Error_i = 100\frac{|AADT_i - AADT_{est,i}|}{AADT_i}$$

These are computed as absolute errors, for purposes of averaging, and to achieve a sense of the overall magnitude of uncertainty inherent in relying on a single day's data and/or relying on other sites' factors.

Misclassification Error

Misclassification error occurs when a site is assigned to an incorrect ATR group. This leads to application of the average factors of the (incorrect) ATR group to the site and may cause large errors in AADT estimation at that site. For example, if an urban site is misclassified as a rural site, the average factors of the rural ATR group are applied, in order to estimate the urban site's AADT. These errors were quantified for the sites in both Florida and Minnesota when the sites were misclassified according to area type and functional class.

Spatial Error

Spatial error occurs when a roadway segment is assigned the AADT from its nearest sampling site, due to non-availability of more local counts. These errors were quantified as follows. The SmartMobility-predicted flows on the Austin travel network were assumed as to be the actual counts on each of the coded 10,594 links. Then, the midpoint of a particular link on a particular roadway was assumed to be the short-term count location. The difference in flow from this location to nearby links, along the same roadway, gave the spatial error involved in assigning the AADT at the short-term count location to those links. The distance between mid-points of the links along the roadway was noted, in order to appreciate how such error varies with distance from the assumed short-term count site. Errors were averaged for every 0.2-mile bin of values, in order to appreciate average error at a given distance. Seven distinct roadway sections were chosen from the Austin network, so that they included different area types, functional classes and numbers of lanes. And each provided the equivalent of three short-term count sites (using different links as starting points, or count sites). Thus, data for 21 hypothetical count sites was analyzed to estimate the extent of error likely caused by spatial extrapolation. Of course, this error is compounded by temporal extrapolation (i.e., using 1-day's count rather than 365 days' count, and forecasting future year's counts), misclassification, and so forth. The Austin data are simply model predictions, rather than actual counts. Actual counts may well vary greatly from day to day and link to link. To address such potential variations in spatial error, a week's worth of loop-detector data from 10 to 15 (consecutive) loop detector stations on each of three Southern California freeways (I 110 S, I 405 S, I 5 N) were used. Extrapolations were made out to almost 3 miles, and a series of five to six consecutive stations were used as the "base" station (to predict downstream counts, up to 3 miles away).

Count Durations

In addition, the effects of longer short-period count durations were studied, to appreciate how AADT prediction errors decline. To estimate AADT using 48- and 72-hour traffic counts, the DOW and MOY factors were modified. Daily counts on consecutive calendar days were combined, and 7 DOW and 12 MOY factors were created. In these cases, DOW really characterized 2 or 3 consecutive days of the week. MOY factors used either one-half, one-third or two-third of the multi-day counts that crossed their edges (i.e., those sequences that overlapped with a different month).

B-2.2 Results and Discussion

The FDOT and MNDOT data sets consisted information on 293 and seventy-eight ATR sites for the years 2004 and 2002 respectively. The traffic data were available on an hourly basis and a functional class, area type and numbers of lanes were associated with each site. SmartMobility's (2005) predicted counts for Austin's over 10,000 coded links also include information on functional class, area type, and number of lanes. These data are described in Table B.7. While the Austin data cover all coded links in Austin's network, they are only predictions. Actual day-to-day counts may vary substantially across links, over space. For this reason, 1 week's worth of actual count data from California's PeMS database (PeMS 2006) also was acquired. These counts come from loop detector stations along three of Southern California's Interstate freeways (I 110 S, I 405 S, and I 5 N) at average spacings of 0.51, 0.58, and 0.68 miles, respectively. Together, the Austin and PeMS databases provide a sense of spatial variations in AADT prediction error, with the PeMS allowing a closer, more realistic look (though on freeways only).

Tables B.8 and B.9 present the prediction error results for Florida and Minnesota. These rely on the factors from similar sites (as determined by area type and functional class), and thus present an actual case. It can be seen from these tables that a short-period count's day of week and site classification have significant effects. Table B.8 indicates that the average errors in estimation of AADT range from 11.5 percent to 20 percent and the maximum errors can be as high as 81 percent. Table B.9 shows how weekdays offer more reliable predictions than weekends, and urban sites tend to be more reliable for prediction than rural sites (particularly in Minnesota, where they average 3.3 percent higher). For example, the average error in AADT estimation across Florida's ATR sites is 17.5 percent when using weekend counts, but just 12.8 percent when using weekday counts. In Minnesota, weekend-count-based errors average 17.8 percent, versus just 11.3 percent on weekdays.

Table B.10 presents the results of regression analysis of percentage error on different variables, including the DOW, MOY, functional class, area type and number of lanes, for both Florida and Minnesota. Counts taken along rural, arterial roadways with more than five lanes on a Sunday in January are also used as the base case, for comparison. A higher negative coefficient on a particular variable means lower error levels for that day, month, or roadway type. For example, Minnesota's AADT errors tend to be lower on Mondays as compared to Tuesdays (coefficient of -6.00% vs. -5.08%). In both Minnesota and Florida the average error is quite a bit less on weekdays, as compared to weekends. In Minnesota, it was found that there is no difference in error between February and January and that March, July, November, and December exhibit the highest errors, among months of the year. In contrast to the Florida results, urban area freeways (and roadways with four or fewer lanes) exhibited less error than did their counterparts. Florida's data exhibits rather dramatic misprediction tendencies when counts come from September and November (an issue that may be specific to the 2004 data year). And errors tend to be larger along freeways and in sites classified as rural (and along arterials, as compared to collectors). Average errors tend to be lowest in the months of March through June in Florida (averaging 10 percent), and August through October in Minnesota (averaging just 6 percent), suggesting that those periods are most suitable for short-term counts.

Figure B.10 compares the various error components (from sampling, factoring, and misclassification). When factors from the site's own traffic counts are used for its AADT estimates, the case is ideal (and unrealistic, of course), and the absolute average error is 6.69 percent, as compared to 11.65 percent when factors from similar sites (properly classified) are used. When sites are misclassified, factor-related errors rise to 19.35 percent in Minnesota. In Florida, the comparable values are 8.28 percent (pure sampling error, ideal factors used), 13.62 percent (proper classification factors used) and 15.09 percent (misclassified factors used). Clearly, classification plays a significant role.

Figure B.11 indicates that multi-day sampling offers little in the way of error reduction, averaging roughly 0.7 percent error reduction for each extra day of sampling [11.0 % (24 hours), 11.7 (48 hours) , and 12.6 (72 hours)].

Figure B.12 shows the results of spatial error variation in the Austin travel model predictions. The results indicate that the average error (for twenty-three calculations) increases with distance, as expected: from 6.33 percent at just 0.2 miles away to a shocking 79.5 percent at just 1.6 miles. The percentage error is much higher for urban areas as compared to rural areas, and is consistently higher for four-lane roads (as compared to two-lane roads). The error appears to be quite small in rural areas (e.g., 2.14 percent within 1 mile), supporting, to some extent, the lower sampling frequencies that states show in these areas. However, such errors increase beyond 1 mile. In urban sites, an average error of 20 percent was computed at distances of 0.5 miles, and 60 percent at 1 mile from count sites. For this reason, DOTs will no doubt want to sample urban locations more frequently than every mile. Arterials and freeways experience higher error (20 percent) compared to collectors (4.82 percent) at short distances, but lower error levels at longer distances. This may be due to the limited number of ramps, versus high frequency of intersections and driveways that occur along collectors. Higher errors for four-lane roads (as compared to two-lane roads) are consistent with the ATR results.

Finally, Figure B.13 shows the variations in spatial error using PeMS 24-hour counts over the course of 7 consecutive days along I 110 S, I 405 S, and I 5 N. The spatial extrapolation errors rise quickly, to roughly 10 percent for I 5 and I 405 and around 40 percent for I 110. The jumps in these counts at the lower intervals of distance is somewhat troubling, particularly for I 110. The same day's data applied just one-half mile away yields sizable misprediction. In the case of I 110, the jumps render such spatial extrapolations practically useless to analysts. Freeways are relatively well-controlled roadway environments, with few points of entrance and exit (though these points certainly can represent major ramps and facility merges).

