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16. Abstract

The Texas construction industry will face new environmental air quality control in 2005. The use of diesel-powered construction equipment ≥50 hp will be restricted during the morning hours throughout the ozone season in both the Dallas/Fort Worth (DFW) and Houston/Galveston (HG) nonattainment areas. Work with these equipment may begin after 10:00 a.m. in DFW and after noon in HG. Texas is currently the only state with such controls in its State Implementation Plan.

The Texas Natural Resource Conservation Commission's (TNRCC's) inputs for the U.S. Environmental Protection Agency's (EPA's) NONROAD model used construction equipment inventory and equipment activity data to improve and reduce NONROAD's emission estimates by two-thirds from its default inputs. The equipment inventory from HG was then scaled and applied to DFW.

As a result of this rule, TxDOT operations will be significantly affected in terms of additional project costs and delayed project schedules. Interviews with TxDOT staff and private contractors in the affected nonattainment areas were used to estimate the budgetary and schedule impacts from the rule. The budgetary impact from both nonattainment areas is estimated to be $116 million annually, or an estimated $350,000 per ton NOx reduced. Project schedules are estimated to increase 5 to 28 percent.

Alternative emission control technologies are available that can reduce NOx and particulate matter. These technologies are typically aftermarket products used to retrofit equipment. The diesel engine emission control technology is generally less than the cost of the construction equipment restriction rule and provides greater NOx emission benefits. Some states have government incentive programs to encourage repower, retrofit, or purchase of cleaner equipment by paying the incremental cost for equipment exceeding a baseline NOx reduction.

This report synthesizes the work performed for this project and documented in other research and letter reports. The purpose of the project was to review TNRCC-modeled results, assess the impacts to TxDOT of the construction equipment restriction rule, assess the cost-effectiveness of alternative control measure technology, and assess mobile source emission changes due to work zone lane closures.

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DISCLAIMER

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LIST OF ACRONYMS

AADT	Average annual daily traffic
AGC	Association of General Contractors
BPA	Beaumont/Port Arthur nonattainment area
CARB	California Air Resources Board
CO	Carbon monoxide
CO_2	Carbon dioxide
CPI	Consumer price index
DDCE	Dallas Diesel Construction Emissions
DFW	Dallas/Fort Worth nonattainment area
DME	Dimethyl ether
DOC	Diesel oxidation catalyst
DOT	Department of Transportation
DPF	Diesel particulate filter
DPM	Diesel particulate matter
EC-D	(Arco's) Emission Control Diesel
EGR	Exhaust gas recirculation
EPA	United States Environmental Protection Agency
ERG	Eastern Research Group, Inc.
FBC	Fuel-borne catalyst
FHWA	Federal Highway Administration
FTP	Federal test procedure
GTL	Gas to liquid
H_2O	Water
HC	Hydrocarbons
HDEWG	Heavy-duty engine working group
HG	Houston/Galveston nonattainment area
HGC	Houston/Galveston Area Council
HHDD	Heavy heavy-duty diesel
LED	Low emission diesel fuel
LHDD	Light heavy-duty diesel
MECA	Manufacturers of Emission Controls Association
MHDD	Medium heavy-duty diesel

MPO	Metropolitan Planning Organization
MTP	Metropolitan Transportation Plan
MUI	Mechanical unit injection
NOx	Oxides of nitrogen
NPV	Net present value
O_2	Oxygen
OTAQ	Office of Transportation Air Quality
PM	Particulate matter
ppm	Parts per million
RAZ	Regional analysis zone
SAE	Society of Automotive Engineers
SCR	Selective catalytic reduction
SIP	State implementation plan
SO_4	Sulfate
SOF	Soluble organic fraction
TDM	Travel demand model
TIP	Transportation Improvement Program
TNRCC	Texas Natural Resource Conservation Commission
tpd	Tons per day
TxDOT	Texas Department of Transportation
USDOT	United States Department of Transportation
USGS	U.S. Geological Survey
VMT	Vehicle-miles traveled
VOC	Volatile organic compound
vpdpl	Vehicles per day per lane
vphpl	Vehicles per hour per lane
WSA	Work schedule alternative

FOREWORD

After the conclusion of this research work, a couple of regulatory changes occurred. First, the Texas Legislature passed Senate Bill 5 to create the Texas Emissions Reduction Plan, which becomes effective September 1, 2001. The legislation creates grants and other financial incentives for emissions reductions and removes the heavy-duty diesel equipment operating restrictions, affecting construction activities within the Dallas/Fort Worth (DFW) and Houston/Galveston (HG) nonattainment area state implementation plans (SIPs). The Texas Emissions Reduction Plan will be operated in part by Texas Natural Resource Conservation Commission (TNRCC). Specifically to this research, the Texas Emissions Reduction Plan establishes the Diesel Emissions Reduction Incentive Program that will offset the incremental costs of projects to reduce oxides of nitrogen (NOx) emissions from construction equipment. The legislation caps the cost-effectiveness at $13,000 per ton NOx reduction.

There were additional changes made by TNRCC in the statewide Low Emission Diesel Fuel (LED) Program. TNRCC voted to change the implementation date from May 1, 2002, to April 1, 2005. Changes to this rule are not final and are currently gathering public comment. The changed rule also reduces the coverage area to 95 counties in East Texas. By moving the implementation date to April 1, 2005, Texas environmental rules become consistent with federal timelines. Implementation of the 15 parts per million (ppm) standard is scheduled for June 2006.

CHAPTER I. INTRODUCTION

TNRCC recently developed SIPs for the DFW and HG nonattainment areas.[1] Ensuring that national air quality standards in Texas' two largest metropolitan areas are met has proven a difficult task for TNRCC and other interested agencies. Tightening of emission budgets for these nonattainment areas results in the consideration and adoption of inventive and sometimes controversial controls and restrictions.

Atmospheric science indicates that the critical time for mixing NOx and volatile organic compounds (VOCs) to form ozone is in the early part of the day. TNRCC photochemical modeling indicated that ozone reductions are possible by reducing or preventing diesel construction equipment emissions during the morning hours when ozone precursors are produced. As a result of its analysis, TNRCC proposed and later adopted a control strategy to postpone or shift construction activities that require the use of heavy-duty diesel engines outside of the critical morning hours leading to ozone formation. This rule seeks to delay NOx production from heavy-duty diesel construction equipment early in the day in the hopes that this will reduce the amount of ozone produced during the afternoon in the presence of sunlight and high temperatures.

Both the DFW and HG SIPs[2] contained requirements restricting the use of heavy-duty diesel construction equipment (≥50 horsepower [hp]) beginning with the 2005 ozone season on April 1, 2005.[3] These equipment will not be allowed to operate between 6:00 a.m. and 10:00 a.m. in DFW from June 1 to October 31. In HG, these equipment will not be allowed to operate from 6:00 a.m. to noon throughout Daylight Savings Time.[4] The regulatory rule also establishes that daily operating records must be maintained on the job site for a minimum of two years. These records will include dates of operation, start and end times of daily operation, types of equipment being used, and the names of the equipment operators. The rule allows certain exemptions.

Exemptions to the construction equipment restrictions are the operation of any heavy-duty construction equipment used exclusively for health and safety purposes (emergency operations), and equipment used in processing wet concrete. Exemptions may also be granted to operators who submit an alternative plan describing fleet modifications that will result in a reduction amount equivalent to the rule.

Alternative plans must demonstrate reductions in NOx equivalent to those required in Sections 114.412 and 114.432 of the Texas Administrative Code and contain adequate enforcement

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[1] The DFW nonattainment area currently includes Dallas, Tarrant, Collin, and Denton counties. The HG nonattainment area includes Brazoria, Chambers, Fort Bend, Galveston, Harris, Liberty, Montgomery, and Waller counties.

[2] Rule adopted for DFW on May 11, 2000. Rule adopted for HG on January 18, 2001.

[3] The rule is limited to Brazoria, Fort Bend, Galveston, Harris, and Montgomery counties within the HG nonattainment area.

[4] First weekend in April through the last weekend in October.

provisions. To receive an exemption, the alternative plans must be submitted to TNRCC by May 31, 2002, with approval granted by TNRCC's executive director and the United States Environmental Protection Agency (EPA) by May 31, 2003. Meeting these conditions will exempt the operator upon implementation of the rule in 2005.

Other adopted statewide control strategies targeting the construction sector include: the implementation of LED, the use of emission control devices, and the accelerated purchase of clean nonroad highway diesel equipment (Tier 2/Tier 3). These strategies are designed to have a far-reaching impact in each of the nonattainment areas.

Analysis of emission credits from the Heavy-Duty Operation Restrictions rule was made by TNRCC assuming an uncontrolled fleet. Subsequent analysis, using a controlled fleet on high-horsepower equipment, was conducted to estimate the emissions credit resulting from Tier 2/ Tier 3 implementation, which requires the use of low-emission diesel fuel. An analysis was also conducted to broaden emission credits using only low-emission diesel fuel for a controlled fleet that included wider horsepower equipment ranges.

SCOPE OF TNRCC'S CONSTRUCTION EQUIPMENT RESTRICTION RULE

The construction equipment restriction rule will affect a small portion of a nonattainment area's NOx inventory. For example, the 1996 NOx inventory for DFW is 581.3 tons per day (tpd) (*1*: Page 2-4). The construction industry contributes 50.3 tpd (2). Figure 1 displays the relationship between the total NOx inventory, area/nonroad sources, construction sector, and heavy-highway sub-sector. This figure shows that the construction sector contributes 10 percent to the total inventory and 37 percent of the area/nonroad source. Approximating the heavy-highway sub-sector's contribution,[5] the Texas Department of Transportation's (TxDOT's) related construction activities represent 4 percent of the area/nonroad source and 1 percent of the total NOx inventory.

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[5] TNRCC staff estimate that the heavy-highway sector contributes 11.5 percent of the total construction sector emissions.

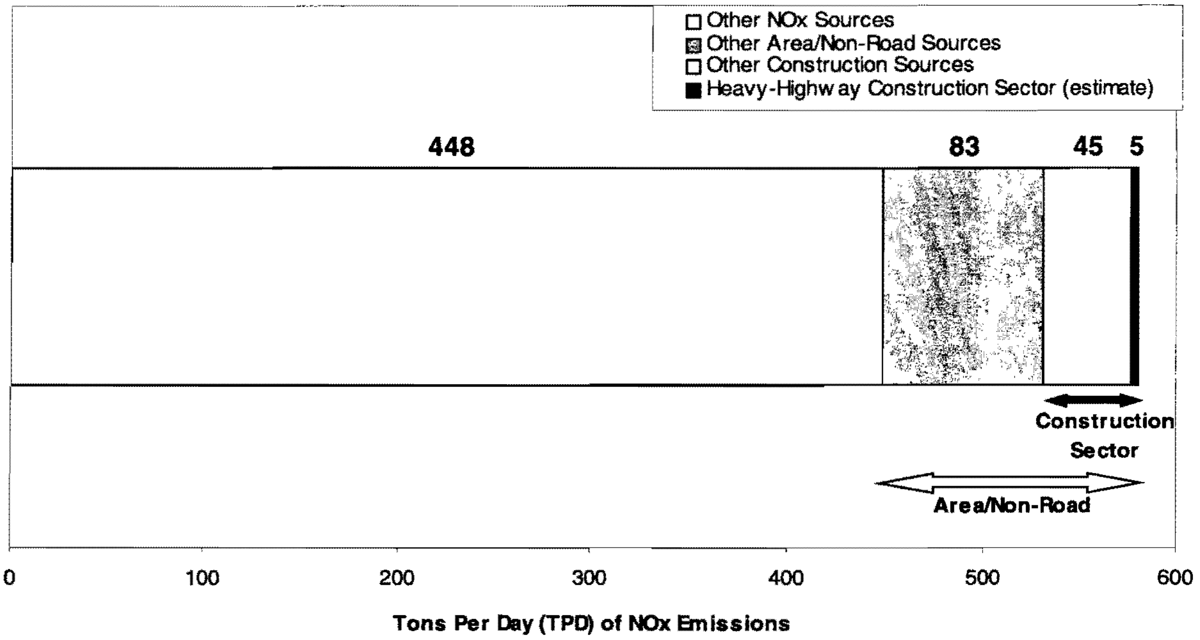

Figure 1. 1996 NOx Inventory for DFW.

TNRCC ESTIMATED EFFECT AND IMPACTS TO THE TEXAS DEPARTMENT OF TRANSPORTATION

TNRCC estimates that an aggregated 16 tpd of NOx will be reduced in DFW by implementing this rule and the Accelerated Purchase rule (*1*: Page 6-13). However, the exact benefit of the construction shift rule in DFW was not explicitly stated within the SIP documentation. In HG, 8 tpd of construction emissions are expected to shift to later hours, producing an equivalent 6.7 tpd NOx reduction (*3*: Page 6-3).

The construction equipment restrictions are expected to increase construction costs for TxDOT and extend the time needed to complete projects. Increased costs are expected to be largely due to increased labor costs, as additional time is needed to complete projects.

TNRCC's *Dallas/Fort-Worth Attainment Demonstration* document dated April 2000 (*1*) states that the agency does not anticipate significant economic impacts to affected agencies and businesses beyond the shift in work schedule, because this strategy does not require additional control equipment or new technology. TNRCC acknowledges that the rule "may require" an adjustment to work schedules and could cause extensions of construction timelines. According to the DFW Attainment Demonstration document, these effects "may have significant fiscal implications in an amount that cannot be determined at this time" (*1*: Page 6-12). The fiscal impacts are dependent on the "scope…and time-critical nature" of the project (*1*: Page 6-12). Shortly after these statements were made, a preliminary cost estimate was provided within the HG Attainment Demonstration document. Here, TNRCC states that they estimate a 15 to 20 percent cost increase to result in an additional $70 to $93 million annually to TxDOT-related construction costs in HG based on FY 99 lettings (*3*: Page 6-8). These statements appear contradictory.

Costs in DFW would likely increase $54 to $72 million annually, based on FY 99 lettings of $359 million in the nonattainment area. A conservative cost estimate of $124 million will affect TxDOT's annual fiscal budget. This is a significant impact to TxDOT and can be represented as being equivalent to the following examples:

- 77.5 million gallons of gasoline,[6] or
- 196 lane-miles carpeted with $1 bills,[7] or
- 48 percent of the total IH-635/US 75 (High Five) Interchange bid in Dallas District,[8]
- 8th largest district in FY 00 construction expenditures, or
- greater than FY 00 construction expenditures for Brownwood, San Angelo, and Abilene Districts combined.

When comparing the preliminary emission reduction estimate of 16 tpd provided by TNRCC (*1*: Page 6-13) to the construction industry inventory, a 32 percent reduction (16 tpd of 50.3 tpd) is expected from the construction industry in DFW through the implementation from both the construction shift and Accelerated Purchase. This is a significant reduction. Using the ratio of construction shift benefits to accelerated purchase of Tier 2/Tier 3 equipment benefits from Houston (39 percent), the construction equipment restriction rule applied in DFW is expected to result in a 12 percent reduction in daily construction sector emissions. Based on figures provided by TNRCC, TxDOT is expected to pay $400,000 per NOx ton reduced in HG, and $500,000 per NOx ton reduced in DFW. Figures 2 and 3 show how these costs were derived.

In comparison, the annual weighted cost of new emission controls for DFW utility boilers (point sources) is estimated to be $2,610 per ton NOx reduced (*4*). One of the higher point source costs was $75,000 per ton NOx for emission controls on peaking turbines in HG (*5*). On average point source controls generally cost less than $2,000 per ton NOx reduced.[9] The costs per ton NOx reduction for the point source emission controls are much less than that estimated for TxDOT as a result of the construction equipment restriction rule.

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[6] Fuel price = $1.60 per gallon.

[7] 194 miles from Dallas to Austin (Source: Texas State Comptroller).

[8] Total bid amount was $261 million. This is the most expensive contract let by TxDOT for a single project.

[9] Telephone conversation with Mr. Randy Hamilton, TNRCC. May 8, 2001.

Houston/Galveston Nonattainment Area

Given:

- 2007 Construction Emissions = 32.1 tpd (*2*)
- 2007 Area/Nonroad Emission Inventory = 147 tpd (*3*: Figure 2.7-4)
- 2007 NOx Inventory = 1064 tpd (*3*: Figure 2.7-4)
- Annual Duration of Rule (beginning to end of Daylight Savings Time) = 214 days
- Expected TxDOT-related Construction Cost Increase = 15-20% (*3*: Page 6-8) or $70-93 million annually
- Heavy-highway Emissions Component of Construction Sector (Source: TNRCC correspondence) = 11.5%

Calculations:

Heavy-highway Sector's Contribution to 2007 Area/Nonroad Inventory
32.1 tpd / 147 tpd * 11.5% = **2.5%**

Heavy-highway Sector's Contribution to 2007 NOx Inventory
32.1 tpd / 1064 tpd * 11.5% = **0.3%**

Heavy-highway Sector's Contribution to Daily Reduction Benefit from Construction Equipment Restriction Rule
6.7 tpd equivalent reduction * 11.5% = **0.8 tpd**

TxDOT's Annual Cost from Construction Equipment Restriction Rule
0.8 tpd benefit * 214 day duration of rule each year = **171 tons**
$70 million estimated cost annually / 171 tons = **$409,357 / ton**

Figure 2. HG Calculations of Heavy-Highway Relative Contribution and Estimated TxDOT Costs per Ton NOx Reduced.

Dallas/Fort Worth Nonattainment Area

Given:

2007 Construction Emissions	= 44.98 tpd (2)
2007 Area/Nonroad Emission Inventory	= 106.6 tpd (*1*: Figure 2.7-4)
2007 NOx Inventory	= 320.5 tpd (*1*: Figure 2.7-4)
Annual Duration of Rule (June 1 – October 31)	= 153 days
TxDOT FY 99 Letting Total for DFW Nonattainment Area	= $359 million (2)
TNRCC Estimated Cost Increase to TxDOT-related Construction Costs	= 15-20% (*3*: Page 6-8)
Heavy-highway Emissions Component of Construction Sector (Source: TNRCC correspondence)	= 11.5%
Ratio of Construction Shift Benefit to Combined Benefit of Construction Shift and Accelerated Purchase of Tier 2/Tier 3 in HG (6.7 tpd / 17.32 tpd)	= 39% (*3*: Page 6-8)

Calculations:

Heavy-highway Sector's Contribution to 2007 Area/Nonroad Inventory
44.98 tpd / 106.6 tpd * 11.5% = **4.6%**

Heavy-highway Sector's Contribution to 2007 NOx Inventory
44.98 tpd / 320.5 tpd * 11.5% = **1.6%**

Construction Equipment Restriction Rule Estimated Daily Benefit
16 tpd * 39% = **6.24 tpd equivalent reduction**

Heavy-highway Sector's Contribution to Daily Reduction Benefit from Construction Equipment Restriction Rule
6.24 tpd equivalent reduction * 11.5% = **0.7 tpd**

TxDOT's Annual Cost from Construction Equipment Restriction Rule
$359 million FY 99 Lettings * 15-20% cost increase = **$54-$72 million annually**
0.7 tpd benefit * 153 day duration of rule each year = **107 tons**
$54 million estimated cost annually / 107 tons = **$504,673 / ton**

Figure 3. DFW Calculations of Heavy-Highway Relative Contribution and Estimated TxDOT Costs per Ton NOx Reduced.

As a result of many factors, including an increase in project costs, efficient or reasonable allocation of construction equipment and manpower resources, and a limited federal and state funding pool, the number of transportation projects that can be built are reduced. Ancillary to this reduction is a potential for additional traffic congestion on project corridors resulting from the lengthened construction schedules.