Table B.7 Data Description

Classification	Sub-division	MNDOT	FDOT	Austin
		Number of sites (n)		Number of links
Area type	Urban	19	139	5822
	Rural	38	154	4772
Functional Class	Arterial	37	130	4807
	Collector	–	17	681
	Freeway	20	73	796
Number of lanes	1	0	–	394
	2	22	–	7550
	3	0	–	636
	4	28	–	1748
	5 or more lanes	8	–	266

Note: Florida did not provide lane count information, and none of the Minnesota sites was labeled as a collector.

Table B.8 Average Errors in AADT Estimation for Different Site Classification Schemes

Classification	Sub-classification	State DOT (#)	Absolute Avg. Error (%)			
			Min.	Max.	Mean	Std. Dev.
Area Type	Urban	MNDOT (n=19)	4.89	81.14	11.47	17.08
		FDOT (n=123)	5.62	37.77	14.28	6.06
	Rural	MNDOT (n=38)	7.06	38.8	12.84	5.88
		FDOT (n=153)	5.27	34.71	13.26	4.86
Functional Class	Arterial	MNDOT (n=37)	7.33	40.81	13.25	6.23
		FDOT (n=123)	5.62	37.77	14.28	6.06
	Collector	MNDOT (n=0)	N/A	N/A	N/A	N/A
		FDOT (n=17)	8.06	21.99	13.96	3.68
	Freeway	MNDOT (n=20)	5.99	83.22	14.6	16.93
		FDOT (n=73)	6.66	40.14	15.24	6.24
Number of Lanes	4 or fewer lanes	MNDOT (n=49)	6.87	41.82	13.06	6.24
	5 or more lanes	MNDOT (n=8)	8.4	80.17	18.48	24.97

Table B.9 Error Comparisons Between Weekdays and Weekends

Classification	Sub-classification	State DOT (#)	Absolute Avg. Error (%)	
			Weekend	Weekday
Area Type	Urban	MNDOT (n=19)	11.33	9.47
		FDOT (n=123)	17.57	12.74
	Rural	MNDOT (n=38)	16.03	12.21
		FDOT (n=153)	17.77	11.26
Functional Class	Arterial	MNDOT (n=37)	16.50	11.95
		FDOT (n=123)	17.54	12.75
	Collector	MNDOT (n=0)	N/A	N/A
		FDOT (n=17)	18.49	12.16
	Freeway	MNDOT (n=20)	18.68	12.97
		FDOT (n=73)	19.00	13.16
Lanes	4 or fewer lanes	MNDOT (n=49)	16.91	11.52
	5 or more lanes	MNDOT (n=8)	20.46	17.69

Table B.10 Regression Analysis with Dependent Variable as Error

Variable	MNDOT		FDOT	
	Beta	t-statistic	Beta	t-statistic
(Constant)	24.738	45.9	19.284	84.1
Monday	-6.004	-14.7	-8.770	-44.4
Tuesday	-5.082	-12.5	-8.933	-45.2
Wednesday	-4.999	-12.2	-8.998	-45.5
Thursday	-6.079	-14.8	-9.643	-49.0
Friday	-6.890	-16.8	-9.853	-50.0
Saturday	-3.196	-7.8	-6.701	-34.0
February	0.000	N/A	-0.508	-2.0
March	2.575	5.6	-2.222	-8.7
April	-0.906	-1.9	-1.958	-7.6
May	-2.703	-5.8	-2.125	-8.4
June	-3.194	-6.8	-2.484	-9.6
July	0.825	1.8	-0.679	-2.7
August	-0.757	-1.6	-0.283	-1.1
September	-1.527	-3.3	11.747	45.5
October	-1.445	-3.1	-0.070	-0.3
November	1.364	2.9	9.788	37.7
December	1.807	3.9	1.359	5.3
Urban	-3.202	-10.9	0.929	8.7
Collector	N/A	N/A	-0.129	-0.6
Freeway	-0.976	-3.4	2.400	17.7
lanes_fewer_4	-6.994	-19.1	-	-
R Square (adjusted)	0.0476	y= Error %	0.1106	
Std. Error of the Estimate	15.766		15.826	
Number of sample sites	57		293	

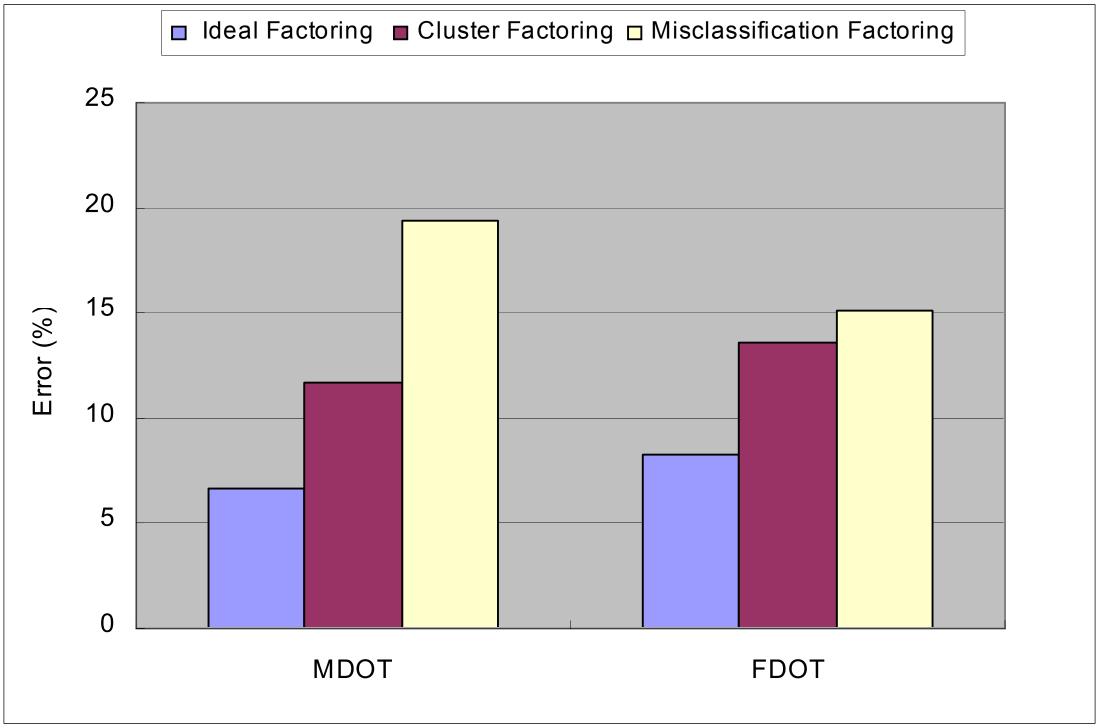

Figure B.10 Variation in AADT Estimate Error by Factoring Method used (using Florida and Minnesota ATR Data)

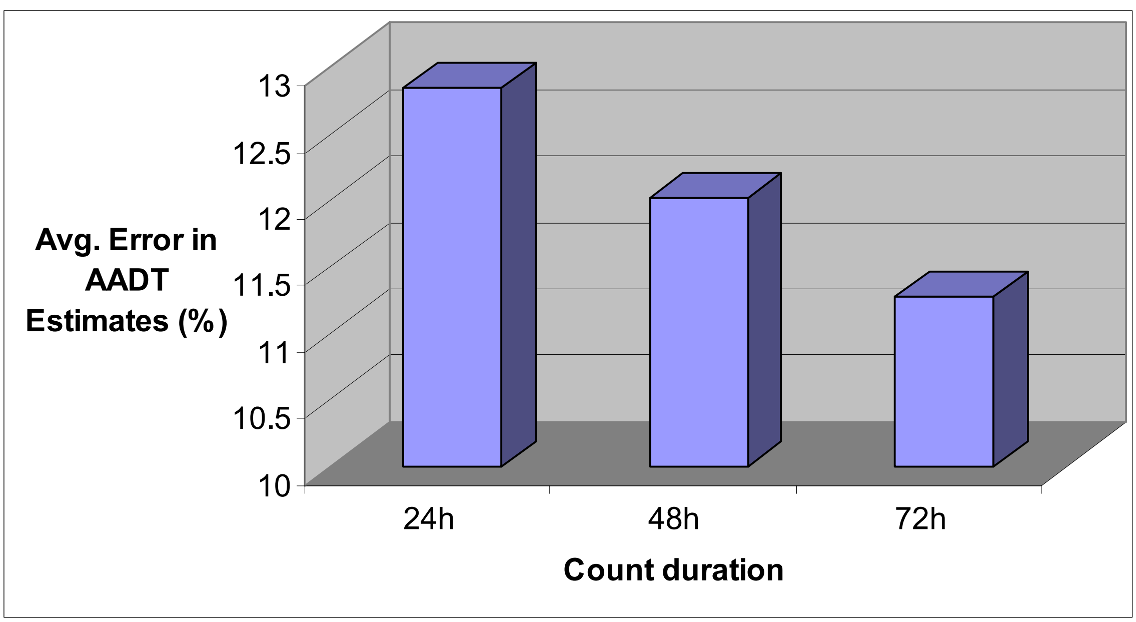

Figure B.11 Effect of Count Duration on AADT Estimate Error (using Florida' ATR Data)

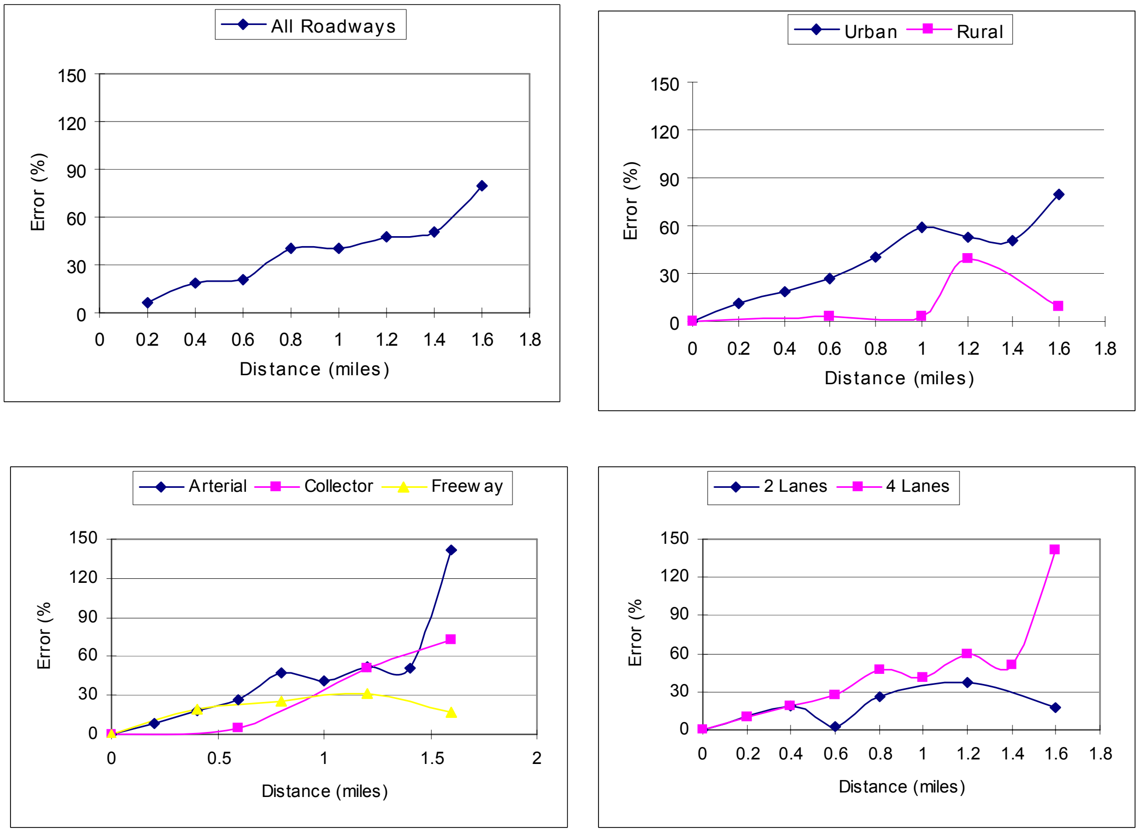

Figure B.12 Spatial Variation in AADT Estimate Error for Different Roadway and Location Types (using Austin TDM data)

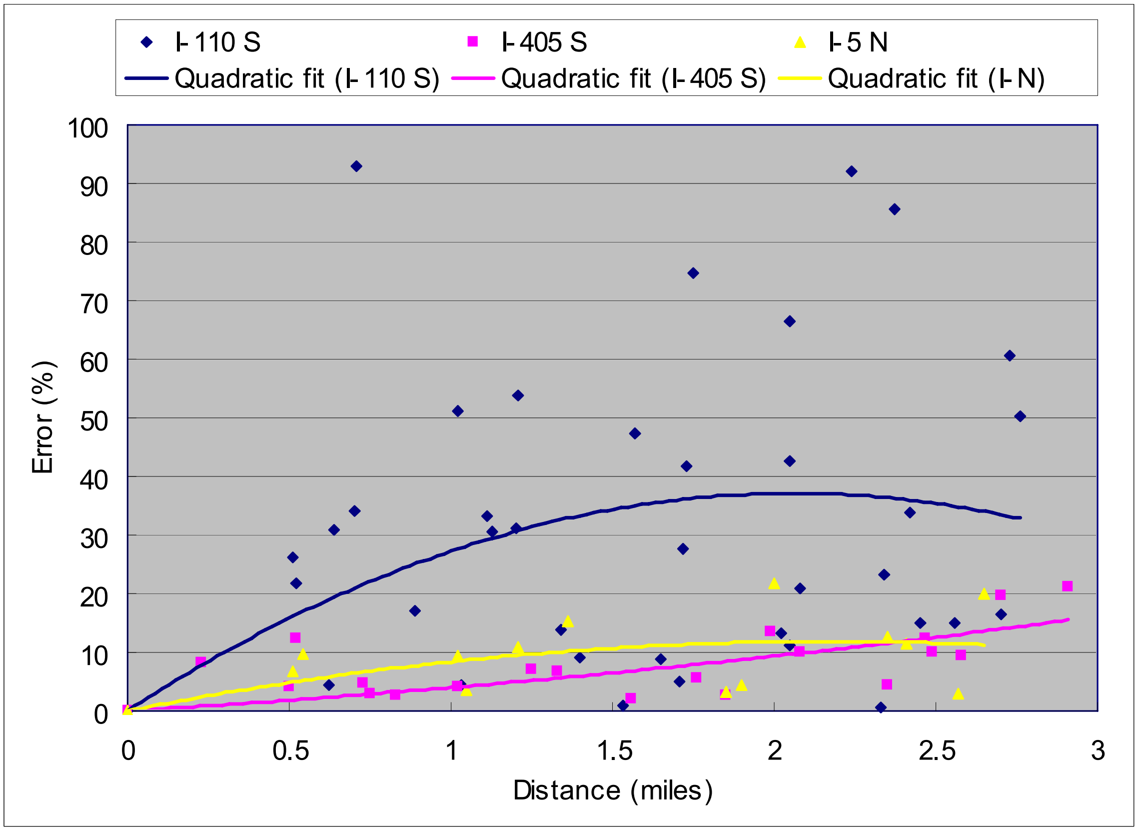

Figure B.13 Spatial Variation in AADT Estimate Error for Freeway Sites using One Week's Worth of PeMS Data at 3 Southern California Sites

References for Appendix B

FHWA (2000) “A Sampling of Emissions Analysis Techniques for Transportation Control Measures: Final Report.” U.S. Department of Transportation, October 2000.

Gulipalli, P., and Kockelman, K. (2006) “Credit-Based Congestion Pricing: A Dallas-Fort Worth Application,” Presented at the 85th Annual Meeting of the Transportation Research Board and under consideration for publication in Transport Policy.

Gulipalli, P. (2005) ‘Credit-Based Congestion Pricing: Impact Assessment for the Dallas-Fort Worth Region and Policy Recommendations,’ Masters Thesis, The University of Texas at Austin.