PROJECT OBJECTIVES

This research project examined several potential impacts of the construction restriction rule. The objectives of the project were to:

- review and monitor construction restrictions as contained in the SIPs of other states,
- review TNRCC modeling processes,
- apply empirical emission data from construction sites to generate regional estimates of TxDOT contributions,
- estimate the cost and schedule impacts from construction restrictions,
- identify and assess potential alternative control technologies, and
- assess mobile source emission changes due to work zone lane closures.

This report addresses and fully documents each objective.

ORGANIZATION OF REPORT

This report is divided into a series of chapters covering status of construction restrictions nationally to work zone lane closures effects on mobile source emissions. Chapter II provides a brief summary of efforts to identify other nonattainment areas adopting or considering construction restrictions to mitigate air quality problems. A critical review of modeling steps used by and documentation provided by TNRCC is documented in Chapter III. An extension of empirical heavy-highway construction site emissions to nonattainment areas is described and contrasted in Chapter IV. Chapter V details research that estimated both project cost and schedule impacts to TxDOT contracts as a result of the construction restrictions. Alternative control measures and their effectiveness are described in Chapter VI, with comparisons of their costs to those estimated as a result of the construction restrictions. Chapter VII presents work to identify the emission impacts from general traffic passing through work zone lane closures using the QUEWZ-98 (Queue and User Cost Evaluation of Work Zones) model and a customized emission workbook supported by MOBILE5a emission rates. Final conclusions are outlined in Chapter VIII and are followed by recommendations in Chapter IX. A series of appendices accompany this report and are referenced throughout this document.

CHAPTER II. REVIEW OF CONSTRUCTION EQUIPMENT CONTROLS IN OTHER STATES' SIPS

INTRODUCTION

The objective of this review was to assess other states' efforts to reduce ozone precursors through controls directed at construction activities. Researchers contacted state environmental agencies and departments of transportation (DOTs) to determine if emission controls for construction activities are proposed or currently contained in their SIPs. No such controls were identified; however, had they been, detailed information regarding these controls would have been obtained, including copies of relevant parts of SIP documents.

RESEARCH STRATEGY / METHODOLOGY

It is very likely that few other states or urban areas are implementing similar measures. Attempting to identify rare events presents specific methodological challenges. Specifically, it is very difficult to determine with confidence whether there is really nothing available or it was simply not found. Consequently, a multi-level convergent research strategy was developed and implemented for this analysis.

The research strategy used for this review involved a three-tiered approach comprised of a top-down segment focused on the 10 EPA regions, a mid-level / technical segment focused on national EPA technical staff whose responsibilities include construction / nonroad SIP emissions programs, and a bottom-up segment focused on implementation agencies and industry associations. This research strategy ensured contact with every agency likely to be involved with SIP construction restrictions at any level.

RESULTS

Convergence in this context means multiple negatives (i.e., findings of no construction restriction programs). This strategy ensures that any SIP-related construction restriction programs will be identified. Conversely, multiple negatives under this convergent strategy provide reasonable confidence that there are, in fact, no such programs in those areas. Each element of this strategy is discussed separately below.

Top-Down

Researchers interviewed regional EPA staff responsible for SIP review and analysis relating to existing or proposed SIP construction restrictions. All 10 EPA regions were contacted. No existing or proposed SIP construction restrictions were identified (other than the two here in Texas).

Mid-Level / Technical

National EPA technical staff with functional responsibilities relating to this aspect of SIP review and emissions monitoring are located in the Office of Transportation Air Quality (OTAQ) in Ann Arbor, Michigan. Researchers interviewed several OTAQ staff regarding SIP-related construction restrictions. No restrictions were identified.

Bottom-Up

Agencies directly impacted or involved in the implementation of SIP-related construction restrictions were also contacted. These included state DOTs (focusing on those states with extreme, severe, and serious nonattainment classifications) and construction industry trade associations (i.e., the Association of General Contractors or AGC).

Interviews with key AGC staff in Austin (with both state and national responsibilities) produced no SIP-related construction restriction programs, other than those in Dallas and Houston. This is particularly telling, since this organization is actively seeking precedents and experience to argue against such programs.

Similar efforts directed at selected state DOTs produced no examples of construction activity restriction SIP programs outside of Texas (though there were several examples of construction equipment upgrade incentive programs, such as the Carl Moyer program in California). Key DOT staff in California, Illinois, Massachusetts, New York, Pennsylvania, and Wisconsin were interviewed.

The Carl Moyer Memorial Air Quality Standards Attainment Program was created in 1999 by the California legislature to pay for the incremental cost of repower, retrofit, and purchase of cleaner engines that meet a specified cost-effectiveness level for NOx reduction. The $50 million fund has significantly reduced NOx and particulate matter (PM) emissions from heavy-duty vehicles and equipment traditionally powered by diesel engines. With the first year's funding, the Carl Moyer Program reduced NOx emissions by approximately four tpd and reduced PM emissions statewide by approximately 100 pounds per day. The types of projects being funded include: purchase of new natural gas transit and school buses; purchase of new natural gas and dual-fuel trucks; purchase of electric forklifts instead of internal combustion forklifts; and replacement of old diesel engines with newer diesel engines in marine vessels, agricultural pumps, and other off-road equipment. For more information see http://arbis.arb.ca.gov/msprog/moyer/moyer.htm.

CONCLUSION

The project used a three-tiered approach to find proposed or adopted SIP controls on construction equipment use. No SIP-related construction restriction programs were identified outside of Texas, either currently in place or proposed. Several construction upgrade incentive programs were identified, as were a few project-specific construction restrictions (e.g., the Boston tunnel project). The project-specific construction restrictions were all very limited in scope and application, were typically justified on the basis of traffic impact rather than air quality, and most importantly, were not part of a SIP program. Construction equipment upgrade incentive programs, like the Carl Moyer Program, may provide contractors with a means to develop exemption plans while sharing the cost with the state.

CHAPTER III. REVIEW OF TNRCC MODELING PROCESS FOR CONSTRUCTION SECTOR EMISSIONS

INTRODUCTION

Researchers performed a detailed and critical review of the regulatory analysis and modeling process for establishing fleet inventory and emissions from the construction sector. The focus of the review was directed at estimates for the heavy-highway sector. This sector covers work performed by and for TxDOT as it relates to the construction of transportation facilities.

RESEARCH STRATEGY / METHODOLOGY

Researchers contacted and interviewed several staff members of TNRCC regarding the processes used to develop and estimate construction equipment emissions. A top-down approach was taken. The interview process began at the photochemical modeling level, advanced to the emission inventory input development, and was followed by the nonroad mobile source inventory development specifically targeting the construction equipment sector. The interviews were supplemented with an extensive review of several publicly available TNRCC documents detailing the development and application of locally developed construction equipment inventories and associated emission estimates.

RESULTS

The results of the work on these tasks are presented in two sections. A summary of the interview findings with TNRCC staff is provided, followed by a critique of TNRCC modeling methodology.

TNRCC Staff Interviews

During July 2000, researchers interviewed several TNRCC staff in the Office of Environmental Policy, Analysis, and Assessment's Technical Analysis Division by both telephone and personal interview methods. Interviews were first conducted at the broad photochemical modeling level and progressed toward the focused development of the construction equipment inventories and activities, in a top-down approach.

Photochemical Modeling

At the photochemical modeling level of analysis,[10] the emission effects of the heavy-highway construction sector cannot be determined. This complex model, combining gross emission inventories (tons) and source locations with meteorology, is not able to distinguish between

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[10] Telephone interview with Mr. Pete Breitenbach, TNRCC. July 10, 2000.

specific groups of sub-sources. Interestingly, the nonroad emissions source is typically treated as an area source.

The photochemical model is used to strictly replicate the day and hour of model events. Model event dates for DFW are June 21-22, 1995 (plus two "ramp-up" days), and July 3, 1996 (plus three "ramp-up" days). Model event dates for HG are September 8-11, 1993 (plus two "ramp-up" days).

Emission Inventory Compilation

The emission inventory group[11] prepares the inputs for the photochemical model. At this point in the process, the emission inventory group compiles all of the sources into their respective classes and distributes them within the grid system of the photochemical model. Only the total construction sector emissions were provided to this group. Therefore, this group could not differentiate between the sources of the construction emissions.

The spatial allocation of emissions within the photochemical model is more of an art than a science. Construction emissions were generally allocated to land areas classified as industrial, residential, and commercial, from U.S. Geological Survey (USGS) data. Heavy-highway sector emission sources were distributed among the regional analysis zones (RAZs) from the travel demand model (TDM) and vehicle-miles traveled (VMT) projections. Within HG, this represented approximately 200 RAZs. The area of a RAZ can vary considerably and did pose some challenges to TNRCC staff. The RAZ was used to allocate heavy-highway sector emissions because the population, employment, and population growth data contained in the TDM is reliable. This process may undercount heavy-highway sector contributions from the rural areas. TNRCC documentation (*3*: Page 3-10) states "using 1993 surrogates for 2007 emissions may artificially concentrate the emissions into the former urban area, which can in turn affect the model's future ozone forecasts." The population, employment, and growth estimates for each RAZ from 2006-2008 were used to forecast the 2007 construction activity.

Once emissions were allocated, TNRCC staff and construction industry experts reviewed them. Upon review, the allocations were concluded to be reasonable. TNRCC staff made the observation that 70 percent of the construction activity in HG was located in Harris County. The location of heavy-highway sector emissions also appeared reasonable to TNRCC staff and outside experts.

At the time of the interviews, TNRCC staff did remark that the municipal and heavy-highway sectors represented 30 and 20 percent of the construction emissions, respectively. In later correspondence,[12] TNRCC staff indicated a modified distribution for HG, as shown in Table 1. Documentation related to the development of this distribution was not available.

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[11] Personal interview with Dr. Jim Smith, TNRCC. July 13, 2000.

[12] Personal correspondence from Mr. Jim McKay, TNRCC. October 6, 2000.

Table 1. Distribution of Construction Sector Contributions to Emissions Inventory.

Construction Sector	Contribution (%)
Heavy-Highway	11.5
Utility and Municipal	48.2
Residential and Commercial	33.5
Industrial	6.8
TOTAL	100.0

Construction Sector Emission Estimates

The construction portion of the nonroad emission inventory was developed in the Technical Analysis Division's Area and Mobile Emissions Assessment Section.[13] EPA's NONROAD model is used to determine emissions from off-road vehicles and equipment. TNRCC staff stated that the default construction equipment population numbers contained in NONROAD are inflated. NONROAD uses the variable 'number of employees' as a surrogate for equipment populations. Because Houston, Texas, is home to several large national and international headquarters, the office headquarters staff was artificially inflating the true population of equipment present and in use within the Houston area. In fact, TNRCC estimates that the defaults may have overestimated the Houston construction equipment population by as much as 2.3 times the locally collected inventory. Because of this concern, TNRCC awarded a contract to develop a local equipment inventory and emission estimate for HG to a consultant.

TNRCC staff expressed a high degree of confidence in the data taken from the heavy-highway sector in the consultant's work. The data from TxDOT were very reliable, and cooperation from their contractors was high. In fact, the consultant reported that this sector of the construction group had the highest survey penetration rate.

TNRCC staff also stated that locally developed load factors were used within NONROAD. These load factors represent the average percent use of full throttle on the equipment. The data were derived from transient operation research done through Southwest Research Institute's fuel consumption studies.

TNRCC staff did recognize the possibility that equipment might be used more aggressively once the rule is enforced than under normal operating conditions without the rule. However, the effect of this response on the emission inventory is not quantifiable.

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[13] Personal interview with Mr. Sam Wells, TNRCC. July 26, 2000.

General Comments

An alternative spatial distribution method for the heavy-highway sector would have been to distribute emissions into the photochemical model grid using historical TxDOT construction activity reports. These reports provide location and an indication, through both estimates of percent time completed and percent work, of the amount of activity at the site. For future years, the region's Metropolitan Transportation Plan (MTP) and Transportation Improvement Program (TIP) documents, and Metropolitan Planning Organization (MPO) staff could be consulted and reviewed for identifying active projects during the model years. These documents provide specific locations for construction activity but do not provide the anticipated level of activity. Equipment activity levels might be estimated or correlated to existing activity levels for similar construction projects.

Critique of TNRCC Construction Emissions Methodology

The comments provided in this section were generated during the review of Appendix V, *Improved Construction Inventory Documentation,* contained in the April 2000 Revision of the DFW Attainment Demonstration (2). Appendix V documents TNRCC's methods to improve the construction inventory for the HG nonattainment area and, by extrapolation, the four-county nonattainment area of DFW. A consultant was contracted by TNRCC to perform a construction equipment population and activity assessment in HG. Their report and other supporting documentation were included as part of Appendix V in support of the application of their results to DFW. Appendix V contains the following three documents:

- "Documentation for the Dallas Diesel Construction Emissions (DDCE) Project,"
- "Development of a Revised Emission Inventory for Construction Equipment in the Houston/Galveston Ozone Nonattainment Area – Draft Report," and
- "Dallas-Ft. Worth Area Construction Equipment Population Estimates."

After the initial review and comment of the documents cited above, the final report of the work performed for HG was received, which contained some corrections to comments previously identified by the researchers. The comments on the draft documentation are included in this report because that documentation remains the basis for the construction sector emission estimate within the DFW attainment documentation.

TNRCC's method for developing construction equipment population and activity data at the local level produces a lower inventory total than the defaults used in EPA's NONROAD model. TNRCC staff and the draft documentation (6) indicated that the NONROAD model overestimates construction equipment population and activity in the Houston area by more than 50 percent. This overestimation results in an inflated inventory for the construction sector and thus an inflated amount of emissions from the sector. Final documentation shows that default NONROAD NOx emissions were overstated by more than three times. TNRCC consultant's locally derived results represent a significant reduction in the construction sector's emission inventory from previous use of NONROAD default values. In proving an overestimate of default NONROAD construction equipment emissions, TNRCC's results are a valuable contribution to the study of state air quality issues.

Local construction equipment inventories and activity data were collected for eight sectors of the construction industry. These sectors included: heavy-highway, municipalities and counties, municipal/utility, commercial, residential, industrial, cranes, and rental. The heavy-highway sector includes TxDOT-related construction. Equipment population estimates by sector are provided in both the body text and summary tables of the document, but the documentation does not provide a breakdown of emissions by construction sector. Correspondence[14] with TNRCC personnel indicated that a breakdown of emissions by sector was not possible due to questions regarding the rental sector. However, TNRCC staff[15] did indicate relative contributions from several sectors.

The underlying work for both the DFW and HG nonattainment areas occurred only in HG. During review of the documents, comments were generated regarding the methodological development and application. The critique of the construction inventory method is subdivided by region: HG and DFW. The HG critique includes comments on both the draft and final reports.

Houston/Galveston Nonattainment Area

In estimating the equipment population for Houston, it appears that there was a shift in methodology during the project. The project began with a "bottom-up" survey method but ultimately relied on a "top-down" method that utilized local experts for residential and commercial categories. The reason behind the shift was the low response rate to the survey by the various private contractors in the sectors. No explanation is given in the reports (6, 7) as to the effect of the different methodologies on the overall analysis and allocation of emissions to the categories.

The draft report's Table 10 (6) includes several numerical errors. The most significant information contained in this table is the projected equipment population by sector. In the preceding discussion of each sector in that document, estimates of that sector's population are given. However, in this table, only two of the sectors display the same populations previously cited. The five remaining sectors in this table show populations less than those previously cited in the text. The sum of the individual sectors (17,303) in this table neither matches the printed total equipment population shown on that page (17,292), nor the sum of individual sectors from the text (17,774). Table 2 shows these differences.

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[14] Personal correspondence with Mr. Sam Wells, TNRCC. September 19, 2000.

[15] Personal correspondence from Mr. Jim McKay, TNRCC (October 6, 2000) and personal interview with Dr. Jim Smith, TNRCC (July 13, 2000).

Table 2. Reporting Errors for Draft HG Equipment Populations by Sector.

Sector	From Summary Table 10	Reported within Preceding Text
Rental	6536	6536
Municipal Contractor	3670	3885
Municipalities/Counties	1884	1911
Cranes [1]	1619	1619
Heavy-Highway	945	1001
Commercial	895	940
Industrial	268	396
TOTAL	17,303	17,774

Notes: [1] NONROAD model default, not local data

Discrepancies are also found in statements of the total equipment population in Houston between documents. Table 10 (6) shows a total equipment population of 17,292, whereas the "Dallas-Ft Worth Area Construction Equipment Population Estimates" paper (8) states the total Houston population as 16,400. No justification for this discrepancy is provided.

The final report reduced, but did not eliminate, numerical errors in the similar summary table (7: Table 12, Page 35). Two sectors, residential and commercial, did not match between the text and the summary table. Also in the final report's Table 12, the total population printed (16,250) matches neither the calculated sum of the printed sector populations from this table (16,247), nor the sum of the sector populations presented in the preceding text (16,179).

Allocation of equipment activity for heavy-highway construction is derived from three different sources in the reports (6, 7). Electronic clock hour data served as the basis for activity estimates for two of the respondents. Labor records were the basis for estimating hours of operation for two other respondents, and estimator/field operator estimates were the basis for the remainder of the sources. These are three different sources for a key variable affecting emissions estimates with no explanation given as to how the three measurements were reconciled in the final analysis. Across all sectors, activity data were collected for 68.4 percent of the surveyed equipment. NONROAD default values were used when activity estimates were not available for a particular equipment category; thus, a minimum of four different sources was used. No reconciliation of the effects of these differences among the data sources is evident in the reports (6, 7).

The base year for TNRCC model was not assessed in depth. Although the vast majority of those interviewed or surveyed by the consultant indicated that 1999 was a "boom year," the consultant assumed the year to be typical. Despite the qualitative nature of the responses, historical construction data could have more clearly indicated the normality of the base year. Using "boom year" activity data represents a conservative approach because it relies on higher equipment activity and, hence, more emissions generated.

The consultant collected equipment population and activity data on diesel engines greater than 25 hp. However, the rule places restrictions only on equipment greater than 50 hp. This point has no effect on the process results but does demonstrate the comprehensive nature of the consultant's work.

Dallas/Fort Worth Nonattainment Area

The construction sector emission estimates developed for DFW are based on the draft report (6) and do not reflect the lower populations presented in the HG final report (7). There is no indication that the DFW estimates were updated.

TNRCC model begins to show weakness as it is extrapolated to DFW. The assumptions behind the equipment population estimates are not documented and do not reflect the computations described in the report. The activity data do not reflect the documentation in the report and have no explanation as to why the activity numbers between the nonattainment areas are different. The total fleet scaling factor derived from the sector scaling factors is not mathematically sound.

In several sections of Appendix V (2), which discusses the DFW equipment populations and activities, the text of the report leads the reader to believe that an intensive inventory and activity survey was performed in the Dallas/Fort Worth, Texas, area. This is not the case. All estimates generated for DFW were derived from data collected in the Houston/Galveston, Texas, area. These base data were then factored, using surrogate values, to represent DFW.

Appendix V (2) shows equipment population numbers that were not verified and do not match the assumptions provided in the supporting reports. Using the equipment population scaling factors documented for each sector and the total fleet, there appears to be a discrepancy with the reported total DFW population number. Summing the individual sector equipment populations for DFW in the text of the "Dallas-Ft. Worth Area Construction Equipment Population Estimates" paper (8), a total of 17,117 pieces of equipment are estimated in DFW. In contrast, the same paper states (8) that the total DFW fleet number is 19,698. This latter population figure is derived simply by applying the total fleet scaling factor (1.20) to the HG equipment population (16,400, contained in the document's text). No explanation accompanied this discrepancy.

The method for generating activity data for DFW shown in Appendix V's Table 1 (2) is neither explained nor documented. Where activity data are concerned, early wording in Appendix V implies that surveys were conducted in DFW, but the "Dallas-Ft. Worth Area Construction Equipment Population Estimates" paper (8) indicates that time constraints prevented the researchers from gathering local data. Furthermore, the "Dallas-Ft. Worth Area Construction Equipment Population Estimates" paper (8) states that the activity data for HG were not modified for DFW, yet several of the numbers are different in the DFW activity table contained in Appendix V. Table 3 below shows the differences between the two nonattainment areas. Of 20 equipment categories, eight show activity levels equal to HG; nine are higher; and three are lower. No explanation for deriving these different numbers is given. As an example, the drill rig activity for HG is 513 hours, while in DFW the number of hours given is 1548. No explanation is given as to why there is three times as much activity for drill rigs in DFW. No other equipment category shows a three-fold increase in activity, and this increase is not explained in terms of a dramatic increase in the amount of construction in DFW. In fact, the heavy-highway sector expert used by the consultant stated that equipment activity levels per mile of highway between HG and DFW are "essentially identical."

Table 3. Differences in Modified Activity Data for DFW and HG Nonattainment Areas.

Source	Modified Activity Data, Hours per Year			% Difference
	DFW	HG Draft	HG Final	(DFW to HG Draft)
Pavers	672	709	719	-5
Rollers	533	549	556	-3
Scrapers	455	455	462	0
Paving Equipment	344	344	344	0
Surfacing Equipment	708	573	575	24
Signal Boards	528	528	532	0
Trenchers	897	601	603	49
Drill Rig	1548	513	513	202
Excavator	833	764	777	9
Concrete Saws	508	508	510	0
Motor Graders	750	717	732	5
Off-Highway Trucks	1257	1257	1257	0
Rough Terrain Forklifts	1041	1041	1033	0
Rubber Tire Loaders	1068	858	872	24
Tractor/Dozer	466	466	469	0
Backhoes	745	765	781	-3
Crawler Tractor	839	819	829	2
Skid Steer Loader	851	844	845	1
Off-Highway Tractor	853	853	853	0
Other Construction Equip.	536	516	N/A	4

HG results for the heavy-highway sector were extrapolated to DFW based on labor cost differences. The extrapolation to DFW lacked the benefit of diverse professional experience in estimating equipment populations of the heavy-highway sector. In generating the heavy-highway sector-scaling factor, the methodology relied on the professional judgment of only one sector expert. This expert stated an increased labor cost for DFW, which was then used to adjust the scaling factor surrogates (TxDOT FY 99 letting totals) holding material costs steady. This expert also provided the assumption that 85 percent of the total letting was non-labor cost.

The report (8) states that the Dallas heavy-highway construction fleet has a scaling factor of 0.722 from HG data. The draft documentation, from which DFW population estimates were derived, shows HG heavy-highway equipment populations of 1001 and 945, within the text (6) and summary table respectively (6: Table 10). Applying the scaling factor to both of these reported populations yields estimates for DFW as 723 and 682, respectively, yet the "Dallas-Ft

Worth Area Construction Equipment Population Estimates" paper (8) states a DFW heavy-highway equipment population of approximately 610 pieces. After further analysis, it appeared that the final population estimate for heavy-highway (845) was the basis for the 610 pieces in DFW. However, additional checks within the other sectors did not show that the final HG populations were used. There are similar problems with the following sectors: municipalities and counties (1700 reported vs. 1740 calculated from draft vs. 1345 calculated from final), commercial (464 reported vs. 1556 calculated from draft vs. 1722 calculated from final), residential (1273 reported vs. 1670 calculated from draft vs. 1635 calculated from final), and rental (8166 reported vs. 9033 calculated from draft vs. 8214 calculated from final). The municipal/utility contractor populations were not significantly different from one another. No justification is provided in the text regarding the source of this discrepancy for any of the sectors.

The total fleet scaling factor derived from the categories in Table 1 of the "Dallas-Ft. Worth Area Construction Equipment Population Estimates" paper (8) is not a weighted average. The total fleet scaling factor is a simple arithmetic mean of six of seven construction sectors for which scaling factors were developed. Three of these sector-scaling factors were developed using fiscal data; one was developed from human population, and the last was developed from permit/completion data. The industrial sector was computed at 0 and was not used in the computation. A weighted average by sector might result in a more accurate activity factor.

No estimate was made for the industrial sector in DFW because there are "no significant chemical/petrochemical or other related facilities" (8). Limiting the industrial sector to these specific industries excludes any possible contributions from other industries, such as manufacturing (e.g., General Motors, Trinity Industries, and Bell Helicopter).

General Comments

If the current form of TNRCC methodology cannot allocate total percentage of emissions by construction sector, then it does not provide a useful method for estimating the amount of emissions by highway construction. In a sense, no strong conclusions regarding highway construction emissions can be drawn. Coupled with the mathematical errors and lack of justification or explanation in some areas of the documentation, the methodological results are not as strong as they could be because of doubts that may arise. Policy recommendations for heavy-highway construction derived from this model are not based on the strongest foundation possible.

The attempt by TNRCC to estimate the role of construction activity was successful in showing that NONROAD overestimates default values for statewide activity by 50 percent. The methodologies created for TNRCC are a good first attempt at formulating a process to derive locally representative data for policymakers to use. However, the methodology contains severe limitations for extrapolation to other areas in the state. It is to their credit that the authors of the report acknowledge and identify some of these limitations.

CONCLUSIONS

The development of sector emissions through to the photochemical modeling is as much art as it is science. Numerous assumptions must be made to generate and distribute emission sources and determine the impacts or effectiveness of proposed control strategies. The methodology framework used by TNRCC staff to estimate construction emissions seems appropriate, though suggested improvements to the spatial allocation of heavy-highway sector emissions are made in this report.

Within the constraints of time and funding, TNRCC's consultant produced a viable method for estimating equipment populations and associated activity at the local level. The resulting efforts document that the default NONROAD values for statewide population and activity produce an emissions overestimation greater than three times that developed. Review disclosed many discrepancies within the consultant's documentation included in the DFW Attainment Demonstration documentation. These discrepancies included arithmetic errors, lack of justification, and the questionable extension of data to another geographic region without validation. The existence of these numerous discrepancies may undermine the public credibility of the methods and results. Many, but not all, of the discrepancies were corrected in the final report. It is questionable to develop corrective measures for a region based on draft documentation produced for another region and not updated when that documentation is finalized.

The estimated local equipment populations and activity results should only be used to develop policy in HG. The surrogates and assumptions used in Houston cannot be applied to DFW without some degree of validation. Validation of even one sector would have assessed the accuracy of scaling data from HG to DFW.

Furthermore, the application of surrogate measures to estimate DFW equipment populations and activity is questionable. As discussed previously, the total fleet scaling factor was computed as a simple arithmetic mean and was not weighted by each sector's influence. In addition, no justification or documentation was provided to explain why equipment activity levels in DFW were different from those in HG, even though statements in the text indicated the activity levels between the two regions did not change.

CHAPTER IV. ESTIMATION OF CONSTRUCTION SECTOR EMISSIONS USING EMPIRICAL HEAVY-HIGHWAY CONSTRUCTION SITE EMISSION DATA

INTRODUCTION

An evaluation of TNRCC construction sector emission estimates was needed to determine if they appeared appropriate. Because TNRCC did not disaggregate diesel construction equipment emissions by sector, and base data collected by their consultant were not available, researchers could not perform a detailed analysis of heavy-highway equipment inventories and activities to TxDOT operations. Instead, an alternative method using empirical data from TxDOT construction sites was used to estimate both the heavy-highway sector emissions and total construction sector emissions for the HG and DFW nonattainment areas.

RESEARCH STRATEGY / METHODOLOGY

TxDOT construction activity information for FY 2000 was collected from the Dallas, Fort Worth, Beaumont, and Houston Districts' construction engineering staffs. This activity information (divided into major and minor construction projects) was then used with adjusted construction site emission factors developed through previous research on Project 0-1745, "Air Quality Impacts of Highway Construction and Scheduling." The adjusted construction site emission factors were derived by excluding contribution from the gasoline-fueled construction equipment inventoried and observed at the construction sites.

The heavy-highway emission estimates for both the HG and DFW nonattainment areas were factored to estimate total construction sector emissions. These estimates were then compared to data – reported and interpolated – based on TNRCC modeled results.

Major projects are those considered to be multi-year, multi-million dollar contracts that have a large impact on corridor/site traffic. Minor projects are more short-term projects that may include maintenance or small construction projects. TxDOT contracts excluded traffic signal work and street landscaping work. Both types of work were considered very minor in terms of equipment use and were not considered significant.

Empirical Heavy-Highway Construction Equipment Inventory and Activity Data

Crawford (9) collected empirical heavy-highway construction equipment inventory and activity data at five locations in Dallas and Tarrant Counties. He inventoried both gasoline- and diesel-fueled equipment and categorized construction sites as either major or minor. Major projects are the multi-year, multi-million dollar projects. Minor projects are much less intensive, with project durations less than one year. Four of the locations were major projects.[16] One minor project[17] was monitored in Tarrant County.

The emissions estimation method assumed that the inventoried equipment is operated at 100 percent throttle. In reality, a piece of equipment is not constantly operated at 100 percent throttle while it is running. There may be significant periods of time when the equipment operates in either an idle or transient mode. This assumption may result in a conservative estimate of emissions produced by the equipment at the site without consideration of transient operations. The effect of transient modes on emission production may cause increased emissions rates, as has been proven in motor vehicles.

Emission factors from EPA's AP-42 guidance document were used to generate emissions for each construction equipment classification at each site. These were then summed to yield a total construction equipment emission production for each observed site.

The equipment inventories used to develop site emission factors may include equipment <25 hp. Eastern Research Group, Inc. (ERG) reports (*6*) that diesel engines <25 hp emit less than 1 percent of the total NOx emissions for the construction sector.

Development of Empirical Construction Site Emission Factors from Site Activity

The researchers had direct access to the site equipment inventory and activity data previously collected. For this project, site NOx emission rates for diesel-fueled equipment were extracted from the study equipment inventory. Table 4 shows the site-wide emission rates for the diesel-only equipment. It is important to note that the highest observed value within the major project classification was the southernmost section of the US 75 (North Central Expressway) reconstruction. Researchers observed the most intense construction equipment activity at this site.

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[16] Two segments of US 75 (North Central Expressway) reconstruction, I-820/SH 183 interchange reconstruction, and I-30/I-35W interchange reconstruction.

[4] Overlay project on FM 156.

Table 4. Daily Site-wide NOx Emission Rates for Diesel-Fueled Construction Equipment Generated from Results of TxDOT Research Project 0-1745.

Project Classification	NOx Emissions (lbs/day)	Range (lbs/day)	Average (lbs/day)
Major	235	235 - 88	135
Major	112		
Major	106		
Major	88		
Minor	103	n/a	n/a

TxDOT Contract Activity Data

Dallas/Fort Worth Nonattainment Area

TxDOT's highway construction activity data were taken for 2000 from personal conversations with Fort Worth and Dallas District staff in the construction engineer's offices. They were asked to provide an estimate of the daily average number of projects fitting either the major or minor site category criteria. Table 5 summarizes the information obtained from these sources.

Table 5. 2000 Ozone Weekday Activity Estimates Provided by TxDOT for DFW.

Area	2000 Activity Classification		Total
	Major	Minor	
Dallas District			
Dallas County	35	13	48
Denton County	13	9	22
Collin County	11	6	17
Fort Worth District			
Tarrant County	10	14	24
Total Nonattainment Area	69	42	111

These activity estimates differ from those obtained in 1997, during work on TxDOT Research Project 0-1745. Strikingly different are the minor activity estimates. At that time, the estimate shown in Table 6 was provided. The number of major projects in 2000 for Dallas and Tarrant Counties is relatively close to those estimates provided by TxDOT in 1997. However, the 1997 estimate of minor projects is 2.8 times greater than the most current estimate provided by TxDOT. Using this factor, the total number of nonattainment area minor projects in 2000 was adjusted upward to yield 117 minor projects. Correcting this activity estimate should result in a more conservative estimate.

Table 6. 1997 Ozone Weekday Activity Estimates Provided by TxDOT for Dallas and Tarrant Counties.

County	Project Classification	
	Major	Minor
Dallas	33	35
Tarrant	8	40
TOTAL	41	75

Houston/Galveston Nonattainment Area

Researchers estimated the 1993 and 2000 HG construction activity from detailed historical data reports received from the Beaumont and Houston Districts. These data, summarized into the two activity classifications, are shown in Tables 7 and 8. The reported totals for 2000 are close to that from DFW; however, DFW reported more major projects and fewer minor projects than HG. As reported, construction activity in the nonattainment area decreased from 1993 to 2000.

Table 7. 1993 Reported Ozone Weekday Activity Estimates Provided by TxDOT for HG.

Area	1993 Activity Classification		Total
	Major	Minor	
Beaumont District			
Chambers County	1	1	2
Liberty County	2	0	2
Houston District			
Brazoria County	1	0	1
Fort Bend County	2	6	8
Galveston County	1	20	21
Harris County	39	56	95
Montgomery County	8	11	19
Waller County	4	7	11
Total Nonattainment Area	58	101	159

Table 8. 2000 Reported Ozone Weekday Activity Estimates Provided by TxDOT for HG.

Area	2000 Activity Classification		Total
	Major	Minor	
Beaumont District			
Chambers County	0	1	1
Liberty County	1	1	2
Houston District			
Brazoria County	0	8	8
Fort Bend County	4	11	15
Galveston County	6	9	15
Harris County	26	25	51
Montgomery County	5	12	17
Waller County	0	1	1
Total Nonattainment Area	42	68	110

RESULTS

Dallas/Fort Worth Nonattainment Area

Applying the average and maximum site emission factors shown in Table 4 to the most recent activity data acquired by TxDOT districts resulted in an estimate of construction equipment emissions generated from TxDOT contracted work within DFW. The unadjusted estimate for the nonattainment area, shown in Table 9, is 7 tpd to 10 tpd.

Table 9. Estimated 2000 NOx Emissions (tpd) for Reported TxDOT Contracted Work in DFW.

Method	Major	Minor	Total
Average value (tpd)	4.7	2.2	6.8
Maximum value (tpd)	8.1	2.2	10.3

Using the upwardly adjusted number of minor projects, a new estimate for the nonattainment area was made. Table 10 displays the results. The adjustment increased the total minor project emissions by 3.8 tpd. The total TxDOT estimated emissions in the nonattainment area are 11 to 14 tpd.

Table 10. Estimated 2000 NOx Emissions (tpd) for Adjusted TxDOT Contracted Work in DFW.

Method	Major	Minor	Total
Average value (tpd)	4.7	6.0	10.7
Maximum value (tpd)	8.1	6.0	14.1

In the DFW Attainment Demonstration document's Appendix V, TNRCC presents their estimates of NOx emissions for the improved construction inventory and activity data. This table is reproduced below as Table 11.

Table 11. TNRCC NOx Construction Sector Emissions, Tons per Ozone Season Weekday.

Scenario	Default NONROAD	Updated NONROAD
1995 Base Case	133.26	49.55
1996 NONROAD Run	135.66	50.33
2007 Attainment Inventory	120.52	44.98

Source: (*1*)

The estimates provided in Table 9 can be expanded to represent the DFW construction sector using TNRCC heavy-highway distribution values previously stated for HG.[18] Applying this distribution (11.5 percent) to the average value method result (10.7 tpd), the construction sector NOx inventory is estimated to be 96 tpd for adjusted construction activity and 61 tpd for unadjusted construction activity. Table 11 compares the results from TNRCC to the empirical-based estimate. Both of the empirically based estimates are considerably higher compared to those construction sector inventory values published by TNRCC. Construction sector emission estimates from empirically based data were 25 to 100 percent greater than estimates generated by TNRCC.

Table 12. Comparison of DFW Construction Sector Emission Estimates.

Model Year	TNRCC Estimate (tpd)	TTI Estimate			
		Adjusted		Unadjusted	
		tpd	% Diff.	tpd	% Diff.
1996	50.33 [1]				
2000	48.4 [2]	95.6	97.5	60.8	25.6
2007	44.98 [3]				

Notes: [1] TNRCC updated NONROAD run
[2] Interpolated
[3] TNRCC attainment inventory value from updated NONROAD

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[18] Personal correspondence from Mr. Jim McKay, TNRCC (October 6, 2000) and personal interview with Dr. Jim Smith, TNRCC (July 13, 2000).

Houston/Galveston Nonattainment Area

Highway construction emissions within HG were estimated for 1993 and 2000 using local activity information previously presented with site-emission rates developed in DFW. Heavy-highway construction activity is assumed to be consistent between major metropolitan regions. Tables 13 and 14 present the results.

Table 13. Estimated 1993 NOx Emissions (tpd) for Reported TxDOT Contracted Work in HG.

Method	Major	Minor	Total
Average value (tpd)	3.9	5.2	9.1
Maximum value (tpd)	6.8	5.2	12.0

Table 14. Estimated 2000 NOx Emissions (tpd) for Reported TxDOT Contracted Work in HG.

Method	Major	Minor	Total
Average value (tpd)	2.8	3.5	6.3
Maximum value (tpd)	4.9	3.5	8.4

Linear interpolation of the construction NOx inventory (*3*) between 1993 (42.4 tpd) and 2007 (32.1 tpd) yields an estimated 35.8 tpd in 2000. An estimate of the heavy-highway construction sector's part of this total is 4.1 tpd (35.8 tpd x 11.5 percent). Table 15 presents a comparison of predicted heavy-highway sector emissions from TNRCC estimates to those estimates made in this report. As with DFW, the empirically based estimates are consistently greater than estimates produced by TNRCC. Table 16 presents estimates and reported values for the construction sector as a whole. Construction sector estimates with empirically based data were 50 to 90 percent greater than estimates generated by TNRCC.

Table 15. Comparison of Predicted Heavy-Highway Sector Daily Emissions in HG.

Year	Tons per Day		
	Construction NOx Inventory (*3*)	Predicted Heavy-Highway Sector Portion [2]	Empirically Based Estimated Heavy-Highway Sector Portion
1993	42.4	4.9	9.1
2000	35.8 [1]	4.1	6.3
2007	32.1	3.7	n/a

Notes: [1] Interpolated inventory value assuming linear relationship.

[2] The heavy-highway sector represents 11.5 percent of the construction sector per TNRCC comments.

Table 16. Comparison of Construction Sector NOx Inventory in HG.

Year	TNRCC Reported (*3*) (tpd)	Empirically Based Construction Sector Estimate	
		tpd	**% Diff.**
1993	42.4	79.1	86.6
2000	35.8 [1]	54.8	53.1
2007	32.1	n/a	n/a

Notes: [1] Interpolated inventory value assuming linear relationship.

General Comments

Extension of the empirical construction site activity and emission data previously collected for TxDOT Research Project 0-1745 shows a tendency to grossly overestimate heavy-highway sector and construction NOx inventory values produced by TNRCC. The application of the empirical data may provide TxDOT with a sketch-planning tool with which to estimate regional construction emissions without the use of regional surrogates, as developed for DFW, or locally developed data, as developed for HG.

TNRCC methodology critiqued in the previous chapter has several advantages through the use of the draft NONROAD model provided by EPA over the use of empirical construction site-wide emission data demonstrated here. The NONROAD model is able to account for impacts from fleet turnover and future year growth. The use of the empirical data results in a static emission rate that cannot reflect lower emission rates due to newer and cleaner equipment, cleaner fuels, or aftermarket emission control devices.

CONCLUSIONS

The use of empirical data as a sketch-planning tool will very conservatively approximate the heavy-highway emission contribution to the construction sector. However, locally derived inventories and activity data should provide a greater degree of accuracy in the emission estimate. Also, the use of the NONROAD model for future years provides analysis techniques for fleet turnover and other effects not reflected in the empirical data. More refined empirical data by specific construction activity might provide a higher level of confidence in future approximations.