Gupta, S., Kalmanje, S., and Kockelman, K. (2006)“Road Pricing Simulations: Traffic, Land Use and Welfare Impacts for Austin, Texas,” Transportation Planning & Technology 29 (1): 1-23 (2006).

Gadda S., Kockelman, K and Damien, P. (2006) “Continuous Departure Time Models: A Bayesian Approach,” submitted for presentation at the 86th Annual Meeting of the Transportation Research Board and for publication in Transportation Research Record.

Gadda S., Magoon A., and Kockelman, K. (2006) ‘Estimates of AADT: Quantifying the Uncertainty,” submitted for presentation at the 86th Annual Meeting of the Transportation Research Board and for publication in Transportation Research Record.

PeMS (2006) Freeway Performance Management System, version 6.3. Accessed on July 25, 2006 at http://pems.eecs.berkeley.edu.

Appendix C: Results of Control Scenario Evaluations for Houston and Dallas

Table C.1 Difference in daily maximum 1-hr average ozone concentrations in the 8-county Houston/Galveston area

HGB Episode	2000 Base	2010 Future	VMT05LDV	VMT05HDV	VMT15LDV	VMT15HDV	VMT25LDV	VMT25HDV	VMT100HDV	IM	Idle	LEVII
Date	**1hr Max**	**1hr Max**	**1hr Diff**	**1hr Diff**	**1hr Diff**	**1hr Diff**	**1hr Diff**	**1hr Diff**	**1hr Diff**	**1hr Diff**	**1hr Diff**	**1hr Diff**
825	156.48	122.82	0.15	0.02	0.42	0.07	0.81	0.15	1.51	0.00	0.00	0.14
826	149.43	107.35	0.27	0.13	0.81	0.38	1.36	0.64	2.68	0.00	0.07	0.17
827	112.26	83.90	0.15	0.06	0.46	0.19	0.78	0.31	1.26	0.00	0.01	0.09
828	131.97	98.58	0.19	0.23	0.59	0.69	0.98	1.17	5.11	0.00	0.02	0.12
829	151.17	110.68	0.17	0.16	0.52	0.50	0.86	0.85	3.82	0.00	0.02	0.12
830	137.22	122.37	0.15	-0.22	0.45	-0.60	0.75	-0.94	-1.83	0.01	-0.01	0.20
831	170.67	145.32	0.23	0.19	0.69	0.58	1.16	0.99	4.87	0.05	0.02	0.18
901	136.70	117.38	0.26	0.16	0.80	0.49	1.34	0.83	3.96	0.04	0.00	0.21
902	152.74	125.53	0.36	0.17	1.09	0.53	1.83	0.89	3.96	0.06	0.02	0.27
903	139.27	113.07	0.24	0.08	0.73	0.25	1.22	0.42	1.76	0.04	0.01	0.17
904	157.95	123.09	0.18	0.07	0.54	0.22	0.90	0.37	1.54	0.09	0.03	0.13
905	209.67	178.50	0.64	0.70	1.93	2.17	3.25	3.70	12.86	0.03	0.15	0.44
906	152.71	122.25	0.23	0.33	0.69	1.00	1.16	1.70	6.90	0.07	0.00	0.15
Average	**145.71**	**116.03**	**0.21**	**0.11**	**0.65**	**0.36**	**1.10**	**0.62**	**2.96**	**0.03**	**0.02**	**0.16**

HGB Episode	2000 Base	2010 Future	RVP	Construct Shift	Construct Zero	15dieselNOx	Marine Zero	Bundle1	Bundle2	Bundle3	Bundle2. areapt25
Date	**1hr Max**	**1hr Max**	**1hr Diff**	**1hr Diff**	**1hr Diff**	**1hr Diff**	**1hr Diff**	**1hr Diff**	**1hr Diff**	**1hr Diff**	**1hr Diff**
825	156.48	122.82	0.00	0.13	0.59	0.11	3.00	0.16	0.94	12.01	6.80
826	149.43	107.35	0.00	0.26	1.24	0.64	4.65	0.47	2.05	10.49	7.13
827	112.26	83.90	0.00	0.23	0.64	0.37	4.41	0.22	1.10	6.17	5.21
828	131.97	98.58	0.00	0.53	1.89	1.03	3.36	0.45	2.42	13.87	6.72
829	151.17	110.68	0.00	0.67	1.63	0.75	4.84	0.36	1.89	14.05	7.54
830	137.22	122.37	0.02	-0.87	-1.00	-0.94	5.08	-0.05	-0.54	15.49	3.33
831	170.67	145.32	0.06	0.70	1.54	0.84	12.92	0.54	2.42	27.79	7.81
901	136.70	117.38	0.04	0.79	1.97	0.80	3.34	0.51	2.40	14.32	5.43
902	152.74	125.53	0.04	0.85	1.76	0.86	3.08	0.65	2.85	13.70	6.16
903	139.27	113.07	0.04	0.36	0.91	0.51	5.46	0.41	1.71	10.76	5.94
904	157.95	123.09	0.08	1.16	2.46	0.83	6.27	0.46	1.90	13.13	6.59
905	209.67	178.50	0.07	1.30	5.76	3.00	2.12	1.61	7.86	26.13	12.64
906	152.71	122.25	0.01	0.13	2.69	1.51	1.64	0.64	3.42	14.60	6.30
Average	**145.71**	**116.03**	**0.03**	**0.41**	**1.36**	**0.61**	**4.84**	**0.40**	**1.88**	**13.86**	**6.25**

(Previous page) Table C.1 Note: Averages do not include Sep. 5th since, due to model performance issues, TCEQ has opted not to use it for control strategy evaluations
(TCEQ. "Phase 2 HGB Mid Course Review Base Case Model Performance Evaluation," 2004.)

Table C.2 Difference in daily maximum 8-hr average ozone concentrations in the 8-county Houston/Galveston area

HGB Episode	2000 Base	2010 Future	VMT05LDV	VMT05HDV	VMT15LDV	VMT15HDV	VMT25LDV	VMT25HDV	VMT100HDV	IM	Idle	LEVII
Date	**8hr Max**	**8hr Max**	**8hr Diff**	**8hr Diff**	**8hr Diff**	**8hr Diff**	**8hr Diff**	**8hr Diff**	**8hr Diff**	**8hr Diff**	**8hr Diff**	**8hr Diff**
825	95.03	84.78	0.24	0.09	0.73	0.29	1.24	0.52	2.04	0.00	0.01	0.18
826	103.41	81.91	0.23	0.12	0.71	0.35	1.19	0.60	2.10	0.00	0.06	0.14
827	87.47	70.42	0.12	0.05	0.37	0.14	0.63	0.23	0.94	0.00	0.01	0.08
828	103.57	79.85	0.20	0.23	0.62	0.67	1.01	1.11	4.26	0.00	0.03	0.13
829	105.18	86.38	0.25	0.25	0.74	0.77	1.25	1.25	2.82	0.00	0.02	0.16
830	110.17	99.71	0.15	-0.03	0.46	-0.06	0.77	-0.08	-0.42	0.01	0.00	0.15
831	135.07	116.61	0.17	0.10	0.52	0.32	0.88	0.56	3.13	0.04	0.01	0.15
901	112.18	94.88	0.31	0.25	0.94	0.76	1.58	1.28	3.24	0.06	0.01	0.22
902	110.19	99.05	0.19	0.08	0.59	0.29	1.00	0.43	1.98	0.05	0.01	0.16
903	102.98	87.29	0.13	0.04	0.39	0.12	0.66	0.20	0.87	0.02	0.00	0.10
904	112.07	95.60	0.09	0.03	0.26	0.08	0.43	0.13	0.52	0.13	0.02	0.07
905	132.77	123.43	0.23	0.19	0.70	0.62	1.19	1.12	5.46	0.05	0.06	0.19
906	126.53	106.35	0.18	0.24	0.56	0.72	0.93	1.17	4.42	0.06	0.01	0.12
Average	**108.66**	**91.90**	**0.19**	**0.12**	**0.57**	**0.37**	**0.96**	**0.62**	**2.16**	**0.03**	**0.02**	**0.14**