CHAPTER V. POTENTIAL REGULATORY IMPACTS TO TXDOT CONSTRUCTION PROJECT SCHEDULES AND COSTS

INTRODUCTION

Reconstruction and rehabilitation activities can result in traffic congestion, increased queues, and longer delays. Materials and equipment used during the construction of these activities may negatively impact air quality, especially during hotter summer months when atmospheric conditions lead to the formation of high ozone levels (*10*). This chapter will focus on quantifying the potential cost and schedule impacts from TNRCC's construction equipment restriction rule on construction projects under TxDOT's jurisdiction.

To forecast the potential cost and schedule impacts due to this rule, researchers developed and distributed a survey to TxDOT area engineers and to construction contractors who perform a majority of TxDOT construction in HG and DFW. The survey was based on possible work schedules alternatives (WSAs) that contractors could adopt to effectively comply with the new restrictions and five distinct project types that exemplify typical TxDOT highway construction projects.

Objectives

This research effort focused on meeting the following objectives as they pertain to HG and DFW:

- Develop a methodology for study that would make use of the experience and expertise available in the industry.
- Identify alternative daily construction work schedules that contractors may implement for projects performed in the ozone nonattainment areas as a consequence of the rule.
- Identify key elements that could affect cost and project duration due to the implementation of construction equipment restrictions by TNRCC.
- Determine the potential cost and schedule impacts to highway construction operations for TxDOT projects in HG and DFW, based on the implementation of alternative daily work schedules.
- Generate base data as a function of project type, metropolitan area, and alternative work schedules.

In addition to initial objectives, the outcome of the research could help TxDOT in understanding the potential new work schedules that the contractors may adopt to comply with the regulations, which may assist in future cost estimating and work planning.

Current Construction Practices in Texas

Methods and practices for the heavy construction industry are laden with the use of diesel-powered equipment. The industry relies on the use of heavy equipment as a necessary means to be productive in the large-scale nature of highway construction. Diesel equipment rated above 50 hp can be found in almost all operations associated with the repair, rehabilitation, reconstruction, and construction of the state's roadway system. Additionally, tasks that are labor-intensive often require the use of heavy equipment for support of their operations.

A large amount of highway construction is conducted during the summer months during extended hours of daylight and under favorable temperature and weather conditions. In Texas, daily highway construction operations typically begin at dawn, around 6:00 a.m. to 8:00 a.m., and continue throughout the day until the late afternoon. The length of daily operations vary depending on many factors, including the phase of the project, weather conditions, traffic, and the amount of daylight available, but normally last for approximately 10 to 12 hours. Night work is common to many TxDOT projects and its construction contractors. Portions of projects, especially those centered in the metropolitan areas, are often conducted at night. Concreting operations are frequently conducted at night or at pre-dawn hours due to the restrictions imposed when placing concrete in high temperatures. However, the overall amount of work conducted at night is a small fraction of that conducted during the daylight hours.

RESEARCH STRATEGY / METHODOLOGY

Methodology Approach

To determine the cost and schedule impact due to TNRCC's rule, researchers considered various approaches. The research team investigated the use of existing cost estimating tools to estimate cost and schedule impacts resulting from the rule. These tools were unable to reflect and quantify the anticipated shifts in the work schedule brought upon by the restricted use of heavy equipment. The research team also considered utilizing the vast line item cost database maintained by TxDOT. But it was found that average low bid unit prices were not indicative of actual installation costs and that line item costs did not separate labor, material, equipment, and overhead costs.

In light of these concerns and the lack of usable historical data, the research team adopted a survey approach to determine the potential cost and schedule impacts from TNRCC's rule. The research team developed five general project types that covered the majority of the projects performed by TxDOT and identified four potential WSAs. A survey document describing these project types and WSAs was prepared and used to gather potential cost and schedule impacts from construction contractors who performed work in the affected areas and TxDOT personnel who let and oversee such work. Conducting interviews and gathering survey data from these parties could reflect the potential cost and schedule impacts resulting from the rule.

Classification of Project Types and Work Schedule Alternatives

Funding and Work Categories

Determining how to categorize the construction work that represents projects within TxDOT was the initial step to develop the survey. Researchers needed survey and interview data collected from contractors and TxDOT area engineers to determine the overall cost and schedule impact to TxDOT. Though TxDOT projects are normally categorized by funding source, each project also maintains a primary project classification. Researchers used this classification to denote the overall type of work.

TxDOT uses 27 different project categories to designate the type of work. Collecting data on each of the 27 different categories was beyond the scope of this project. However, it was evident that a majority of the funding and work conducted by TxDOT fell into a relatively small scope of project types. A majority of the funding and work was allocated to major highway and bridge construction and reconstruction. Therefore, an effort was made to focus on these types of projects in the surveys. The research team selected five separate project types (from the appropriate TxDOT classifications) to form the basis for the survey. These project types are shown in Table 17 and further discussed in the following section.

Table 17. Project Types and Percent Distribution of Funds for Each Project Type.

Project Types	Project Categories	% of Funds	
		HG	DFW
Freeway Reconstruction and Widening	Convert non-freeway to freeway	34.0	23.0
	Widen freeway		
	Portion: Bridge widening or rehabilitation		
	Upgrade to standard freeway		
Non-Freeway Reconstruction and Widening	Widen non-freeway	20.2	23.9
	Portion: Bridge widening or rehabilitation		
	Upgrade to standard non-freeway		
New Construction	New location freeway	10.3	21.0
	New location non-freeway		
	Interchange (new or reconstructed)		
Bridge Replacement	Bridge replacement	4.3	6.1
Rehabilitation and Overlay	Seal coat	25.8	23.0
	Overlay		
	Restoration		
	Rehabilitation of existing road		
	Miscellaneous construction		
Other: Safety/Traffic Control Environmental Others	Safety rest areas	5.4	3.0
	Traffic signal		
	Hazard elimination and safety		
	Corridor traffic management		
	Grade crossing protection		
	Traffic protection devices		
	Landscape and scenic enhancement		
	Junkyard control		
	Utility adjustment		
	Outdoor advertisement		
	Ferry boat		
	Tunnel construction		
	Railroad relocation		
	Remove hazardous paint		
Total		100.0	100.0

The distribution of funds data are based on information provided by TxDOT in the form of project costs for years 1997, 1998, 1999, and 2000. The numbers are based on the funds allocated to the Houston and Beaumont Districts for HG, and to the Dallas and Fort Worth Districts for DFW.

The five project types used for the impact evaluation are:

1. freeway reconstruction and widening;
2. non-freeway reconstruction and widening;
3. new construction;
4. bridge replacement; and
5. rehabilitation and overlay.

These project types represent 94.6 percent of the total funding allocated by TxDOT for highway construction projects in HG and 97 percent in DFW. For the purpose of analysis, researchers considered only these five project types; and the funding for these project types was assumed to be 100 percent.

Standard TxDOT Project Types

TNRCC restrictions on heavy equipment operations can have varying impacts on the cost and schedule of projects, depending on the unique characteristics associated with each TxDOT project. Projects differ in many aspects, including physical attributes (such as the number and type of bridge overpasses), amount of traffic, frequency of lane closures, the type and use of heavy equipment, construction methods, and materials. To best capture the potential effects of the equipment restrictions on varying types of work, the five representative project types were defined and provided to all survey participants. From a variety of existing TxDOT projects and through feedback from TxDOT representatives, the research team developed the following project types and their corresponding definitions and characteristics. These project types represent a majority of the construction projects conducted in HG and DFW.

Freeway Reconstruction and Widening. This project type is defined as freeway reconstruction projects that exceed $20 million. These projects involve heavy traffic (100,000 vehicles/day) and consist of typical continuous reinforced concrete pavement, 2 to 4 miles in length, with a three-span overpass every 0.75 mile.

Non-Freeway Reconstruction and Widening. This project type is defined as non-freeway reconstruction projects that range from $10 to $20 million. These projects involve moderate to heavy traffic volumes (15,000 - 20,000 vehicles/day) and consist of typical continuous reinforced concrete pavement. This project type is defined as converting a two-lane road into a five-lane road with a center left-turn lane. This project type also includes one three-span structure.

New Construction. This project type is defined as new construction projects that also range from \$10 - \$20 million. These projects involve virtually no traffic and consist of typical continuous reinforced concrete pavement, approximately 5 to 6 miles in length, with five lanes including a center left-turn lane. This project type also includes one three-span structure.

Bridge Replacement. This category is defined as a simple bridge replacement project valued at approximately \$500,000. These projects involve relatively low traffic volume (1000-1500 vehicles/day) and consist of concrete I-beam construction with a 150-foot, three-span bridge with asphalt tapers. The project scope is further defined as having a 45-foot width, two lanes and two shoulders with a roadway consisting of transitions and minimum embankment widening.

Rehabilitation and Overlay. The final project type consists of rehabilitating and overlaying a typical road with asphaltic concrete. Since traffic can vary immensely between urban and rural areas, the project type was broken into sub-project types: traffic with less than 30,000 vehicles/day (rural) and traffic with more than 100,000 vehicles/day (urban). The scope of the project included a five-lane road with a length of 5 miles. Work includes full depth repair with asphalt-stabilized base and a 2-inch asphalt surface overlay.

Work Schedule Alternatives

To better anticipate the effects of TNRCC's rule, researchers attempted to forecast the reaction of the construction contractor in terms of daily construction operations. Initial discussions with personnel from TxDOT construction offices and construction contractors gave researchers insight into the options available to the contractor to execute the project while complying with the restrictions. In short, construction relies heavily on the use of diesel equipment for daily operations. Very little, if any, work can be conducted without the use of equipment targeted by the restrictions. After careful consideration and deliberation, researchers developed four WSAs that represent potential future work schedules that could be implemented as a result of the equipment restrictions.

WSAs are daily work schedules a contractor could implement to comply with the rule. Overall cost and schedule impacts will vary according to the WSA selected by contractors. Therefore, four potential alternatives were designed to accommodate most types of work performed in the impacted areas and traffic restriction policies implemented by TxDOT. The initial alternatives were defined based on their potential to allow continuous work, and each considered the time of day that could provide a full day's work. Because of time restrictions imposed by the rule, one WSA did not allow for a full workday in DFW, and one WSA did not allow for a continuous workday. These alternatives support the belief that only limited portions of construction projects can be conducted without the use of heavy equipment. The defined alternatives and their explanations follow.

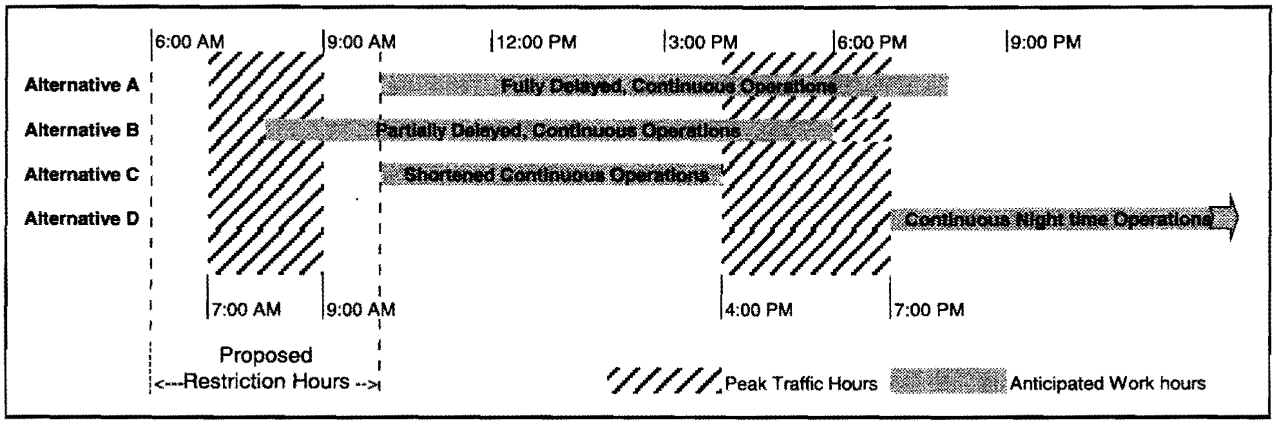
Fully Delayed Continuous Operations (Alternative A). The first anticipated revised work schedule would simply delay daily operations until after the restriction period. Therefore, as shown in Figure 4a, all construction operations could be shifted to coincide with the end of the restriction period, 12 noon for HG and 10:00 a.m. for DFW. This research assumes the workday consists of 10 hours, thereby shifting the end of the workday to 10:00 p.m. for HG and 8:00 p.m. for DFW. It is also assumed that minor preparation for daily construction work could begin prior to the restricted period as long as it complies with restriction requirements. This WSA is compatible with projects that do not have to stop operations due to traffic restriction policies.

Partially Delayed, Continuous Operations (Alternative B). The second anticipated revised work schedule assumes that some operations can be executed without using heavy diesel equipment. Thus, researchers anticipate that contractors could begin some work two hours prior to the restricted period; then continue for the remainder of the day until completing a regular 10-hour workday (Figure 4a). It should be noted that this alternative could also be used if the operating restrictions are reduced. Thus, all construction operations will be shifted to 10:00 a.m. for HG and 8:00 a.m. for DFW. The end of the workday would consequently be shifted to 8:00 p.m. for HG and 6:00 p.m. for DFW. This WSA is also compatible with projects that do not require lane closures.

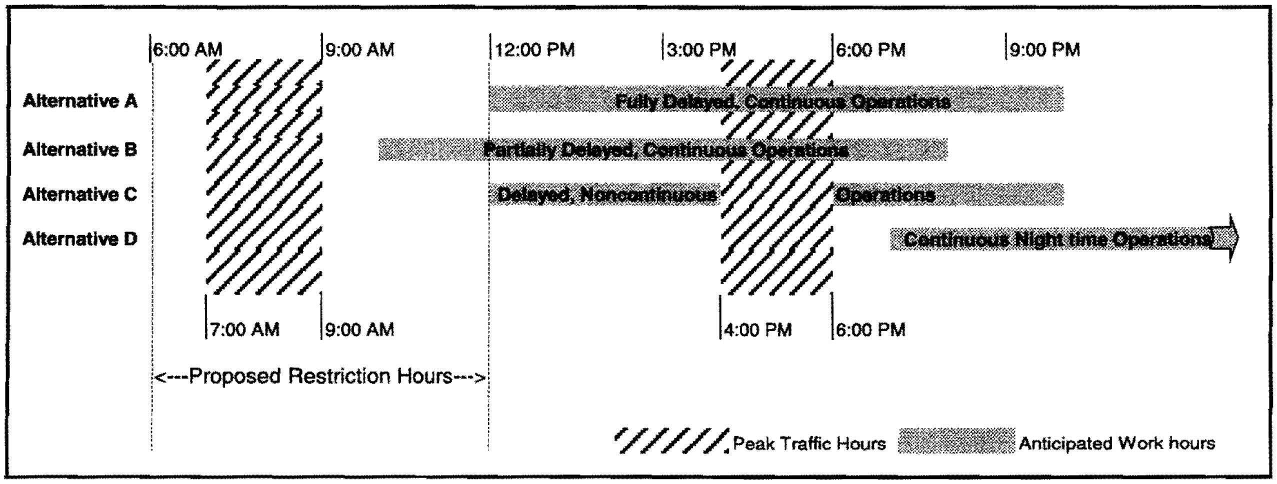
Delayed, Non-Continuous Operations (Alternative C – HG Area). For construction that will directly affect traffic and require lane closures, TNRCC's equipment restriction rule could have a significant impact. For such projects in HG, TxDOT requires that all lanes must be available through the afternoon peak traffic hours, starting at 3:00 p.m. The additional restriction placed by the rule delays the onset of operations until late morning, thus preventing continuous operations because of TxDOT traffic restriction policies (Figure 4b). Therefore at times, the contractor's only option is to split the operations for the day: work from the end of the restriction period, 12 noon; halt activities for approximately two hours in the late afternoon to coincide with traffic restrictions; and then continue operations afterward. This alternative assumes the contractor workday will still consist of 10 hours; however, very little or no work will be conducted during a two-hour time period when traffic restrictions are imposed.

Shortened Continuous Operations (Alternative C – DFW Area). Restricted lane closures in the afternoon are less stringent for DFW than those required for HG. Therefore, rather than splitting the workday, researchers anticipate that contractors would shorten the workday during construction periods that interfere with traffic restriction policies. Figure 4a displays this potential work schedule and was included in the survey submitted to contractors in DFW.

Continuous, Nighttime Operations (Alternative D). Contractors may find it necessary or more effective to conduct construction operations totally at night. Continuous, nighttime operations may be the only viable alternative for construction that either directly interferes with traffic or takes place during periods of excessive heat (Figures 4a and 4b).



a) DFW Area



b) HG Area

Figure 4. Work Schedule Alternatives for DFW and HG.

Survey Development

Factors Affecting Cost and Schedule

Based on data collected from TxDOT area engineers, construction contractors, and a literature search, the main factors affecting urban highway construction project costs and schedule include direct field labor rates, traffic control, equipment (including construction lighting), insurance, workers' compensation, and rework. Researchers also identified the need for an analysis of impact on the individual constituents of the project cost.

Cost Elements

As previously noted, for this portion of the project, researchers seek to correlate the impacts of the rule on various aspects of TxDOT construction projects to the overall cost and schedule impact. Since the survey relies heavily on input from construction contractors, identifying the key cost elements most recognized by contractors is very beneficial. The cost elements used in this project include direct field labor, material, equipment, field indirect, and home office costs. As common components of cost estimates for the construction contractor, researchers used these cost elements in the survey to generate the potential cost impacts.

Survey Implementation

The survey was conducted with TxDOT area engineers, as well as contractors currently performing a significant amount of TxDOT work in the two targeted nonattainment areas. Researchers provided the survey form to all respondents and gathered responses through personal interviews, phone interviews, or via completed written forms. The process was performed during August and September 2000.

Researchers asked respondents to anticipate potential cost and schedule impacts based on specific project types and WSAs. It was noted that resources assigned (number of work crews and equipment, for example) would remain constant compared to those currently used during a normal daytime work schedule. The survey requested estimates of impacts on various elements for each project type and WSA. Impact values were assigned as a percentage of the original total. Results gathered for each project type included the overall project cost impact, the overall project duration impact, the anticipated percent of work to be performed under each type of WSA, and the impact on specific pre-identified factors that could affect cost and schedule.

The overall project cost impact was determined through information compiled regarding impacts on the various cost elements (labor, equipment, material, field indirect, and home office costs). Researchers mailed or faxed surveys to each participant after initial discussion of the purpose and intent of the study. Different approaches were used to contact and collect information from the prospective respondents. Personal interviews and telephone interviews were conducted. In some cases, the survey document was faxed to the respondent and later explained through telephone conversations. Researchers conducted follow-up visits to gather the respondents' data and comments regarding the implementation of the rule and on the survey.

Analysis Methodology

Once all interviews were conducted, researchers entered the data into spreadsheets to arrive at the total anticipated cost and schedule impact for HG and DFW. To produce these gross amounts, information was aggregated from the lowest levels of detail provided by the survey respondents, to the overall cost and schedule impacts.

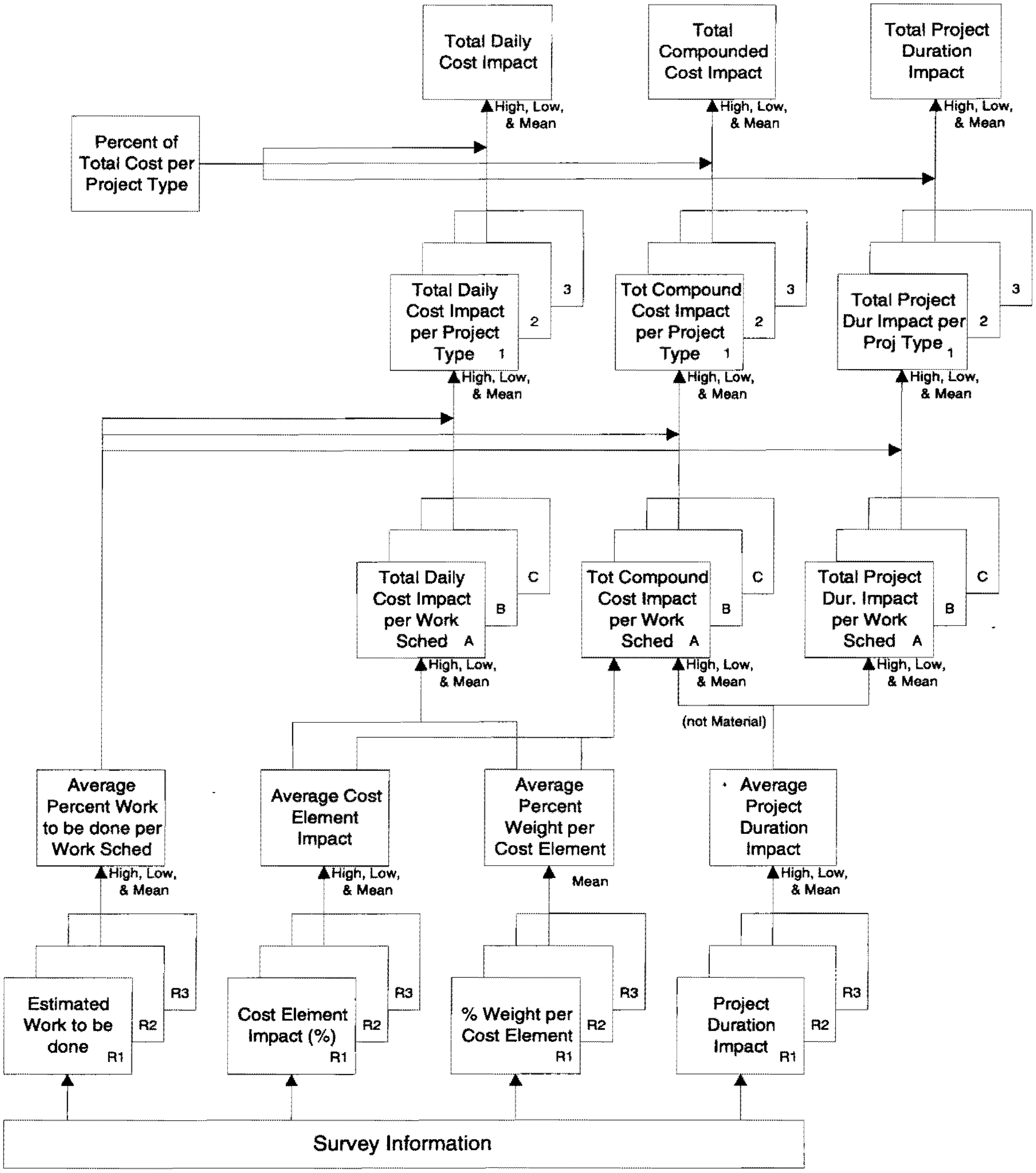
The total daily cost impact summarizes the anticipated cost increments for highway construction projects during the restriction period on a day-to-day basis without accounting for the cost changes due to extended project duration. The total project duration indicates the expected changes resulting from the rule on the overall project schedule. The total compounded cost impact incorporates these two elements, providing an estimated total cost impact due to day-to-day changes and those produced by the extended schedules. The cost and schedule results are for the restriction period only.

Researchers evaluated the total daily cost impact using the daily cost impacts for each project type. These totals were obtained from the daily cost impacts for each WSA and project type. The individual WSA daily cost impacts were calculated from aggregating the data collected from the surveys regarding individual cost changes for the various cost elements. This procedure was also followed for the evaluation of the total project duration impact and the total compounded cost impact.

Researchers documented the survey information as a percent change for each of the following survey elements:

- *cost elements:* direct field labor, materials, equipment, field indirect, and home office;
- *percent weight of cost elements:* the relative cost of each cost element compared to total project cost;
- *schedule elements:* project duration and overall labor productivity;
- *estimated work performed under each WSA;* and
- *individual cost factors.*

With the exception of cost elements, respondents provided input as a range of expected values. Therefore, calculations determined a low, high, and average value for each survey element. Figure 5 displays the methodology for determining cost and schedule impact. As shown, each respondent was queried for information on the anticipated use (as a percentage) of each WSA, the percent increase in cost for each cost element (i.e., field labor, material, equipment, etc.), the percentage of the overall cost for each cost element, and the potential impact on project duration. These data were then used to determine the total daily cost impact, the total project duration impact, and the compounded cost impact (includes costs associated with increased cost and longer schedules).



Legend:
R1, R2, R3: Respondent information supplied in the surveys
A, B, C: WSAs
1, 2, 3: Project types
High, Low, & Mean: High, low, and mean (average) values were calculated for the element

Figure 5. Procedure for Evaluating Overall Cost and Schedule Impact.

RESULTS

Researchers evaluated the data provided by leading highway construction contractors in HG and DFW and compared it to input obtained from TxDOT area engineers and district construction representatives. The results of the analyses provide information on potential organizational and schedule changes by TxDOT and the contractors when the construction equipment restriction rules are implemented in 2005.

Houston/Galveston Area

A total of 11 contractors that perform a majority of the work for TxDOT in HG were initially selected for the study, nine of which were subsequently contacted. Researchers delivered surveys to each contractor and interviewed five contractors for their responses, finding that four had completed the survey. The survey-return rate for HG was 44 percent. The volume of work performed by these four contractors is 64 percent of the total funds allocated for highway projects in HG by TxDOT (based on TxDOT August 2000 data).

To obtain expected percent changes for HG, researchers extended the anticipated daily cost increases over the increases expected in project duration, to arrive at an overall total increase in cost. This process was conducted for each of the principal construction project types associated with TxDOT. The evaluation considered the total funds allocated by TxDOT on highway construction projects to determine the percent weight of each of the project types. The relative percent weights of the project types, used to evaluate the total cost and schedule impacts, were calculated using the funds allocated to the five project types included in the analysis. Table 18 shows the relative percent weight of the major construction project types conducted in HG for TxDOT.

Table 18. Relative Percent Weight of Project Types (HG).

Project Type						**Total (%)**
1	*2*	*3*	*4*	*5a/5b*		
Freeway (%)	**Non-Freeway (%)**	**New Construction (%)**	**Bridge Replacement (%)**	**Rehab & Overlay (%)**		
				Rural	**Urban**	
36.0	21.4	10.8	4.6	13.7	13.7	100

Researchers contacted and interviewed all TxDOT engineers in the HG area. Six personal interviews were carried out, and the remaining interviews were performed via telephone conversations. Eight area engineers completed and forwarded comments to the research team. The survey return rate for the HG TxDOT was 80 percent.

The following sections summarize findings gathered from interviews conducted with construction contractors in HG into a variety of categories. First, the report summarizes by the representative TxDOT project type. The section continues with the summarized findings of the various cost elements included in each of these projects. Results for separate cost factors are presented, followed by the anticipated cost and schedule changes for various work schedules. Lastly, overall findings for the cost and schedule impact are then summarized.

Project Types

The five project types exhibited different trends of cost and schedule impacts. Table 19 shows the anticipated percent impacts for different project types. The table shows the increase in cost for the different project types falls within a small range. The increase in the cost of bridge replacement projects was forecasted to be the maximum cost increase.

Table 19. Overall Cost and Schedule Results (HG).

Project Types	**Anticipated Duration Change (%)**	**Anticipated Cost Change (%)**
1 – Freeway Reconstruction and Widening	10	13
2 – Non-Freeway Reconstruction and Widening	9	13
3 – New Construction	8	10
4 – Bridge Replacement	12	16
5a – Rural Rehab/Overlay	8	9
5b – Urban Rehab/Overlay	9	9

Cost Elements

The cost elements used to develop a budget, as previously described, include direct field labor, materials, equipment, field indirect, and home office costs. Effects on elements differ according to the WSAs implemented and project type. Nonetheless, a general pattern evolved from the survey responses between the various project types for the impacts on the cost elements. Table 20 shows the overall average expected cost increase calculated from the information supplied by the respondents, including the cost of an extended schedule for the cost elements of each project type.

Table 20. Overall Average Cost Element Impacts per Project Type (HG).

Project Type	Anticipated Increase in Cost Elements (%)				
	Field Labor	Materials	Equipment	Field Indirect	Home Office
1 – Freeway Reconstruction	27	8	16	22	23
2 – Non-Freeway Reconst.	23	7	15	20	21
3 – New Construction	19	6	14	18	19
4 – Bridge Replacement	28	8	17	24	25
5a – Rural Rehab/Overlay	22	6	14	18	19
5b – Urban Rehab/Overlay	19	5	13	17	8

The values determined from the data collected from the survey indicate that direct field labor cost is expected to change the most. The construction equipment restriction rules may have a serious impact on field labor costs, primarily because of the premiums that may have to be implemented as a result of the altered work schedules. The respondents indicated that reduced productivity might be another potential cost impact. Respondents pointed out that it is difficult to estimate future wage rates, and the new conditions regarding the work schedules could reduce their capacity to attract workers. It was thought that workers might opt to transfer to areas where these restrictions do not apply, work in other industries, or apply to other companies that can offer more typical daytime work schedules.

Several respondents also noted that this could further put smaller companies at a disadvantage. The altered work schedules could also affect workers' morale, which can have potentially negative effects on productivity and quality (*11*). In addition, labor costs are dependent on project duration and thus will increase proportional to the total project duration. Some respondents indicated that labor productivity could increase during nighttime operations due to reduced interference and distractions.

Indirect costs (field indirect and home office) were anticipated to increase as a result of the additional personnel who may be required to work during the extended hours in the home office. Several respondents noted that field indirect costs could change as a result of construction lighting and added traffic control requirements for night operations. The respondents commented that additional supervision and special surveying equipment might also be required for night operations.

As a consequence of the modified schedules, TxDOT may be required to transfer portions of their non-critical quality control and assurance tasks to the contractors or private testing agencies. Both home office and field indirect costs are time dependent and, as such, are expected to vary as a function of project duration.

Results calculated from the survey information indicate that the cost for materials and equipment will not be severely impacted. Material costs will be affected when certain materials, such as asphalt or concrete, have to be placed during non-routine hours. Cost due to extra operating hours of asphalt and concrete plants are anticipated to increase material cost. Start-up plant costs could be required. In addition, the transportation cost of many supplies could increase as a result of altered receiving times. A limited number of material suppliers may be required to alter their business hours or remain open for longer hours, which can also affect material costs. In general, material costs are not significantly affected by the schedule alterations.

Respondents indicated that equipment costs could be affected by increases in the overall project duration and the lower productivity. When work is conducted at dusk or night, equipment productivity is likely to decrease because of limited visibility. On the other hand, respondents indicated that the day-to-day costs associated with equipment would most likely not be significantly impacted, because additional equipment would not be required to comply with the restrictions.

Other potential issues regarding equipment cost impacts resulting from the construction equipment restriction rule could include increased costs resulting from off-hour equipment maintenance and increased down time resulting from the lack of availability of spare parts. Part suppliers' and repair shops' business hours may not be compatible with the alternative schedules. This may force the contractors to keep standby equipment for critical operations, stock extra spare parts, hire additional personnel dedicated to minor equipment repair work, or negotiate with repair shops so they can work on down equipment during irregular hours.

The contribution of the impacts in the individual cost elements toward the project cost depends on the average relative weight of each cost factor compared to the overall project cost. The average relative weight per cost element indicates the relative allocation of funds toward a cost element from the project cost. The contribution of each cost element on a project level is calculated by multiplying each cost element's respective impact by its average relative weight. Table 21 shows the average relative weights, the average impacts, and the contribution of each cost element toward the project cost impact.

Table 21. Overall Average Cost Element Impact (HG).

	Field Labor	Materials	Equipment	Field Indirect	Home Office	Total
Average Relative Weights (%)	13	61	13	7	6	100
Average Impact (%)	24	7	15	20	20	-
Contribution to Total Impact (%)	3.5	4.5	2	1	1	12

Cost Factors

Changes to a typical construction work schedule can affect the cost and duration of a project. Certain factors that lead to these changes have been identified in the literature (12). These factors can have varying effects on cost and schedule. Interview and feedback data gathered during the research indicate expected changes in these factors when TNRCC's rule is implemented. The cost factors included as part of this research are:

- labor productivity;
- labor wage rates;
- traffic control;
- construction lighting;
- safety: insurance and worker's compensation; and
- quality: rework.

The overall impacts to these factors resulting from the implementation of the rule, as determined from the information gathered through the surveys, were consistent throughout the various project types. Table 22 displays the estimated daily impacts as a percent of the original value on the cost factors per project type. The impacts on the cost factors per project type account for the estimated work to be performed under each WSA.

Table 22. Average Cost Factors Impacts per Project Type (HG).

Cost Factor	Anticipated Increase in Cost Factors per Project Type (%)						Average (%)
	1	*2*	*3*	*4*	*5a*	*5b*	
Labor Productivity	- 13	- 12	- 10	- 11	- 10	- 9	- 11
Labor Wage Rates	15	13	11	14	14	6	+ 13
Traffic Control	5	4	1	2	8	4	+ 5
Construction Lighting	33	25	18	27	32	32	+ 29
Safety	12	11	8	9	11	7	+ 10
Quality	4	3	3	4	5	2	+ 4

The factors that are expected to experience the most significant changes are overall labor productivity, construction lighting, labor wage rates, and safety. Productivity has a significant impact on project cost and duration. The literature did not provide quantitative information regarding productivity impacts, but it did mention the various factors that affect productivity levels such as worker morale, fatigue (*11*), and degree of illumination (*12*) for nighttime construction work.

Hinze and Carlisle (*13*) found that for nighttime construction, cost for lighting could increase by 63 percent. The estimated cost differential associated with construction lighting for nighttime work (WSA D only) determined from this study averaged 52 percent for all project types. It is important to observe that respondents noted little need for lighting on projects performed during daytime hours, but most respondents indicated that incidental lighting costs are common.

The estimated labor wage rate impact, in the literature, was estimated to be 18 percent for nighttime work (*12*). Survey results indicate a change of 18 percent for the fraction of work anticipated to be conducted under continuous nighttime operations. The main impacts on labor costs are due to premiums and overtime that affect the daily construction costs.

An evaluation of the safety-based cost issues, such as accidents, were only evaluated qualitatively. The survey respondents commented that increased risk to construction workers during evening and nighttime operations would have adverse affects on worker safety, and thus would increase costs, in part due to sleep deprivation and fatigue. There are also additional safety risks to drivers resulting from construction operations.

The survey respondents also indicated that night and dusk operations may require additional traffic control. It cannot be concluded from the literature that quality will suffer due to night operations. The respondents' data indicate that the expected impact of the different WSAs on quality, identified as rework, is minimal (4 percent).

Overall Cost and Schedule Impacts

Table 23 shows the anticipated cost and schedule impacts in HG calculated from contractor interviews and survey results. The total anticipated change reflects the overall cost impact that is determined from the anticipated increases in daily costs extended over longer projected project duration. Respondents attribute these anticipated cost increases to greater impacts from traffic, lower labor productivity, and other effects from night/evening work hours. It should be noted that these changes in schedule and costs cover only the time periods when the construction equipment restriction rule is in effect.

Table 23. Overall Cost and Schedule Results (HG).

Freeway Reconstruction and Widening	**Average (%)**	**Low (%)**	**High (%)**
Anticipated Change in Daily Cost	+ 8	+ 3	+ 15
Anticipated Change in Duration	+ 9	+ 4	+ 17
Total Anticipated Cost Change	+ 12	+ 4	+ 23

Respondents indicated that the restrictions pose a significant concern for small contractors. Smaller contractors tend to have a limited labor pool and resources, which limits their ability to adjust to irregular work hours. Similarly, many subcontractors may lose some of their flexibility in working for multiple general contractors.

The WSAs used in the research reflect possible daily work schedules that contractors could adopt in order to comply with TNRCC's rule, as well as with the existing TxDOT construction restrictions. Contractors typically employ three main criteria when selecting the anticipated WSA for each project type. The primary selection criterion was the desire to perform the work over a continuous period. The other two factors include whether the work can be completed during the daytime hours and the potential for work methods and sequences to comply with the construction equipment restrictions.

Contractors indicated that they would choose a continuous work schedule rather than having a split shift. Contractors also indicated that the amount of productive work that could be performed behind barriers during rush hour traffic was limited, thus forcing the contractors to close traffic lanes to maintain productivity. However, lane closures are typically only authorized during non-peak traffic hours that would limit the daily production. Additionally, contractors wanted to perform as much of the work during the daylight to minimize risks. Contractors also indicated that the amount of productive work that can be performed without heavy equipment is limited; therefore, they would opt to implement schedules that would allow them to operate equipment continuously.

Table 24 indicates the allocation of work preferences for each project type and WSA. The reported values are average values.

Table 24. Work Schedule Alternative Preference per Project Type (HG).

WSA	Implementation of WSA per Project Type (%)						Average (%)
	1	*2*	*3*	*4*	*5a*	*5b*	
A - Delayed, Continuous Operations	31	45	60	51	76	12.5	42
B - Partially Delayed, Continuous Operations	18	25	34	22	7	0	17
C - Delayed, Non-Continuous Operations	6	5	2	1	0	12.5	5
D - Continuous Nighttime Operations	45	25	4	26	17	75	36
Total	100	100	100	100	100	100	100

Dallas/Fort Worth Area

Researchers contacted a total of seven contractors who perform work for TxDOT in DFW, and delivered surveys to each of them. Five contractors answered the surveys and were interviewed. One set of data was excluded from the quantitative evaluation because values were more than an order of magnitude higher than the average values. The acceptable survey reply rate for DFW was 57 percent.

The approach used to survey DFW TxDOT personnel differed from the approach used in HG. Instead of performing individual interviews with each TxDOT area engineer, common meetings were held with TxDOT area engineers in the Dallas and Fort Worth Districts (separately) that will be impacted by the construction equipment restriction rule. Five area engineers were present in the Dallas meeting and two in the Fort Worth District. Two additional TxDOT construction personnel were also present in the Fort Worth meeting. Survey responses were obtained during the two interviews from the participants. The respondents discussed the values of the different impacts, and a consensus was achieved. The data product of this consensus was recorded in the survey. The survey reply rate for the participating DFW TxDOT area engineers was 100 percent.

As with the HG analysis, the overall expected impacts in cost and schedule for DFW on highway construction projects were calculated from the estimated impacts to the different project types. Calculations used information provided by TxDOT regarding funds allocation to highway projects for the years 1997, 1998, 1999, and 2000 to determine the relative weight of each project type for DFW. Table 25 reflects the relative percent weights for the major construction project types conducted in DFW for TxDOT.

Table 25. Relative Percent Weight of Project Types (DFW).

Project Type						**Total (%)**
1	*2*	*3*	*4*	*5a/5b*		
Freeway (%)	**Non-Freeway (%)**	**New Construction (%)**	**Bridge Replacement (%)**	**Rehab & Overlay (%)**		
				Rural	**Urban**	
24	25	22	6	11.5	11.5	100

Project Types

Based on the information gathered from the contractors' interviews, the cost and duration increase in five different project types was determined. Table 26 shows the results. The table shows generally higher increases in cost and duration as compared to that in HG.

Table 26. Overall Cost and Schedule Results (DFW).