HGB Episode	2000 Base	2010 Future	RVP	Construct Shift	Construct Zero	15dieselNOx	Marine Zero	Bundle1	Bundle2	Bundle3	Bundle2. areapt25
Date	**8hr Max**	**8hr Max**	**8hr Diff**	**8hr Diff**	**8hr Diff**	**8hr Diff**	**8hr Diff**	**8hr Diff**	**8hr Diff**	**8hr Diff**	**8hr Diff**
825	95.03	84.78	0.00	0.30	1.05	0.41	1.16	0.35	1.44	8.35	3.97
826	103.41	81.91	0.00	0.50	1.24	0.59	2.57	0.41	1.69	7.38	4.33
827	87.47	70.42	0.00	0.29	0.56	0.29	2.48	0.18	0.87	5.14	3.05
828	103.57	79.85	0.00	0.67	1.59	0.89	1.46	0.47	2.30	9.82	4.29
829	105.18	86.38	0.00	0.97	1.65	1.07	1.15	0.53	1.83	8.42	4.90
830	110.17	99.71	0.01	0.01	0.22	-0.11	1.46	0.15	0.55	6.04	3.81
831	135.07	116.61	0.06	0.34	1.25	0.51	2.98	0.38	1.65	13.15	4.97
901	112.18	94.88	0.03	0.73	2.25	1.22	-0.74	0.66	2.43	8.06	4.19
902	110.19	99.05	0.04	0.38	1.08	0.47	0.22	0.38	1.59	6.48	2.88
903	102.98	87.29	0.04	0.25	0.57	0.27	2.26	0.24	0.95	5.47	3.33
904	112.07	95.60	0.08	0.75	1.20	0.38	4.10	0.33	1.00	7.00	3.61
905	132.77	123.43	0.06	0.58	1.88	0.88	0.79	0.60	2.82	12.34	5.64
906	126.53	106.35	0.01	0.43	1.87	1.10	1.21	0.50	2.33	10.36	4.70
Average	**108.66**	**91.90**	**0.02**	**0.47**	**1.21**	**0.59**	**1.69**	**0.38**	**1.55**	**7.97**	**4.00**

Table C.3 Difference in daily maximum 1-hr average ozone concentrations in the 9-county Dallas/Fort Worth area

DFW Episode	1999 Base	2010 Future	VMT05LDV	VMT05HDV	VMT15LDV	VMT15HDV	VMT25LDV	VMT25HDV	VMT100HDV	IM	CBCP	LEVII
Date	**1hr Max**	**1hr Max**	**1hr Diff**	**1hr Diff**	**1hr Diff**	**1hr Diff**	**1hr Diff**	**1hr Diff**	**1hr Diff**	**1hr Diff**	**1hr Diff**	**1hr Diff**
815	114.88	94.55	0.31	0.10	0.92	0.31	1.55	0.52	2.13	0.05	0.00	0.21
816	139.84	122.73	0.33	0.24	1.01	0.73	1.70	1.23	5.18	0.06	0.42	0.24
817	133.30	133.24	0.36	0.17	1.08	0.51	1.82	0.88	4.31	0.04	0.41	0.27
818	127.99	114.92	0.30	0.18	0.90	0.56	1.52	0.94	4.08	0.06	0.48	0.23
819	134.22	112.61	0.31	0.21	0.87	0.58	1.45	0.96	4.06	0.08	0.31	0.24
820	110.77	103.14	0.18	0.05	0.56	0.16	0.97	0.29	2.09	0.01	0.18	0.17
821	119.44	100.94	0.28	0.11	0.86	0.34	1.45	0.57	2.42	0.06	0.00	0.20
822	116.32	92.78	0.28	0.11	0.86	0.32	1.44	0.53	2.19	0.04	0.00	0.18
Average	**124.59**	**109.36**	**0.29**	**0.15**	**0.88**	**0.44**	**1.48**	**0.74**	**3.31**	**0.05**	**0.23**	**0.21**
DFW Episode	**1999 Base**	**2010 Future**	**RVP**	**Construct Zero**	**15dieselNOx**	**Bundle1**	**Bundle2**	**Bundle3**	**Bundle2. areapt25**			
Date	**1hr Max**	**1hr Max**	**1hr Diff**	**1hr Diff**	**1hr Diff**	**1hr Diff**	**1hr Diff**	**1hr Diff**	**1hr Diff**			
815	114.88	94.55	0.04	1.17	0.74	0.50	2.23	5.66	3.77			
816	139.84	122.73	0.06	3.33	1.40	0.69	3.49	12.03	5.65			
817	133.30	133.24	0.05	2.78	1.01	0.61	3.05	11.45	5.78			
818	127.99	114.92	0.08	2.90	1.16	0.62	3.01	10.94	5.40			
819	134.22	112.61	0.09	2.63	1.17	0.66	2.91	9.63	5.19			
820	110.77	103.14	0.01	1.43	0.29	0.26	1.41	7.59	3.20			
821	119.44	100.94	0.09	1.63	0.84	0.55	2.37	6.48	4.05			
822	116.32	92.78	0.04	1.36	0.78	0.47	2.17	5.74	3.50			
Average	**124.59**	**109.36**	**0.06**	**2.15**	**0.92**	**0.54**	**2.58**	**8.69**	**4.57**			

Table C.4 Difference in daily maximum 8-hr average ozone concentrations in the 9-county Dallas/Fort Worth area

DFW Episode	1999 Base	2010 Future	VMT05LDV	VMT05HDV	VMT15LDV	VMT15HDV	VMT25LDV	VMT25HDV	VMT100HDV	IM	CBCP	LEVII
Date	**8hr Max**	**8hr Max**	**8hr Diff**	**8hr Diff**	**8hr Diff**	**8hr Diff**	**8hr Diff**	**8hr Diff**	**8hr Diff**	**8hr Diff**	**8hr Diff**	**8hr Diff**
815	105.81	88.64	0.23	0.08	0.71	0.24	1.19	0.40	1.62	0.05	0.00	0.16
816	113.09	105.64	0.19	0.10	0.58	0.32	0.98	0.56	2.77	0.05	0.16	0.15
817	109.66	108.42	0.21	0.10	0.65	0.32	1.10	0.54	2.03	0.04	0.19	0.17
818	113.71	101.78	0.17	0.08	0.52	0.25	0.87	0.43	2.12	0.06	0.19	0.15
819	114.44	98.69	0.23	0.15	0.71	0.44	1.18	0.74	3.08	0.09	0.24	0.18
820	101.82	90.39	0.21	0.12	0.63	0.35	1.05	0.59	2.35	0.00	0.14	0.15
821	105.70	91.05	0.22	0.08	0.65	0.25	1.09	0.41	1.72	0.07	0.00	0.16
822	102.59	85.70	0.23	0.08	0.68	0.24	1.11	0.39	1.56	0.04	0.00	0.15
Average	**108.35**	**96.29**	**0.21**	**0.10**	**0.64**	**0.30**	**1.07**	**0.51**	**2.15**	**0.05**	**0.11**	**0.16**
DFW Episode	**1999 Base**	**2010 Future**	**RVP**	**Construct Zero**	**15dieselNOx**	**Bundle1**	**Bundle2**	**Bundle3**	**Bundle2. areapt25**			
Date	**8hr Max**	**8hr Max**	**8hr Diff**	**8hr Diff**	**8hr Diff**	**8hr Diff**	**8hr Diff**	**8hr Diff**	**8hr Diff**			
815	105.81	88.64	0.03	0.98	0.59	0.39	1.74	4.46	3.00			
816	113.09	105.64	0.04	1.80	0.65	0.38	1.86	7.46	3.37			
817	109.66	108.42	0.03	1.46	0.70	0.39	1.71	5.98	3.29			
818	113.71	101.78	0.06	1.46	0.61	0.37	1.71	6.49	3.44			
819	114.44	98.69	0.08	2.38	1.00	0.55	2.44	7.87	4.23			
820	101.82	90.39	0.02	1.88	0.74	0.34	1.80	5.96	2.99			
821	105.70	91.05	0.05	1.34	0.67	0.41	1.83	4.91	3.04			
822	102.59	85.70	0.02	1.08	0.61	0.36	1.65	4.19	2.68			
Average	**108.35**	**96.29**	**0.04**	**1.55**	**0.70**	**0.40**	**1.84**	**5.92**	**3.25**			