Project Types	**Anticipated Duration Change (%)**	**Anticipated Cost Change (%)**
1 – Freeway Reconstruction and Widening	13	16
2 – Non-Freeway Reconstruction and Widening	13	16
3 – New Construction	13	15
4 – Bridge Replacement	12	17
5a – Rural Rehab/Overlay	15	13
5b – Urban Rehab/Overlay	17	16

Cost Elements

The cost element impacts, as provided by the respondents, present a consistent pattern with the results obtained from HG for the different WSAs and project types. Table 27 indicates the average expected impacts on the cost elements according to the project types, as calculated from the information supplied through the contractor surveys.

Table 27. Overall Average Cost Element Impacts per Project Type (DFW).

Project Type	Anticipated Increase in Cost Elements (%)				
	Field Labor	Materials	Equipment	Field Indirect	Home Office
1 – Freeway Reconst.	35	6	24	20	14
2 – Non-Freeway Reconst.	34	4	24	21	14
3 – New Construction	33	6	23	20	14
4 – Bridge Replacement	34	7	26	23	17
5a – Rehab/Overlay (Rural)	35	6	24	21	15
5b – Rehab/Overlay (Urban)	41	7	28	25	17

Data from the survey indicate that contractors expect direct field labor would experience the largest cost increase, followed by equipment and field indirects. Labor was affected primarily through wage premiums and increased overtime. A potential side effect of the construction equipment restriction rule on labor is a reduction in labor productivity. Survey respondents commented that the construction labor force might migrate toward other metropolitan areas not bound by the equipment restrictions. The necessity of modifying the current work schedules and practices might affect labor productivity.

Contractors in DFW anticipate similar impacts to their construction operations, when compared to contractors in HG. Field indirect costs could increase due to the premium policy that may be implemented for the field personnel. The impact on labor productivity may affect equipment productivity. Limited visibility during night and dusk hours may also have a negative impact on equipment productivity. Equipment costs could also be impacted by increases in the overall project duration changes.

Contractors in DFW also noted that home office costs could increase as a result of the addition of personnel required to fill the extended hours and/or as a result of paying increased overtime. These costs are further increased by the anticipated lengthening of the project duration. Material costs may be affected by the need for suppliers to adjust delivery schedules to match the altered construction activity. Respondents pointed out that site material storage areas are limited and, therefore, delivery schedules may have to adjust to the new work schedules.

Table 28 reflects the overall contribution of each cost element toward the total project cost impact. This contribution is based on the average percent weight of each element.

Table 28. Overall Average Cost Element Impact (DFW).

	Field Labor	Materials	Equipment	Field Indirect	Home Office	Total
Relative Weights (%)	15	51	17	10	7	100
Average Impact (%)	35	6	24	21	15	-
Contribution to Total Impact (%)	5	3	4	2	1	16

Forecasted field labor cost increases contribute the most to the total change as a result of the relatively high, anticipated increase for this element. Similarly, equipment cost contributes 17 percent of the total project cost and could experience a potential impact of 24 percent. Thus, the cost impact due to equipment is forecasted to be 4 percent (17 percent multiplied by 24 percent) at the overall project level. Although material cost increases are anticipated to be minimal, the overall cost impact is found to be approximately 3 percent, because material costs account for a large portion of the overall construction costs.

Cost Factors

The cost factors included in the DFW survey were the same as those included in the HG survey: labor productivity, labor wage rates, traffic control, construction lighting, safety (insurance and workers' compensation), and quality (rework).

Table 29 shows the anticipated cost increases for the various cost factors by DFW contractors, as calculated from the data obtained from the surveys. The factors expected to be impacted the most by the implementation of the construction equipment restriction rule are labor productivity, construction lighting, labor wage rates, and traffic control.

Table 29. Average Cost Factors Impacts per Project Type (DFW).

Cost Factor	Anticipated Increase in Cost Factors per Project Type (%)						Average (%)
	1	*2*	*3*	*4*	*5a*	*5b*	
Labor Productivity	-18	-17	-16	-16	-17	-20	-17
Labor Wage Rates	15	15	15	13	15	19	16
Traffic Control	12	12	7	7	13	17	11
Construction Lighting	40	41	38	32	33	45	39
Safety	9	9	8	7	8	11	9
Quality	8	8	8	6	4	8	7

The findings of this research indicate an increase of 39 percent for the total compounded cost impact and a 100 percent increase for lighting costs for nighttime operations (WSA D). Currently, most projects in DFW are performed during daytime hours, and a shift toward night schedules would force full use of construction illumination.

The analysis of the survey results for labor wage rates indicated that the cost would increase by 31 percent. The limited experience in nighttime operations may be one of the reasons for this relatively large expected change. Labor wages are a major part of the field labor cost in DFW, and the anticipated increases in the wages account for a significant part of the overall labor cost impact.

The survey respondents commented that increased risk to construction workers during evening and nighttime operations would have adverse effects on worker safety, in part due to sleep deprivation and fatigue. Thus, the WSA associated with nighttime work (option D) contributes to the anticipated cost increase for safety. The expected overall cost impact for safety in DFW was determined to be 9 percent. In addition, the respondents noted that the expected impact resulting from rework and other quality issues would result in a 9 percent increase in costs.

Overall Cost and Schedule Impacts

Results from contractors in DFW indicate that TNRCC's rule may have adverse impacts to construction costs and schedules in DFW. Table 30 summarizes specific anticipated impacts. Daily construction operations for TxDOT projects are projected to increase in cost by approximately 8 percent, while the project duration is expected to increase 14 percent on average. Thus, the overall total impact is estimated to range between 4 percent and 32 percent, with a most likely value of 16 percent.

Table 30. Overall Cost and Schedule Results (DFW).

Freeway Reconstruction and Widening	**Average (%)**	**Low (%)**	**High (%)**
Anticipated Change in Daily Cost	8	2	16
Anticipated Change in Duration	14	5	28
Total Anticipated Cost Change	16	4	32

Table 31 shows the contractor preference for the different WSAs developed for the survey. As in HG, the selection of a WSA is primarily based on the ability of conducting continuous operations. Similar to HG, the contractors noted the importance of performing day work rather than night work. Night operations convey a series of additional costs and risks that contractors tend to avoid, when possible. The ability to perform work without changing normal methods and sequences is another factor that was considered by the contractors when selecting WSAs. Contractors prefer the majority of work to be performed under schedules that would allow them to use heavy equipment continuously and during the entire workday, instead of limiting its use during the first hours of the workday as a result of the restrictions.

Table 31. Work Schedule Alternative Preference per Project Type (DFW).

WSA	**Implementation of WSA per Project Type (%)**						**Average (%)**
	1	***2***	***3***	***4***	***5a***	***5b***	
A - Delayed, Continuous Operations	32	38	40	38	65	40	40
B - Partially Delayed, Continuous Operations	30	26	30	38	18	18	27
C - Delayed, Shortened Operations	13	11	8	9	7	15	11
D - Continuous Nighttime Operations	25	25	22	15	10	27	22
Total	100	100	100	100	100	100	100

CONCLUSIONS

In order to assess the cost and schedule impact of TNRCC's construction equipment rule, researchers surveyed local contractors and TxDOT engineers. Each contractor performs a large portion of work in the two targeted nonattainment areas. All TxDOT participants were employed in offices located in the targeted nonattainment areas.

The highway construction work was grouped into five different project types for analyzing the potential impacts. Different WSAs that could be implemented by the contractors were for five general project types. Based on these WSAs and the five typical project types, participants were surveyed to determine potential cost and schedule impacts (as a percentage of the expected cost). After analyzing the survey responses and comments provided by the respondents, the following conclusions can be drawn:

- There are limited historical data available to support a cost impact evaluation; all data gathered are drawn from professional experience of those people who are most intimately familiar with the highway construction operations in the nonattainment ozone areas.
- Several quantifiable factors are expected to increase costs and schedules resulting from TNRCC's construction equipment restriction rule. These factors include labor productivity, labor wage rates, traffic control, construction lighting, safety, and quality.
- There are a considerable number of non-quantifiable factors that may further impact the cost and schedule to TxDOT projects. These include lower morale and increased safety concerns for TxDOT and contractor personnel.
- The anticipated average overall construction cost impact during the time periods when the rule is in effect (including the costs of extended schedules) is anticipated to be between 8 percent and 16 percent for HG area and between 4 percent and 32 percent for DFW area. This compares favorably with initial TNRCC cost impacts of 15 to 20 percent.
- The average overall project duration impact for the period when the rule is in effect is anticipated to increase project schedules between 6 percent and 12 percent for HG area and between 5 percent and 28 percent for DFW area.
- There is a consistent tendency by the contractors to favor work schedules that provide continuous operations for their crews. This tendency is reflected in the cost and schedule impacts.

CHAPTER VI. ALTERNATIVE CONSTRUCTION EMISSION CONTROL MEASURES

INTRODUCTION

As stated in Chapter I, alternative control plans may be prepared and submitted for approval to gain exemption from the construction equipment restrictions in DFW and HG beginning in 2005. This chapter presents a brief overview of some available control technologies that can be used within the construction equipment fleet. One alternative control technology is used to demonstrate the estimated cost-effectiveness.

The control measures examined and presented within this chapter are limited to two broad categories for nonroad diesel applications: engine emission control devices and fuels. The technologies, associated costs, and potential emission reductions are detailed. Appendix A provides a glossary of diesel terminology.

Nonroad Diesel Emission Controls

Diesel Engine Emission Control

The primary sources for information on diesel emission control devices and fuel are EPA, California Air Resources Board (CARB), and the Manufacturers of Emission Controls Association (MECA). In particular the sources are: EPA's May 2000 *Draft Regulatory Impact Analysis for the Heavy-Duty Engine and Vehicle Standards and Highway Diesel Fuel Sulfur Control Requirements Rule* (*14*); CARB's October 2000 report by the Stationary Source Division and Mobile Source Control Division entitled *Risk Reduction Plan to Reduce PM Emission from Diesel-Fueled Engines and Vehicles* (*15*); and the MECA March 2000 report: *Emission Control Retrofit of Diesel-Fueled Vehicles* (*16*).

Diesel emissions control can be achieved by:

- modifying the engine design,
- treating the exhaust (also referred to as after-treatment),
- modifying the fuel source, or
- a combination of these controls.

A brief review of after-treatment, engine modification, and fuel as means to reduce diesel emissions is presented below. The review is limited to current regulatory strategies.

Retrofit Controls and Diesel Exhaust After-Treatment. Diesel exhaust after-treatment devices include diesel traps or filters and diesel catalysts. Diesel traps, which are primarily diesel filters, control diesel particulate matter (DPM) emissions by physically trapping the particulates, usually through a porous medium. The major challenge in the design and use of diesel filter systems is regenerating the filter's trap in a reliable and cost-effective manner.

DPM is a complex aggregate of solid and liquid material generally classified into three fractions:

- the inorganic/solid fraction (soot);
- the organic fraction, often referred to as a soluble organic fraction (SOF); and
- the sulfate (SO_4) fraction (hydrated sulfuric acid).

The composition of these sub-micron size particles in diesel exhaust varies depending on engine load and usage conditions.

Diesel catalysts control emissions by promoting oxidation processes in the exhaust gas similar to those in catalytic converters used in automobiles. Diesel oxidation catalysts (DOCs) most effectively reduce the SOF of diesel particulates, gas-phase hydrocarbons (HC), and carbon monoxide (CO). DOCs have been commercially used for many over-the-road and off-highway applications. Some retrofit emission control systems use a combination of DOCs, filters, air enhancement, and engine adjustments for emission reduction. Diesel filters and DOCs alone have little effect on NOx emissions.

Diesel Particulate Filters (DPFs) and Traps. Diesel particulate filters positioned in the exhaust stream capture particulates as the exhaust passes through the exhaust system. As expected, the volume of particulates trapped from diesel exhaust is sufficient to clog most filters over time. Therefore, filter systems need a means to dispose of trapped particulates or to regenerate the filter. One method of regeneration is through burning or oxidizing the particulates. Another method used primarily in nonroad applications is to size the filter to collect enough particulates to be effective for a working shift and to replace it regularly (*16*).

Most commercial filter materials in use include ceramic monoliths, fiber-wound cartridges, silica carbide, and temperature-resistant paper for disposable filters. The PM efficiency for these types of filters ranges from 50 to 90 percent. The challenge lies in the regeneration of the filters. The relatively low temperature of diesel exhaust is inadequate to allow a catalyst to work effectively. Therefore, regeneration methods include the use of fuel-borne catalysts (FBCs) to raise ignition temperatures, fuel burners to heat exhaust, and, more commonly, catalyst coatings on the filter element (*16*).

According to MECA, filter system costs range from \$10 to \$20 per horsepower, depending on the application and conditions of use. Per-vehicle costs range from approximately \$600 to \$2,000 and also depend on the technology and application in use. Diesel particulate filter systems have been used since the mid-1980s (*17*).

Diesel Oxidation Catalyst. DOCs are the leading retrofit control strategy to reduce PM, CO, and HC emissions for both nonroad and on-road diesel applications, and have been in use for more than 20 years (*16*). Modern catalytic converters consist of honeycomb substrate coated with metal (e.g., platinum or palladium) catalyst packaged in a stainless steel container. The honeycomb structure uses many small channels and acres of high catalytic contact area to exhaust gases. As the hot gases contact the catalyst, oxidation converts several exhaust pollutants into harmless substances: carbon dioxide (CO_2) and water (H_2O).

The DOC is designed to oxidize CO, gas phase HC, and the SOF fraction of DPM to CO_2 and H_2O. The catalyst activity increases with temperature, and the level of particulate reduction is influenced by the percentage of SOF. The sulfur content of diesel fuel is critical to catalysts. The lower the sulfur content in the fuel, the more effective oxidation catalysts can become. Retrofits for vehicles are effective on vehicles using greater than 0.05 percent sulfur fuel, and typical nonroad retrofit applications reduce PM, HC, and CO emissions for fuel containing 0.25 percent weight sulfur. The performance of an oxidation catalyst using an elevated fuel sulfur level can vary greatly depending on the catalyst formulation, engine type, and duty cycle (*16*).

Most DOCs are used in mining equipment and material handling (forklifts) equipment. The underground mining and material handling industries have installed over 250,000 catalysts; the urban bus retrofit program has installed more than 10,000 oxidation catalysts; and over 1000 systems have been retrofitted to highway trucks. DOC-equipped engines fueled with low-sulfur diesel (levels at or below 0.05 percent sulfur) have achieved reductions of 20 to 50 percent for PM, as well as 60 to 90 percent reductions for both HC (including those HC species considered toxic) and CO. A Society of Automotive Engineers (SAE) technical paper indicated DOCs were capable of reducing the SOF fraction of particulates by 90 percent and reducing total PM by 40 to 50 percent under certain conditions (*17*). DOCs have minimal effect on reducing NOx.

Based on experience from EPA urban bus retrofit program, the life-cycle costs of DOCs are reported to be less than $2,300 per bus. Due to the wide range of horsepower ratings for equipment used in nonroad applications, the cost variation is greater. The cost for small in-line muffler replacements ranges from $300 to $600 per unit ($1.00 to $2.00 per hp) to several thousand dollars for large units on large nonroad vehicles (*16*).

Catalyst-Based Filters. CARB evaluated various types of diesel emission control technologies and found that the most effective control technologies were catalyst-based diesel particulate filters that include filter catalysts. Catalyst-based filters use catalyst materials to reduce the temperature at which collected diesel PM oxidizes. The catalyst material can either be directly incorporated into the filter system or added to the fuel as an FBC. Although catalyst-based filters function with diesel fuels of varying sulfur content, the greatest reductions come from using very low-sulfur fuels. Used with very low-sulfur (<15 ppm by weight sulfur) diesel fuel, catalyst-based filters can reduce diesel PM emissions by over 85 percent (*15*).

Table 32 presents the range of control efficiency of catalyst-based filters and new diesel-fueled engines. Based on available test information summarized from CARB's technology review, the control efficiency information ranges from 85 to 90 percent for catalyst-based filters. Effectiveness of catalyst-based filters has been demonstrated in Europe on more than 6500 buses and heavy-duty trucks and on a much more limited basis in the United States, particularly in California and New York.

Table 32. Control Technology Efficiencies.

Control Technology	Diesel PM Control (%)	Efficiency Description
Catalyst-Based DPFs /Very Low-Sulfur Fuel	85 to 97	Particulate filter system where the catalyst material is either incorporated into the filter or added to the fuel; diesel fuel with a sulfur content <15 ppm
New Engine	Up to 85	Replaces existing engines with engines certified to meet CARB/U.S. EPA off-road engine emission standards.

Source: Table 1 from CARB Risk Reduction Plan, October 2000 (16).

Tables 33 and 34 list the costs of control technologies under different types of use. The cost data from CARB are consistent with data from MECA that indicate a range of $30 to $50 per horsepower (16). EPA reported the cost for light heavy-duty diesel (LHDD) engines at $634, medium heavy-duty diesel (MHDD) engines at $796, and heavy heavy-duty diesel (HHDD) engines at $1,029; these estimates are consistent with other estimates. It is important to note that retrofit costs are four to five times higher than costs for new engine modification.

Table 33. Retrofit Costs for Catalyst-Based Filters.

Technology	40 hp	100 hp	400 hp	1400 hp
Capital Cost	$1,300-$5,000	$2,000-$7,500	$7,000-$10,000	$30,000-$44,000

Source: Table 2 from CARB Risk Reduction Plan, October 2000 (16).

Table 34. Retrofit Costs for Off-Road Catalyst-Based Filters.

Technology	190 hp	275 hp	475 hp
Catalyst Based DPF	$5,700-$9,500	$8,250-$13,750	$13,500-$23,750

Sources: Table 1, Table 2, and Table 3 from CARB Risk Reduction Plan to Reduce PM Emission from Diesel-Fueled Engines and Vehicles, Stationary Source Division, Mobile Source Control Division. October 2000. Some catalyst-based technologies require low-sulfur fuel. The incremental cost of this fuel is projected to be less than $ 0.05 per gallon.

NOx Targeted Technologies

Whereas catalyst-based filters and traps are effective in reducing diesel particulates, the technologies reviewed below aim toward reducing NOx emissions.

Selective Catalytic Reduction (SCR). Unlike most stand-alone filter-based applications, the technology known as SCR effectively reduces NOx. SCR introduces urea as a reducing agent ahead of the catalyst to provide reductions of NOx (75 to 90 percent), HC (50 to 90 percent), and PM (30 to 50 percent) (17). SCR use is more prevalent among higher horsepower diesel engines such as marine vessels, locomotives, and fixed sources such as boilers and power plants. However, demonstration projects have used SCR for lower horsepower trucks and buses.

TNRCC reported that Siemens Westinghouse SCR is designed for engines greater than 175 horsepower. TNRCC assumes that SCR could be implemented on 80 percent of nonroad sources greater than 175 horsepower (*3*). Since the modal horsepower range for HG construction equipment is 100-175 horsepower, the use of Siemens Westinghouse SCR for construction equipment may be limited at this time; however, the NOxTECH, Inc., SCR system is available for lower horsepower ranges.

The cost of SCR is difficult to determine, according to MECA, because it is a relatively new application for trucks, buses, and lower horsepower ranges. The cost for retrofitting nonroad construction specifically is unavailable, but a 1997 study (*18*) reported the effectiveness of SCR as $1,100 per ton NOx reduced, based on limited testing.

The NOxTECH Emission Control System by NOxTECH, Inc., is being used on stationary diesel engine generators. The manufacturer reports the initial costs are $52 to $75 per horsepower for installations requiring urea injection and heat exchanger. Urea costs were estimated at $300 per ton of NOx reduced with a fuel efficiency penalty of 5 to 8 percent.

Based on a stationary engine, the SINOX SCR system by Siemens Westinghouse Power Corporation reportedly had an initial cost of $7,000 for a 367 hp engine ($19 per hp) with similar urea and fuel penalty costs (*18*: Appendix IX, Page ix-11). Among the NOx emission control devices reviewed, the SCR technology is one of few commercially available at this time demonstrating NOx reduction results.

Lean NOx Catalysts. Two types of lean NOx catalysts (active and passive) have been under development, but neither is commercially available. Active lean NOx catalysts inject a reductant upstream to reduce NOx to N_2 and O_2. Active lean NOx catalysts have demonstrated up to 30 percent reduction of NOx under limited steady state conditions, but there is a 7 percent fuel economy penalty. Additionally, NOx reductions over the heavy-duty transient federal test procedure (FTP) are approximately 12 percent because of the excedance of optimum NOx reduction efficiency range (*7*).

The passive lean NOx catalysts' washcoat incorporates a ceramic coating called zeolite to adsorb HC from the exhaust stream. Passive lean NOx catalysts are capable of steady state NOx reductions of less than 10 percent. EPA views neither active nor passive lean NOx catalysts as favorable NOx reduction technologies without major improvements (*14*) Both types of lean NOx catalysts require low-sulfur diesel fuel because zeolite catalysts are sulfur intolerant.

NOx Adsorbers. The application of NOx adsorbers to diesel engines is relatively new. The power generation industry began using NOx adsorbers on stationary sources less than five years ago. Recent applications include the use of lean-burn gasoline engine NOx control. The NOx adsorbers consist of an oxidation catalyst (e.g., platinum), an alkaline earth metal to store NOx (e.g., barium), a NOx reduction catalyst (e.g., rhodium), and a container substrate to hold the catalyst wash support. Unlike catalysts, NOx adsorbers store NOx under lean conditions and release and catalytically reduce the stored NOx under rich conditions. The NOx adsorbers are periodically regenerated using reductants such as CO or HC in the diesel fuel (*14*).

The cost for NOx adsorbers is estimated to range from $890 to $1,410 depending on the application (*14*). EPA reported the cost for LHDD at $890, MHDD at $1,047, and HHDD at $1,410. It is important to note that retrofit costs are four to five times higher than costs for new engine modification (*14*). The greatest challenge to the NOx adsorbers' effectiveness is the adverse affects caused by the sulfur content in fuel. Nonetheless, EPA looks favorably toward NOx adsorbers as the most effective technology to achieve new NOx standards when used with low-sulfur fuels, since NOx adsorbers can provide NOx conversions in excess of 90 percent over a wide range of temperatures.

Air Enhancement Technology. Air enhancement technologies, such as electronic superchargers, have demonstrated simultaneous reductions of PM (20 to 40 percent), CO (30 to 65 percent), and visible smoke (25 to 90 percent). These systems can improve vehicle performance without reducing fuel efficiency and have gained a "universal exemption" by CARB for heavy-duty mechanical unit injection (MUI) diesel engines. The technology has been used in transit buses, line haulers, and water tankers in the U.S. and worldwide.

The cost of air enhancement technologies varies depending on horsepower and airflow requirements. However, MECA reports medium and heavy-duty applications range from $3,000 to $5,000, with some manufacturers aiming for costs of $1,500 to $2,000 (*18*).

Combination Technologies

In many instances, combining technologies and engine modifications, as well as control technologies combined with low-sulfur fuel, result in desired diesel emission reductions. This is particularly true for NOx emissions. Engine modifications may include the use of injection timing retard or exhaust gas recirculation (EGR). MECA summarizes the following combinations (*18*: Page 20):

- A combination of DOCs, DPM filters, air enhancement, and engine modifications used for emission reduction. One system using zeolites with fuel injection retardants and an oxidation catalyst demonstrated a 40 percent NOx reduction and maintained low particulate emissions (*15*).
- Thermal management technologies combine the use of catalysts with lean-NOx fuel to achieve reductions in PM, CO, HC, and NOx.
- FBC filter systems combined with EGR demonstrate reductions in NOx and CO.
- Substantial PM emission reductions have been achieved using a proprietary camshaft modification combined with oxidation catalysts.

Engine Modifications. Engine modifications encompass both retrofit and new engine purchases. Retrofit engine modifications involve rebuilds to integrate changes in timing, fuel injection, exhaust, or other components to retrofit diesel engines. Several engine modifications and design changes proposed to control emission include stand-alone modifications, as well as others used in conjunction with after-treatment and/or fuel changes.

Exhaust Gas Recirculation. EGR involves mixing exhaust gas with intake air – a technology that has been used in gasoline automobiles. A test by MECA and the Southwest Research Institute used EGR combined with an oxidation catalyst to achieve a NOx + HC emission of less than 2.5 g/bhp-hr (*16*). EGR is estimated to cost $600 per unit (not including installation), with potential NOx reduction cost of approximately $44 per ton (*16*).

Injection Timing Retard. Injection timing retard involves the use of electronic controls and software codes to improve fuel injection systems and produce more efficient combustion. NOx reductions of up to 40 percent were achieved in on-road vehicles using injection-timing retard. EPA's urban bus retrofit program has approved this technology.

Cam Shaft Cylinder Reengineering Kit. The camshaft cylinder reengineering kit consists of specific engine retrofit components, including a proprietary camshaft. It reduces NOx by increasing the volume of exhaust gas remaining in the combustion chamber after the power stroke. The residual gas remaining in the chamber absorbs heat and reduces combustion temperature, thereby lowering NOx emissions. The technology has been certified by CARB. The manufacturer indicates no greater than 1.0 g/bhp-hr HC, 8.5 g/bhp-hr CO, 5.8 g/bhp-hr NOx, and 0.16 g/bhp-hr PM. The product is commercially available with a cost of $3,480 to $15,680 depending on horsepower. The CARB technology review identified engine retrofits that ranged in price from $1,500 to $3,000 for smaller light duty engines and up to $15,000 for high horsepower engines (*15*).

MECA Summary and Conclusions

The MECA report, *Emission Control Retrofit of Diesel-Fueled Vehicles,* offered the following conclusions based on its review of emission controls for diesel-fueled engines (*18*: Page 20):

- Oxidation catalyst technology can substantially reduce particulates, HC, smoke, and odor from diesel engines, and improvements in oxidation catalyst technology continue to evolve to further enhance the application of this technology to diesel engines.
- Selective catalytic reduction can simultaneously reduce NOx, PM, and HC.
- Filter technology can reduce harmful particulate emissions by up to 90 percent or more, as well as substantially reduce smoke.
- Air enhancement technologies can be used to reduce emissions of PM, CO, and smoke. They can also be used to enhance the performance of other retrofit controls, such as oxidation catalysts.
- Thermal management technologies combined with catalyst technology, including lean-NOx catalyst technology, can be used to simultaneously reduce PM, CO, HC, and NOx.

- Both oxidation catalysts and filters can be used in conjunction with engine management techniques, e.g., injection timing retard or EGR, to reduce diesel particulate CO, HC, and NOx emissions.
- Several oxidation catalysts systems have been approved under EPA's urban bus rebuild/retrofit program along with three 0.1 g/bhp-hr systems. Another 0.1 g/bhp-hr system has been submitted for certification approval.
- For oxidation catalyst retrofit applications, fuel sulfur levels below 0.05 percent weight are desirable, but not required. Lower fuel sulfur levels increase the PM reductions provided and make vehicle integration simpler.
- When selecting a retrofit control technology, it is important to ensure that the technology is compatible with the duty cycle of the vehicle, the available fuels, and the desired emissions reductions.

Diesel Fuel

Both EPA and TNRCC recognize reducing the sulfur content in diesel fuel as an important strategy for reducing future diesel engine emissions. Achieving effective emission control technologies for diesel engines requires low-sulfur fuel. Federal requirements for new diesel engine emission standards that take effect in 2007 and low-sulfur fuel requirements that take effect in 2006 will combine to effectively reduce NOx and nonmethane HC emissions. TNRCC will begin implementing its requirements for low-sulfur fuel in 2002. Additionally, TNRCC requirements will encompass both on-road and nonroad engines.

TNRCC's approach to reformulating diesel fuel to benefit air quality involves reducing the sulfur and aromatic HC content, and increasing cetane content. Reduction of sulfur in diesel fuels serves to enable new engine and after-treatment technologies that are sensitive to sulfur compounds in exhaust.

Texas Low Emission Diesel Fuel Program. TNRCC has initiated a program to implement low-emission diesel fuels. The LED Program begins May 1, 2002, and requires that, beginning May 1, 2002, diesel fuel produced for delivery and ultimate sale to the consumer in affected areas shall not exceed 500 ppm sulfur, must contain less than 10 percent by volume of aromatic HC, and must have a cetane number of 48 or greater. The LED Program requires that low-emission diesel fuel be used year-round in all diesel-fueled compression-ignition engines in both on-road vehicles and nonroad equipment operating within the affected counties. In addition, these rules will require the diesel fuel supplied to the DFW, Beaumont/Port Arthur (BPA), and HG ozone nonattainment areas, and 95 central and eastern Texas counties reduce the sulfur content to 15 ppm beginning June 1, 2006. The rule also requires diesel fuel producers and importers who provide fuel to the affected areas to register with the commission and provide quarterly status reports. The new rule applies not to the user of the fuel, but directly to the supplier, in an attempt to regulate the fuel available to consumers in the state.

LED Program rules will require fuel for both on-road and nonroad use in:

- eight counties in the HG region, including Brazoria, Chambers, Fort Bend, Galveston, Harris, Liberty, Montgomery, and Waller Counties;
- four counties in the DFW region, including Collin, Dallas, Denton, and Tarrant Counties;
- three counties in the BPA region, including Hardin, Jefferson, and Orange Counties; and
- 95 additional counties in central and eastern Texas, including Anderson, Angelina, Aransas, Atascosa, Austin, Bastrop, Bee, Bell, Bexar, Bosque, Bowie, Brazos, Burleson, Caldwell, Calhoun, Camp, Cass, Cherokee, Colorado, Comal, Cooke, Coryell, De Witt, Delta, Ellis, Falls, Fannin, Fayette, Franklin, Freestone, Goliad, Gonzales, Grayson, Gregg, Grimes, Guadalupe, Harrison, Hays, Henderson, Hill, Hood, Hopkins, Houston, Hunt, Jackson, Jasper, Johnson, Karnes, Kaufman, Lamar, Lavaca, Lee, Leon, Limestone, Live Oak, Madison, Marion, Matagorda, McLennan, Milam, Morris, Nacogdoches, Navarro, Newton, Nueces, Panola, Parker, Polk, Rains, Red River, Refugio, Robertson, Rockwall, Rusk, Sabine, San Augustine, San Jacinto, San Patricio, Shelby, Smith, Somervell, Titus, Travis, Trinity, Tyler, Upshur, Van Zandt, Victoria, Walker, Washington, Wharton, Williamson, Wilson, Wise, and Wood Counties.

Effects of Low-Emission Diesel. In a literature review, Lee, Pedley, and Hobbs (*17*) studied the fuel quality effects on NOx and PM diesel emissions. In general, they reported:

- Reducing sulfur from 0.30 percent (3000 ppm) to 0.05 percent (500 ppm) yields large benefits for PM but little or no effect on NOx, HC, or CO.
- Reducing sulfur content below 0.05 percent (500 ppm) yields minimal benefits, but low sulfur content is necessary as an enabler of after-treatment technology to reduce NOx and HC.
- Increasing cetane yields small benefit in NOx, and variable to no effect on PM.
- Large decreases in aromatics (from 10 to 30 percent) give small reductions (up to 5 percent) in NOx; it has no effect on PM, HC, or CO.
- Reducing poly-aromatic HC yields a small benefit in HC and NOx emissions, and large PM benefits for high-emission engines; but it has no effect on low-emission engines.

TNRCC, in referencing its own study by ERG (*19*), and its own participation in EPA's heavy-duty engine working group (HDEWG), has countered some industry skepticism regarding potential NOx benefits from modifying cetane and aromatic HC concentrations in reformulated diesel fuel. TNRCC claims reductions of 7 percent statewide are indeed reasonable and conservative. According to TNRCC, the 7 percent NOx emission reduction value is only slightly higher than the 5.7 percent figure used for electronically controlled engines reported in the ERG analysis.

In supporting its claim, TNRCC referenced the SAE paper (*17*) by citing a less than 5 percent impact for total aromatic reductions from 30 to 10 percent by weight, stating that on a percent basis, poly-aromatics should contribute more to NOx than a corresponding amount of mono-aromatics. Furthermore, if poly-aromatics are reduced disproportionately compared to mono-aromatics, total aromatic reductions could be even greater. Since the HDEWG predictive model accounts for both poly- and mono-aromatic levels, TNRCC claims that the modeled result of 5.7 percent is within the range of reasonable reductions (*19*).

TNRCC estimates that the LED Program can achieve a 7 percent reduction in NOx by 2007 and estimates a 30-tpd reduction in NOx statewide, 6.84 tpd attributable to HG. CARB claims a higher potential emission reduction (about 12 percent) than TNRCC for electronically controlled diesel engines using an equivalent fuel specification. TNRCC bases NOx benefits on testing under HDEWG, utilizing a sophisticated fuel matrix and EGR representative of engines meeting the upcoming 2004 standards (*19*).

Although reformulated diesel fuels alone may have a limited effect on NOx emissions, low-sulfur diesel fuels in combination with various control technologies can yield significant emission benefits. A MECA study demonstrated the enabler effect of low-sulfur fuels. The study used two low-sulfur fuels, 384 ppm sulfur diesel and 54 ppm sulfur diesel, in combination with DOCs, DPFs, and SCRs. The study demonstrated that PM emissions of 0.03 g/bhp-hr combined with NOx+HC emissions of 1.5 g/bhp-hr could be achieved (*20*).

Diesel Fuel Costs. Identifying low-sulfur diesel fuel price projections is challenging in light of competing interests, changing technologies, and fluctuating fuel prices in general. For the purposes of this report, researchers present the range of prices so that a broad comparison can be made. Just as emission control equipment prices vary, so do fuel price projections.

Predictions on the cost increase for low-sulfur fuels (<500 ppm) vary from $0.04 to $0.14 per gallon depending on the source. TNRCC reports production cost of $0.04 to $0.08 per gallon of diesel fuel to comply with the new rules. Industry sources say retail cost increases will range from $0.10 to $0.14 per gallon. For very low-sulfur fuel, with sulfur content of less than 15 ppm required by 2006, some sources estimate an additional $0.05 to $0.19 per gallon increase. Potential implementation of desulfation processes at fuel refineries may also affect future price.

In its regulatory impact analysis, EPA reports that low-sulfur diesel fuel cost will increase $0.044 per gallon, and per-vehicle costs adjusted to net present value (NPV) range from $3,704 for heavy-duty vehicles to $536 for light-heavy duty vehicles. A detailed cost analysis is available in EPA420-F-00-022 (*14*: Chapter V).

Alternative Diesel Fuels. Several diesel formulations and diesel emulsions have demonstrated emission benefits including: Swedish Urban Diesel, ARCO's Emission Control Diesel (EC-D), synthetic diesel, and two diesel emulsion products. These fuels are summarized below (*15*):

- ARCO's EC-D is a very low-sulfur, low-aromatic, and high-cetane diesel fuel produced from typical crude oil. Preliminary tests indicate a 10-15 percent NOx reduction for buses and 11 percent and 3 percent for trucks.

- The Fischer-Tropsch gas to liquid (GTL) conversion process refines ultra-low aromatic synthetic diesel fuels. Preliminary tests compared to CARB fuel resulted in a 4 percent reduction in NOx, 36 percent reduction in HC, 20 percent reduction in CO, and 26 percent reduction in PM.
- Fuel/water emulsions from A-55 Incorporated and Lubrizol Corporation have demonstrated emission benefits. A-55 has patented a diesel/water emulsion and a naptha/water emulsion. The presence of water, which lowers combustion temperatures, reduces both diesel PM and NOx emissions. Preliminary tests on A-55 fuel in transit buses showed NOx reductions of 54 percent and diesel PM reductions of 20 percent (7). The Lubrizol fuel, called PuriNOX™, is a diesel/water emulsion with reported NOx reduction of 15 percent and PM reduction of 51 percent. Other diesel emulsions under development include ethanol/diesel micro-emulsions.
- Dimethyl ether (DME) is made from fossil feedstocks including natural gas, coal, and some renewable feedstocks. When used as fuel for diesel engines, DME offers potential NOx and PM emissions benefits.

RESEARCH STRATEGY / METHODOLOGY

This section develops and presents estimates of the relative cost and benefits of two control measures. The first estimate is based on the cost and emission benefits for using the construction shift for both HG and DFW. The second estimate is based on the cost and emission benefit of using emission control technology. Finally, a comparison of the two control measures is presented.

Construction Shift Estimate Methodology

Using information previously presented in Chapter I, the costs associated with regulatory action to restrict construction equipment operations is estimated to result in a cost to TxDOT construction projects of $400,000 to $500,000 per ton NOx reduced. Using the construction project cost impacts documented in Chapter V of this report, an adjusted cost is $350,000 to $550,000 per ton NOx reduced.

Diesel Engine Emission Control Estimate Methodology

The methodology for estimating cost and emission benefits from using emission control devices was formulated as a sketch-planning tool to compare the relative cost per ton reduced of various control measures; in particular, researchers wanted to compare the cost per ton of NOx reduced from a construction shift to the cost per ton of using emission control technology. The methodology for estimating the emission control cost and benefits involved four steps:

1. selecting viable emission control technologies for the heavy-highway equipment inventories for both HG and DFW,
2. estimating the cost to install the emission controls on the heavy-highway equipment fleet for HG and DFW,

3. estimating the potential NOx reduction from using the emission control equipment installation, and
4. applying the NOx reduction potential of the emission control technology to the heavy-highway sector of the NOx inventory developed from the construction shift estimate.

Emission Control Technologies

The review of emission control technologies identified relative costs and emission benefits. Among the control devices reviewed, SCR technologies were chosen as the comparative control measure because of the greater potential for NOx reduction, commercial availability, and a cost representative of other emerging NOx emission control technologies. The selection of SCR for this comparison is not an endorsement of the technology – it is used simply as a representative emission control technology to compare against the construction shift.

The literature suggests that, as production of the various emission control devices increases, the cost of those devices should decline. Although PM control devices are generally less expensive to purchase and install, SCR is used in this comparison because it offers NOx reduction benefits. Another consideration in selecting SCR for the comparison was its ability to be used with diesel fuel containing 500 ppm sulfur, which will be implemented by 2002 under the Texas LED Program. Other NOx reduction emission technologies considered required very low-sulfur diesel fuel (<15 ppm sulfur). Greater NOx and PM reductions will be realized as the LED Program is fully implemented with the introduction of 15 ppm sulfur by 2006, but immediate reductions are possible beginning in 2002 with the introduction of diesel fuels containing 500 ppm sulfur.

Control Technology Cost (Using CARB Annualized Cost)

Researchers reviewed cost information on SCR systems from the manufacturers and CARB, along with the annualized cost estimate from CARB for various control technologies. The CARB annualized cost estimates are based on manufacturer surveys of the current retail price, 500 hours per year operation, a maximum economic life of 10 years, and a 9 percent interest rate. CARB estimates the cost will decline as production volumes increase (*15*). The annualized cost for 10 years was used to estimate the total cost of installing the NOx reduction control equipment on the heavy-highway nonroad construction equipment inventory for HG and DFW. The annualized cost was adjusted over 10 years, back to the first year NPV, to derive the total cost. Although using SCR and placing the entire cost of implementation in the first year may exaggerate actual costs, the estimate is conservative. The actual cost of implementing emission control technologies would likely be less expensive than those represented in this comparison.

Another consideration is the cost per horsepower to implement emission controls. Generally, the cost per horsepower increases for lower horsepower equipment (50 to 100 hp), and the cost per horsepower decreases for higher horsepower equipment. Most of the current diesel emission control devices targeting NOx reduction were first designed for stationary high horsepower diesel equipment (275 hp and greater). As product development improves for mobile equipment and lower horsepower, the cost for emission controls should decline.