Table C.5 Future 8-hour ozone design values at monitors in the 8-county Houston/Galveston area

Site	2010 Future	VMT05LDV	VMT05HDV	VMT15LDV	VMT15HDV	VMT25LDV	VMT25HDV	VMT100HDV	IM	Idle	LEVII
Houston East C1	91.07	90.96	91.04	90.76	90.96	90.51	90.89	89.87	91.02	91.06	90.98
Aldine C8	93.27	93.05	93.10	92.60	92.79	92.16	92.44	89.26	93.21	93.21	93.09
NW Harris C26	89.02	88.78	88.81	88.31	88.39	87.86	87.96	84.11	88.93	88.96	88.84
Galveston C34	92.92	92.84	92.90	92.76	92.84	92.63	92.82	92.21	92.90	92.92	92.90
Deer Park C35	96.87	96.76	96.82	96.52	96.74	96.29	96.66	95.78	96.82	96.85	96.77
Bayland Park C53	100.07	99.86	99.92	99.42	99.61	98.99	99.28	96.07	100.01	100.07	99.90
Hou RegOff C81	86.00	85.90	85.96	85.65	85.84	85.40	85.70	84.17	85.96	86.00	85.89
Clinton C403	82.44	82.33	82.40	82.13	82.31	81.91	82.22	81.10	82.40	82.44	82.35
N Wayside C405	78.98	78.85	78.92	78.56	78.73	78.28	78.55	76.88	78.96	78.97	78.87
Monroe C406	83.33	83.23	83.30	83.00	83.18	82.75	83.09	81.72	83.29	83.33	83.24
Lang C408	74.75	74.62	74.68	74.37	74.54	74.14	74.35	72.27	74.72	74.73	74.65
Croquet C409	92.14	91.95	92.04	91.54	91.77	91.12	91.47	88.46	92.07	92.14	91.98
Westhollow C410	88.14	87.97	88.03	87.61	87.78	87.26	87.52	85.12	88.12	88.14	88.01
Clute C11	83.43	83.43	83.43	83.43	83.43	83.43	83.34	83.15	83.43	83.43	83.43
Texas City C10	85.01	84.94	84.99	84.83	84.92	84.71	84.87	84.12	84.99	85.01	84.99
Conroe C65	72.75	72.56	72.56	72.24	72.23	71.90	71.89	69.13	72.69	72.70	72.65

(Continued) Table C.5 Future 8-hour ozone design values at monitors in the 8-county Houston/Galveston area

Site	2010 Future	RVP	Construct Shift	Construct Zero	15dieselNOx	Marine Zero	Bundle1	Bundle2	Bundle3	Bundle2. areapt25
Houston East C1	91.07	91.04	90.95	90.61	90.86	90.13	90.86	90.23	85.34	88.20
Aldine C8	93.27	93.22	92.77	91.81	92.46	92.34	92.78	91.07	83.47	89.15
NW Harris C26	89.02	88.99	88.46	87.04	88.03	88.50	88.45	86.43	78.25	84.93
Galveston C34	92.92	92.90	92.53	92.18	92.69	91.21	92.76	92.29	87.25	90.84
Deer Park C35	96.87	96.84	96.67	96.28	96.60	95.74	96.61	95.97	92.21	93.86
Bayland Park C53	100.07	100.03	99.61	98.34	99.33	99.58	99.61	97.94	89.45	96.10
Hou RegOff C81	86.00	85.98	85.79	85.35	85.72	85.21	85.78	84.91	79.50	82.89
Clinton C403	82.44	82.41	82.26	81.85	82.20	81.63	82.22	81.55	76.84	79.64
N Wayside C405	78.98	78.97	78.68	78.07	78.57	78.63	78.71	77.63	72.60	76.09
Monroe C406	83.33	83.30	83.11	82.58	83.02	82.76	83.09	82.27	77.47	80.52
Lang C408	74.75	74.75	74.45	73.72	74.31	74.23	74.47	73.51	67.56	72.07
Croquet C409	92.14	92.09	91.71	90.63	91.47	91.82	91.71	90.14	82.77	88.61
Westhollow C410	88.14	88.14	87.82	86.81	87.54	87.69	87.74	86.38	79.89	84.65
Clute C11	83.43	83.43	83.34	83.15	83.25	82.15	83.34	83.06	81.24	82.52
Texas City C10	85.01	84.99	84.69	84.35	84.76	82.88	84.85	84.35	79.35	82.79
Conroe C65	72.75	72.74	72.29	71.62	71.89	71.87	72.27	70.67	65.42	69.03

Table C.6 Future 8-hour ozone design values at monitors in the 9-county Dallas/Fort Worth area

Site	2010 Future	VMT05HDV	VMT05LDV	VMT15LDV	VMT15HDV	VMT25LDV	VMT25HDV	VMT100HDV	IM	CBCP	LEVII
Frisco C31	92.46	92.43	92.36	92.08	92.34	91.79	92.24	91.11	92.41	92.46	92.38
Dallas Hinton C60	86.93	86.90	86.82	86.55	86.80	86.30	86.68	85.70	86.87	86.93	86.82
Dallas North C63	86.66	86.63	86.53	86.31	86.52	86.03	86.42	85.41	86.60	86.66	86.54
Dallas Executive C402	83.42	83.35	83.31	83.08	83.22	82.84	83.06	81.72	83.37	83.35	83.33
Denton C56	88.81	88.73	88.63	88.26	88.55	87.87	88.37	86.79	88.77	88.76	88.69
Midlothian C94	85.14	85.07	85.04	84.85	84.99	84.65	84.90	83.92	85.07	85.07	85.07
FtW NW C13	86.91	86.82	86.77	86.51	86.68	86.26	86.51	85.19	86.82	86.87	86.80
FtW Keller C17	85.16	85.06	85.00	84.64	84.88	84.30	84.67	83.06	85.08	85.10	85.02
Arlington C57	85.81	85.76	85.74	85.56	85.66	85.40	85.55	84.56	85.76	85.78	85.74

Site	2010 Future	RVP	Construct Zero	15dieselNOx	Bundle1	Bundle2	Bundle3	Bundle2. areapt25
Frisco C31	92.46	92.45	91.17	92.00	92.19	91.17	87.44	90.04
Dallas Hinton C60	86.93	86.90	85.89	86.48	86.66	85.71	82.74	84.72
Dallas North C63	86.66	86.63	85.49	86.22	86.38	85.46	82.26	84.37
Dallas Executive C402	83.42	83.39	81.88	82.86	83.13	82.07	78.50	80.96
Denton C56	88.81	88.81	87.31	88.15	88.44	87.06	83.31	85.91
Midlothian C94	85.14	85.09	83.80	84.58	84.90	83.94	80.98	83.06
FtW NW C13	86.91	86.85	85.40	86.29	86.59	85.43	82.26	83.89
FtW Keller C17	85.16	85.14	83.58	84.47	84.78	83.44	79.60	82.37
Arlington C57	85.81	85.78	84.50	85.27	85.56	84.66	82.04	83.12

Table C.7 Maximum differences in 1-hr average ozone concentrations in the 8-county Houston/Galveston area

HGB Episode	VMT05LDV	VMT05HDV	VMT15LDV	VMT15HDV	VMT25LDV	VMT25HDV	VMT100HDV	IM	Idle	LEVII
Date	**1hr Diff**	**1hr Diff**	**1hr Diff**	**1hr Diff**	**1hr Diff**	**1hr Diff**	**1hr Diff**	**1hr Diff**	**1hr Diff**	**1hr Diff**
825	0.67	0.40	2.03	1.27	3.43	2.09	10.13	0.38	0.35	0.45
826	0.63	0.31	1.90	0.93	3.20	1.56	6.88	0.27	0.24	0.38
827	0.40	0.17	1.20	0.50	2.02	0.83	3.47	0.16	0.12	0.24
828	0.50	0.57	1.14	1.40	1.91	2.40	11.21	0.19	0.39	0.39
829	0.42	0.46	1.28	1.42	2.15	2.42	11.62	0.28	0.38	0.28
830	0.52	0.45	1.15	1.43	1.92	2.29	10.06	0.57	0.28	0.36
831	0.74	0.54	1.55	1.99	2.27	3.02	11.93	0.82	0.47	0.65
901	0.44	0.35	1.33	1.06	2.24	1.79	8.09	0.39	0.38	0.31
902	0.43	0.27	1.30	0.82	2.19	1.53	5.74	0.46	0.21	0.28
903	0.50	0.20	1.53	0.60	2.60	1.01	4.42	0.39	0.12	0.33
904	0.55	0.29	1.67	0.68	2.84	1.14	4.89	0.60	0.11	0.36
905	0.69	0.84	2.52	2.77	3.79	4.29	18.94	1.02	0.87	0.47
906	0.30	0.43	0.91	1.33	1.53	2.25	10.22	0.27	0.20	0.19
Average	**0.51**	**0.37**	**1.42**	**1.12**	**2.36**	**1.86**	**8.22**	**0.40**	**0.27**	**0.35**
HGB Episode	**RVP**	**Construct Shift**	**Construct Zero**	**15dieselNOx**	**Marine Zero**	**Bundle1**	**Bundle2**	**Bundle3**	**Bundle2. areapt25**	
Date	**1hr Diff**	**1hr Diff**	**1hr Diff**	**1hr Diff**	**1hr Diff**	**1hr Diff**	**1hr Diff**	**1hr Diff**	**1hr Diff**	
825	0.33	4.22	4.87	1.84	11.35	1.11	5.47	22.68	8.09	
826	0.05	2.12	3.14	1.40	16.79	0.95	4.61	17.48	7.29	
827	0.02	1.15	1.64	0.79	8.91	0.59	2.71	9.29	5.37	
828	0.01	3.81	3.89	1.88	8.79	0.91	4.62	20.29	7.13	
829	0.02	4.45	3.97	1.94	11.30	0.97	4.93	21.88	8.13	
830	0.05	3.81	5.30	1.85	10.06	0.98	4.30	19.24	9.79	
831	0.47	4.64	4.55	2.62	14.23	1.54	5.52	27.79	8.92	
901	0.18	3.48	3.73	1.73	14.91	0.97	4.44	19.77	6.61	
902	0.28	1.63	2.38	1.49	9.49	0.91	3.99	16.10	6.42	
903	0.28	0.89	1.67	0.94	11.04	0.79	3.52	12.68	6.80	
904	0.16	4.83	6.67	1.91	11.59	0.95	4.74	17.53	9.30	
905	0.15	6.28	6.59	3.37	18.42	2.48	9.31	37.86	12.76	
906	0.09	3.14	3.34	1.85	3.95	0.81	4.31	18.51	6.49	
Average	**0.16**	**3.18**	**3.76**	**1.69**	**11.03**	**0.96**	**4.43**	**18.60**	**7.53**	

Table C.8 Maximum differences in 8-hr average ozone concentrations in the 8-county Houston/Galveston area

HGB Episode	VMT05LDV	VMT05HDV	VMT15LDV	VMT15HDV	VMT25LDV	VMT25HDV	VMT100HDV	IM	Idle	LEVII
Date	**8hr Diff**	**8hr Diff**	**8hr Diff**	**8hr Diff**	**8hr Diff**	**8hr Diff**	**8hr Diff**	**8hr Diff**	**8hr Diff**	**8hr Diff**
825	0.34	0.21	1.02	0.65	1.73	1.10	5.21	0.24	0.22	0.22
826	0.37	0.18	1.11	0.56	1.86	0.94	4.04	0.21	0.13	0.22
827	0.23	0.09	0.71	0.27	1.19	0.45	1.87	0.11	0.17	0.14
828	0.32	0.36	0.88	1.03	1.48	1.73	7.61	0.14	0.17	0.22
829	0.28	0.33	0.84	1.01	1.41	1.71	7.59	0.17	0.18	0.18
830	0.30	0.38	0.80	1.15	1.33	1.93	8.29	0.39	0.13	0.20
831	0.32	0.44	0.98	1.33	1.64	2.25	10.20	0.55	0.17	0.21
901	0.33	0.28	1.00	0.85	1.69	1.43	6.34	0.32	0.09	0.23
902	0.26	0.16	0.78	0.48	1.32	0.80	3.43	0.33	0.07	0.18
903	0.26	0.10	0.79	0.32	1.34	0.53	2.22	0.30	0.05	0.17
904	0.33	0.13	1.03	0.40	1.75	0.67	2.90	0.41	0.05	0.23
905	0.33	0.43	1.01	1.30	1.69	2.19	9.45	0.60	0.30	0.22
906	0.22	0.30	0.68	0.90	1.14	1.52	6.89	0.21	0.06	0.14
Average	**0.30**	**0.25**	**0.89**	**0.75**	**1.49**	**1.26**	**5.55**	**0.28**	**0.12**	**0.20**
HGB Episode	**RVP**	**Construct Shift**	**Construct Zero**	**15dieselNOx**	**Marine Zero**	**Bundle1**	**Bundle2**	**Bundle3**	**Bundle2. areapt25**	
Date	**8hr Diff**	**8hr Diff**	**8hr Diff**	**8hr Diff**	**8hr Diff**	**8hr Diff**	**8hr Diff**	**8hr Diff**	**8hr Diff**	
825	0.13	1.91	2.83	1.07	4.89	0.57	2.93	12.93	4.94	
826	0.03	0.96	2.27	0.92	7.36	0.57	2.80	10.36	4.72	
827	0.01	0.54	1.16	0.49	5.15	0.33	1.59	6.00	3.54	
828	0.01	1.65	2.65	1.36	5.52	0.66	3.40	14.41	5.45	
829	0.01	1.95	2.97	1.40	6.01	0.76	3.38	15.33	5.33	
830	0.03	2.04	3.66	1.51	3.79	0.72	3.54	14.61	7.11	
831	0.11	2.34	3.35	1.88	5.73	0.97	4.53	18.05	6.17	
901	0.07	1.54	3.07	1.42	4.40	0.75	3.59	13.31	5.16	
902	0.14	0.60	1.49	0.90	4.34	0.58	2.47	7.47	4.07	
903	0.16	0.49	0.95	0.63	4.62	0.49	1.92	5.70	3.90	
904	0.11	2.96	4.12	1.19	4.54	0.63	3.02	11.00	5.62	
905	0.08	3.32	3.30	1.76	7.83	1.13	4.54	18.43	6.74	
906	0.04	1.60	2.22	1.27	2.03	0.60	3.04	12.75	4.80	
Average	**0.07**	**1.55**	**2.56**	**1.17**	**4.87**	**0.63**	**3.02**	**11.83**	**5.06**	

Table C.9 Maximum differences in 1-hr average ozone concentrations in the 9-county Dallas/Fort Worth area

DFW Episode	VMT05LDV	VMT05HDV	VMT15LDV	VMT15HDV	VMT25LDV	VMT25HDV	VMT100HDV	IM	CBCP	LEVII
Date	**1hr Diff**	**1hr Diff**	**1hr Diff**	**1hr Diff**	**1hr Diff**	**1hr Diff**	**1hr Diff**	**1hr Diff**	**1hr Diff**	**1hr Diff**
815	0.39	0.26	1.02	0.42	1.72	0.58	2.38	0.39	0.00	0.33
816	0.53	0.27	1.17	0.82	1.97	1.38	6.13	0.34	6.27	0.27
817	0.41	0.23	1.24	0.82	2.09	1.20	5.51	0.41	11.34	0.31
818	0.40	0.30	0.98	0.64	1.65	1.08	4.52	0.36	9.56	0.33
819	0.37	0.28	1.14	0.77	1.86	1.34	5.13	0.39	10.03	0.27
820	0.28	0.19	0.84	0.56	1.41	0.96	4.31	0.24	21.87	0.22
821	0.31	0.13	0.93	0.38	1.56	0.64	2.65	0.43	0.22	0.21
822	0.41	0.11	0.97	0.33	1.54	0.57	2.25	0.25	0.00	0.19
Average	**0.39**	**0.22**	**1.04**	**0.59**	**1.73**	**0.97**	**4.11**	**0.35**	**7.41**	**0.27**

DFW Episode	RVP	Construct Zero	15dieselNOx	Bundle1	Bundle2	Bundle3	Bundle2. areapt25
Date	**1hr Diff**	**1hr Diff**	**1hr Diff**	**1hr Diff**	**1hr Diff**	**1hr Diff**	**1hr Diff**
815	0.07	1.94	0.87	0.57	2.49	6.82	4.09
816	0.07	5.31	1.66	0.76	3.95	15.42	5.92
817	0.09	5.33	1.51	0.71	3.81	15.92	6.01
818	0.12	3.85	1.33	0.66	3.11	11.67	5.46
819	0.16	4.87	1.58	0.78	3.67	13.44	5.59
820	0.06	3.05	1.08	0.52	2.61	10.67	4.64
821	0.13	2.75	0.96	0.59	2.58	7.49	4.18
822	0.05	1.89	0.78	0.59	2.20	6.02	3.73
Average	**0.09**	**3.63**	**1.22**	**0.64**	**3.05**	**10.93**	**4.95**

Table C.10 Maximum differences in 8-hr average ozone concentrations in the 9-county Dallas/Fort Worth area

DFW Episode	VMT05LDV	VMT05HDV	VMT15LDV	VMT15HDV	VMT25LDV	VMT25HDV	VMT100HDV	IM	CBCP	LEVII
Date	**8hr Diff**	**8hr Diff**	**8hr Diff**	**8hr Diff**	**8hr Diff**	**8hr Diff**	**8hr Diff**	**8hr Diff**	**8hr Diff**	**8hr Diff**
815	0.27	0.09	0.80	0.26	1.35	0.43	1.77	0.32	0.08	0.18
816	0.24	0.17	0.74	0.52	1.24	0.87	3.76	0.26	1.65	0.17
817	0.27	0.16	0.80	0.50	1.35	0.84	3.67	0.28	2.73	0.19
818	0.25	0.18	0.76	0.56	1.27	0.93	3.91	0.26	2.47	0.19
819	0.24	0.15	0.72	0.46	1.21	0.77	3.29	0.22	3.24	0.18
820	0.22	0.12	0.68	0.38	1.14	0.63	2.82	0.20	6.50	0.16
821	0.24	0.09	0.72	0.28	1.22	0.47	1.95	0.34	0.06	0.17
822	0.24	0.08	0.71	0.24	1.20	0.41	1.67	0.17	0.00	0.15
Average	**0.25**	**0.13**	**0.74**	**0.40**	**1.25**	**0.67**	**2.85**	**0.26**	**2.09**	**0.17**

DFW Episode	RVP	Construct Zero	15dieselNOx	Bundle1	Bundle2	Bundle3	Bundle2. areapt25
Date	**8hr Diff**	**8hr Diff**	**8hr Diff**	**8hr Diff**	**8hr Diff**	**8hr Diff**	**8hr Diff**
815	0.05	1.64	0.72	0.44	2.00	5.41	3.44
816	0.05	3.41	1.02	0.49	2.49	9.72	4.07
817	0.05	2.69	0.97	0.49	2.52	8.99	4.11
818	0.08	2.97	1.17	0.53	2.69	9.31	3.82
819	0.11	2.75	1.10	0.55	2.49	8.50	4.49
820	0.04	2.15	0.80	0.36	1.98	7.40	3.67
821	0.06	2.02	0.80	0.45	2.05	6.13	3.24
822	0.03	1.39	0.63	0.38	1.77	4.67	2.99
Average	**0.06**	**2.38**	**0.90**	**0.46**	**2.25**	**7.52**	**3.73**

Appendix D: Specifications for SEMTECH-D Gas Analyzers and Audit Limits

Table D1. Specifications for heated FID (191°C).
This subsystem requires a warm-up time of 60 minutes and has a flow rate of 2 liter per minute.

Range	**0 – 100 ppmC**	**0 – 1000 ppmC**	**0 – 1%C**
Accuracy	±2.0% or ±5 ppmC whichever is greater	±2.0% or ±5 ppmC whichever is greater	±2.0% or ±25 ppmC whichever is greater
Resolution	0.1 ppmC	1.0 ppmC	1.0 ppmC
Noise	< 2 ppmC	±2 ppmC	±10 ppmC
Span drift (over 8 hours)	±1.0% or ±3 ppmC whichever is greater	±1.0% or ±3 ppmC whichever is greater	±2.0% or ±15 ppmC whichever is greater
Zero drift (over 2 hours)	5 ppmC	5 ppmC	10 ppmC
Zero drift (over 8 hours)	10 ppmC	10 ppmC	20 ppmC
Response	T90<2s	T90<2s	T90<2s
Data Rate	Up to 4 Hz	Up to 4 Hz	Up to 4 Hz

Table D2. Specifications for NDIR CO and CO2 analyzer.

This subsystem requires a warm-up time of 45 minutes and has a flow rate of 2 liters per minute.

Gas	CO	CO2	HC
Range	0-8%	0-20%	0 – 2000ppmC hexane 0-4000 ppmC propane
Accuracy	±3% of reading or 50 ppmC whichever is greater	±3% of reading or 0.1% whichever is greater	±3% of reading or 4 ppmC6 whichever is greater
Resolution	10 ppm	0.01%	1 ppmC6
Noise	±20 ppm	±0.02%	±1 ppmC6
Span drift (over 8 hours)	±2% or 20 ppmC whichever is greater	±2% of reading or 0.1% whichever is greater	±2.0% or 2.0 ppmC6 whichever is greater
Zero drift (over 2 hours)	±0.005% (50 ppm)	±0.1%	±4 ppmC6
Zero drift (over 8 hours)	10 ppmC	10 ppmC	20 ppmC
Response	T90<3s	T90<3s	T90<3s
Data Rate	0.833 Hz	0.833 Hz	0.833 Hz

Table D3. Specifications for NDUV NO and NO_2 analyzer.

This subsystem requires a warm-up time of 45 minutes and has a flow rate of 3 liters per minute.

Gas	NO	NO2
Range	0-2500 ppm	0-500 ppm
Accuracy	±3% of reading or 15 ppm whichever is greater	±3% of reading or 10 ppm whichever is greater
Resolution	1 ppm	1 ppm
Noise	±2 ppm	±2 ppm
Span drift (over 8 hours)	±2% or 20 ppm whichever is greater	±10 ppm
Zero drift (over 2 hours)	±10 ppm	±10 ppm
Response	T90<2s	T90<2s
Data Rate	Up to 4 Hz	Up to 4 Hz

Table D4. Specifications for oxygen sensor.

This subsystem requires a warm-up time of 5 minutes and has a flow rate of 0.5 to 3 liters per minute.

Range	0-25%
Accuracy	±1% Oxygen
Resolution	0.1%
Noise	±0.1% oxygen
Span drift (over 8 hours)	±1.0% of reading or 0.5% oxygen whichever is greater
Response	T90<6s

Table D5. Default audit limits

Gas	Absolute Tolerance Limit	Relative Tolerance Limit
CO	0.005%	3.0% of bottle value
CO2	0.2%	3.0% of bottle value
O2	0.5%	3.0% of bottle value
NO	15.0 ppm	3.0% of bottle value
NO2	12.0 ppm	3.0% of bottle value
THC	6.0 ppmC	2.0% of bottle value
CH_4	6.0 ppmC	2.0% of bottle value

Appendix E: Activity Log for Field Testing

TxDOT Project 0-5191: PEMS Notes Sheet Page ____ of ____

Date: ________ **Location:** ____________________ **Truck ID** (Make/Model)**:** ____________________
Start Time: ________ **Job Activity:** ____________________ **Start Mileage:** ____________________
End Time: ________ **File Name:** ____________________ **End Mileage:** ____________________
Start Fuel: ____________________
End Fuel: ____________________

Time HH:MM:SS	**Activity**						**Notes** (description of load weight, other activity/conditions)	**PEMS**			
	Travel	Speed	Stop	Idle	Load	Dump		Time	Calibration	FID Fuel	Gen. Refuel
				`							