Construction Emissions and Equipment Inventories

The NOx emissions inventory data and equipment inventory data were taken from attainment demonstration documents for the construction equipment restriction rule estimate and used as the basis for estimating the cost per ton reduced of implementing emission control technology. The modal horsepower rating for the equipment inventory was reported as 100 hp to 175 hp (2). Researchers used both the maximum (275 hp) and minimum (100 hp) values in the calculations in order to provide a conservative range of costs. It is assumed that most equipment and most of the NOx emissions from the inventory are below 175 hp. The lower range of NOx emission reduction effectiveness using SCR (65 percent) was chosen in the calculation to provide a more conservative estimate.

Emission Control Estimate

Researchers estimated the cost of implementing NOx reducing control technology over the entire heavy-highway equipment inventory at $16.9 to $24.5 million for HG, and $12.2 to $17.7 million for DFW. The NOx emission reduction was estimated to be 444 tons for HG and 510 tons for DFW. Therefore, the cost per ton reduction of technology controls for HG is estimated to be $38,000 to $55,000 per ton NOx reduced, and $24,000 to $35,000 per ton NOx reduced in DFW. The emission control estimates for DFW and HG are presented in Figures 6 and 7, respectively.

RESULTS

Tables 35 through 40 compare the following control measures:

- construction shift based on TNRCC estimated emission and cost,
- construction shift based on TNRCC emissions estimate and TTI-estimated cost impact,
- use of SCR as emission control technology on the heavy-highway fleet,
- limited use (30 percent) and limited NOx reduction (30 percent) of SCR,
- LED Program, and
- accelerated purchase program.

Construction Shift Comparison

The construction shift in HG is estimated to produce a NOx reduction benefit of 0.8 tpd, or a total of 171 tons during the 214 days of Daylight Savings Time, from the heavy-highway sector. The cost of the shift to TxDOT, based on TNRCC estimates, would be $70 million annually, resulting in a cost of roughly $400,000 per ton of NOx reduced. (See Table 35.)

Researchers adjusted the initial cost (in Chapter I) impact of the construction shift for HG and DFW based on a survey (21) of contractors and TxDOT personnel from each nonattainment area.

Information from the survey was used to develop cost and duration impacts for various types of construction projects and alternative work schedules. Researchers found that the total cost impact was 12 percent for HG and 16 percent for DFW.

Given:

2007 HG construction NOx emissions = 32.1 tpd (*7*)
2007 NOx inventory = 1064 tpd (*2*)
Annual duration of rule is 214 days (beginning to end of Daylight Savings Time)
CARB estimated annualized cost for 100 hp engine = $3,060 (*15*)
Rounded NPV (P/A) annualized cost for 10 years on 100 hp engine: $3,060 × (6.418) = $19,640 ea = **$20,000**
CARB estimated annualized cost for 275 hp engine = $4,460 (*15*)
Rounded NPV (P/A) annualized cost for 10 years on 275 hp engine: $4,460 × (6.418) = $28,624 ea = **$29,000**

Control Technology Assumptions

Modal equipment horsepower = 100-175 hp (*2*)
HG nonroad heavy-highway sector diesel construction equipment inventory = **845 pieces** (*7*)
Minimum estimated NOx reduction from control technology = **65%** (*16*)

NOx Inventory Assumptions

Heavy-highway sector represents 11.5 percent of the construction sector (source: correspondence from TNRCC staff)

Cost Calculations of NOx Control Technology for Construction Equipment Inventory

845 pieces × $20,000 ea. per 100 hp = **$16,900,000 NPV**
845 pieces × $29,000 ea. per 275 hp = **$24,505,000 NPV**

NOx Inventory Calculations

Heavy-highway sector contribution to 2007 NOx inventory = 32.1 tpd ÷ 1064 tpd × 11.5% = 0.3%
Heavy-highway sector NOx contribution (tpd) = 0.3% × 1064 tpd = 3.19 tpd
Heavy-highway sector NOx contribution (tons) = 3.19 tpd × 214 days = **683 tons**

NOx Reductions from Control Technology

65% reduction from NOx control equipment = 683 tons × 65% = **444 tons reduced annually**

Cost per Ton Range

Cost of control technology per ton reduced = $16,900,000 ÷ 444 tons = **$38,063 per ton NOx**
Cost of control technology per ton reduced = $24,505,000 ÷ 444 tons = **$55,191 per ton NOx**

$38,000 to $55,000 per ton NOx reduced

30% Reduced Implementation and 30% Reduced Efficiency Alternative

254 pieces × $20,000 ea. per 100 hp = $5,080,000 NPV
254 pieces × $29,000 ea. per 275 hp = $7,366,000 NPV
30% reduction efficiency on 30% of equipment = 9% reduction × 683 tons = **61 tons NOx**

Cost per Ton Range:

Cost of control technology per ton reduced = $5,080,000 ÷ 61 tons = **$83,278 per ton NOx**
Cost of control technology per ton reduced = $7,366,000 ÷ 61 tons = **$120,754 per ton NOx**

$83,000 to $121,000 per ton NOx reduced

Figure 6. HG Emission Control Technology Cost Estimate per Ton NOx Reduced.

Given:
2007 DFW construction NOx emissions: 44.98 tpd (*2*)
2007 NOx inventory: 320.5 tpd (*1*)
Annual duration of rule is 153 days (June 1 – October 31)
CARB estimated annualized cost for 100 hp engine = $3,060 (*16*)
Rounded NPV (P/A) annualized cost for 10 years on 100 hp engine: $3,060 × (6.418) = $19,640 ea = **$20,000**
CARB estimated annualized cost for 275 hp engine = $4,460 (*16*)
Rounded NPV (P/A) annualized cost for 10 years on 275 hp engine: $4,460 × (6.418) = $28,624 ea = **$29,000**

Control Technology Assumptions
Modal equipment horsepower = 100-175 hp (*2*)
DFW nonroad diesel construction equipment inventory = **610 pieces** (*7*)
Minimum estimated NOx reduction from control technology = **65%** (*16*)

NOx Inventory Assumptions
Heavy-highway sector represents 11.5% of the construction sector (source: correspondence with TNRCC staff)

Cost Calculations of NOx Control Technology for Construction Equipment Inventory
610 pieces × $20,000 ea. per 100 hp = **$12,200,000 NPV**
610 pieces × $29,000 ea. per 275 hp = **$17,690,000 NPV**

NOx Inventory Calculations
Heavy-highway sector contribution to 2007 NOx inventory = 44.98 tpd ÷ 320.5 tpd × 11.5% = 1.6%
Heavy-highway sector NOx contribution (tpd) = 1.6% × 320.5 tpd = 5.13 tpd
Heavy-highway sector NOx contribution (tons) = 5.13 tpd × 153 days = **784.6 tons**

NOx Reductions from Control Technology
65% reduction from NOx control equipment: 784.6 tons × 65% = **510 tons reduced annually**

Cost per Ton Range
Cost of control technology per ton reduced: $12,200,000 ÷ 510 tons = **$23,921 per ton NOx**
Cost of control technology per ton reduced: $17,690,000 ÷ 510 tons = **$34,682 per ton NOx**

$24,000 to $35,000 per ton NOx reduced

30% Reduced Implementation and 30% Reduced Efficiency Alternative
183 pieces × $20,000 ea. per 100 hp = $3,660,000 NPV
183 pieces × $29,000 ea. per 275 hp = $5,307,000 NPV
30% reduction efficiency on 30% of equipment = 9% reduction × 510 tons = **46 tons NOx**

Cost per Ton Range:
Cost of control technology per ton reduced = $3,660,000 ÷ 46 tons = **$79,565 per ton NOx**
Cost of control technology per ton reduced = $5,307,000 ÷ 46 tons = **$115,369 per ton NOx**

$80,000 – $115,000 per ton NOx reduced

Figure 7. DFW Emission Control Technology Cost Estimate per Ton NOx Reduced.

Assuming $490 million in annual lettings for fiscal year 1999 in HG, researchers estimated the total cost impact of the construction shift to be approximately $59 million, or $344,000 per ton of NOx reduced. Table 35 also presents this information.

Table 35. Construction Shift for HG.

Control Measure	Description	Heavy-Highway NOx Benefit	Estimated Cost (annually)	Effectiveness
Construction shift based on SIP and attainment demonstration	Approved by TNRCC; 214-day duration (during Daylight Savings Time)	0.8 tpd (171 tons annually)	$70 million	$409,000 per ton
Construction shift based on TTI total cost impact	TTI comparison; 214-day duration (during Daylight Savings Time)	0.8 tpd (171 tons annually)	$59 million	$344,000 per ton

Using TNRCC cost estimates, the construction shift in DFW is estimated to cost $54 million annually and yield 107 tons of NOx reduced for approximately $505,000 per ton of NOx reduced. In DFW, researchers estimated the total cost impact of the construction shift to be approximately $57 million annually, or $537,000 per ton of NOx reduced based on $359 million in annual lettings. See Table 36.

Table 36. Construction Shift for DFW.

Control Measure	Description	Heavy-Highway NOx Benefit	Estimated Cost (annually)	Effectiveness
Construction shift based on SIP and attainment demonstration	Approved by TNRCC; 153-day duration (June 1– October 31)	0.7 tpd (107 tons annually)	$54 million	$505,000 per ton
Construction shift based on TTI total cost impact	TTI comparison; 153-day duration (June 1– October 31)	0.7 tpd (107 tons annually)	$57 million	$537,000 per ton

Emission Control Comparison

As presented in Table 37, the estimated cost for installing SCR on the entire heavy-highway fleet in HG is between $17 and $24 million and will yield an estimated NOx reduction of 2.1 tpd, or approximately 444 tons annually. In Table 38, DFW's cost of implementing emission controls is estimated to range from $12.2 to $17 million.

Since full implementation is unlikely to occur, an alternative scenario was estimated for both HG and DFW. This partial implementation scenario uses the same basic assumption except that it implements the SCR emission controls on 30 percent of the fleet and assumes the emission control is only 30 percent effective.

Tables 37 and 38 show the estimated costs and effectiveness for partial implementation in DFW and HG. The DFW full implementation should achieve 0.3 tpd NOx reduction, for a total of 510 tons. The partial implementation scenario results in NOx reduction cost of approximately $80,000 to $120,000 per ton of NOx reduced for HG and DFW.

Table 37. HG Emission Control Cost.

Control Measure	**Description**	**Heavy-Highway NOx Benefit**	**Estimated Cost**	**Effectiveness**
Emission control technology using SCR on entire heavy-highway fleet	Comparison using SCR NOx emission-reduction equipment on heavy-highway sector, assuming modal hp of 100-175 hp and 845 pieces	2.1 tpd (444 tons annually)	$17 million to $24 million	$38,000 per ton to $55,000 per ton
Partial implementation of control technology (30% fleet / 30% NOx reduction efficiency)	Comparison using SCR NOx emission-reduction equipment on heavy-highway sector, assuming modal hp of 100-175 hp and 254 pieces	0.28 tpd (61 tons annually)	$5.1 million to $7.4 million	$83,000 per ton to $121,000 per ton

Table 38. DFW Emission Control Cost.

Control Measure	Description	Heavy Highway NOx Benefit	Estimated Cost	Effectiveness
Emission control technology using SCR	TTI comparison for DFW using SCR NOx emission control on heavy-highway sector, assuming modal hp of 100-175 hp and 610 pieces	3.3 tpd (510 tons annually)	$12.2 million to $17.7 million	$24,000 per ton to $35,000 per ton
Partial implementation of control technology (30% of fleet and 30% NOx reduction efficiency)	Comparison using SCR NOx emission reduction equipment on heavy-highway sector, assuming modal hp of 100-175 hp and 183 pieces	0.3 tpd (46 tons annually)	$3.7 million to $5.3 million	$80,000 per ton to $115,000 per ton

LED and Accelerated Purchase

Tables 39 and 40 present the estimates for both costs and emissions benefits from both the LED Program and accelerated purchase control measures. Unlike the previous comparisons, the cost and emission benefit information in Tables 39 and 40 rely heavily on information from regulatory impact analyses from TNRCC and EPA sources.

The NOx reduction benefit of the LED Program is assumed to be 7 percent, as stated in the rule's regulatory impact analysis. This rule was applied to the heavy-highway NOx inventory for both HG and DFW. The cost of the program per piece of equipment was not easily defined due to various estimates from industry and regulatory agencies that usually give only fuel cost increases or costs for the entire program. Therefore, researchers found it difficult to separate out the cost for the heavy-highway equipment sector. The equipment cost estimate is based on EPA's *Draft Regulatory Impact Analysis for the Heavy-Duty Engine and Vehicle Standards and Highway Diesel Fuel Sulfur Control Requirements Rule* (*14*). In this report, EPA calculated the long-term incremental cost of $0.044 per gallon for low-sulfur diesel fuel and calculated the cost per vehicle by class and average fuel economy. Researchers then brought back total fuel cost to a total NPV in the year of sale per vehicle and yielded the following costs: $536 for a light heavy-duty vehicle; $1,004 for a medium heavy-duty vehicle; $3,704 for a heavy heavy-duty vehicle; and $4,364 for an urban bus.

Researchers also took emission benefits from the accelerated purchase program from the regulatory impact analyses reported by TNRCC, where available. The NOx benefit for the accelerated purchase program is taken from EPA estimates of 40 percent PM reduction and 60 percent NOx reduction over the entire length of the program. Researchers were unable to locate and identify the cost information for the HG accelerated purchase program contained in an appendix to the SIP and attainment demonstration documents.

Comparison Summary

The combined comparison for HG and DFW are presented in Tables 41 and 42, respectively.

Table 39. HG LED and Accelerated Purchase Comparison.

Control Measure	Description	Heavy-Highway NOx Benefit	Estimated Cost	Effectiveness
Low-Emission Diesel Fuel Program	Approved by TNRCC. LED Program begins May 1, 2002; requires diesel fuel produced for delivery and sale; shall not exceed 500 ppm sulfur, less than 10 percent by vol. aromatic HC, and cetane number of 48 or greater	0.22 tpd 48 tons (7% by TNRCC)	*\$2.6 million Cost range: \$0.04 - \$0.14 per gal	*\$54,000 per ton (based on \$0.044 per gal)
Accelerated Purchase Tier 2 Equipment Fleet	Approved by TNRCC Tier 2 equipment fleet <u>50-100 hp:</u> 25% Tier 2 by end 2004 50% Tier 2 by end 2005 75% Tier 2 by end 2006 100% Tier 2 by end 2007 <u>100-175 hp:</u> 10% Tier 2 by end 2004 20% Tier 2 by end 2005 30% Tier 2 by end 2006 50% Tier 2 by end 2007	**60% NOx **40% PM	NA	NA

*NPV cost based on EPA 15 ppm LED lifetime cost per piece in first year, modal hp 100-175, equip, 845 pieces @ \$3,704 ea. = \$2,597,530, 7 percent reduction for 48 tons reduced = \$54,000/ton

**Based on EPA estimates for entire span of program.

NA – not available

Table 40. DFW LED and Accelerated Purchase Comparison.

Control Measure	Description	Heavy-Highway NOx Benefit	Estimated Cost	Effectiveness
Low-Emission Diesel Fuel Program	Approved by TNRCC. LED Program begins May 1, 2002; requires diesel fuel produced for delivery and sale; shall not exceed 500 ppm sulfur, less than 10 percent by vol. aromatic HC, and cetane number of 48 or greater	0.31 tpd 47 tons (7% by TNRCC)	*$2,259,440 Cost range: $0.04. - $0.14 per gal.	*$48,000 per ton (based on $0.044 per gal)
Accelerated Purchase Tier 2 Equipment Fleet	Approved by TNRCC Tier 2 equipment fleet <u>50-100 hp:</u> 25% Tier 2 by end 2004 50% Tier 2 by end 2005 75% Tier 2 by end 2006 100% Tier 2 by end 2007 <u>100-175 hp:</u> 10% Tier 2 by end 2004 20% Tier 2 by end 2005 30% Tier 2 by end 2006 50% Tier 2 by end 2007	**60 percent NOx **40 percent PM	NA	$8,700 per ton-$11,700 per ton (based on TNRCC Ch 114 p. 10 preamble)

*NPV cost based on EPA 15 ppm LED lifetime cost per piece in first year, modal hp 100-175, equip, 610 pieces @ $3,704 ea. = $2,597,530, 7 percent reduction for 48 tons reduced = $48,000/ton

**Based on EPA estimates for entire span of program.

NA – not available

Table 41. HG Control Measure Comparison Summary.

Control Measure	Description	Heavy-Highway NOx Benefit	Estimated Cost	Effectiveness
Construction shift based on SIP and attainment demonstration	Approved by TNRCC. 214-day duration (during Daylight Savings Time)	0.8 tpd (171 tons annually)	$70 million (annually)	$409,000 per ton
Construction shift based on TTI total cost impact	TTI comparison. 214-day duration (during Daylight Savings Time)	0.8 tpd (171 tons annually)	$59 million (annually)	$344,000 per ton
Emission control technology using SCR on entire heavy-highway fleet	Comparison using SCR NOx emission-reduction equipment on heavy-highway sector, assuming modal hp of 100-175 hp and 845 pieces	2.1 tpd (444 tons annually)	$17 million to $24 million	$38,000 to $55,000 per ton
Partial implementation of control technology (30% of fleet and 30% NOx reduction efficiency)	Comparison using SCR NOx emission-reduction equipment on heavy-highway sector, assuming modal hp of 100-175 hp and 254 pieces	0.28 tpd (61 tons annually)	$5.1 million to $7.4 million	$83,000 to $121,000 per ton
Low Emission Diesel Fuel Program	Approved by TNRCC. LED Program begins May 1, 2002; requires diesel fuel produced for delivery and sale; shall not exceed 500 ppm sulfur, less than 10 percent by vol. aromatic HC, and cetane number of 48 or greater	0.22 tpd (48 tons) (7 percent by TNRCC)	*$2.6 million Cost range: $0.04 per gal - $0.14 per gal	*$54,000/ton (based on $0.044 per gal)
Accelerated Purchase Tier 2 Equipment Fleet	Approved by TNRCC Tier 2 equipment fleet 50-100 hp: 25% Tier 2 by end 2004 50% Tier 2 by end 2005 75% Tier 2 by end 2006 100% Tier 2 by end 2007 100-175 hp: 10% Tier 2 by end 2004 20% Tier 2 by end 2005 30% Tier 2 by end 2006 50% Tier 2 by end 2007	**60 percent NOx **40 percent PM	NA	NA

*NPV cost based on EPA 15 ppm LED lifetime cost per piece in first year, modal hp 100-175, equipment, 845 pieces @ $3,704 ea. = $2,597,530, 7 percent reduction for 48 tons reduced = $54,000/ton

**Based on EPA estimates for entire span of program.

NA – not available

Table 42. DFW Control Measure Comparison Summary.

Control Measure	Description	Heavy-Highway NOx Benefit	Estimated Cost	Effectiveness
Construction shift based on SIP and attainment demonstration	Approved by TNRCC 153-day duration (June 1-October 31)	0.7 tpd (107 tons annually)	\$54 million (annually)	\$505,000 per ton
Construction shift based on TTI totals cost impact	TTI comparison 153-day duration (June 1-October 31)	0.7 tpd (107 tons annually)	\$57 million (annually)	\$537,000 per ton
Emission control technology using SCR on entire heavy-highway fleet	Comparison using SCR NOx emission-reduction equipment on heavy-highway sector, assuming modal hp of 100-175 hp and 610 pieces	3.3 tpd (510 tons annually)	\$12.2 million to \$17.7 million	\$24,000 to \$35,000 per ton
Partial implementation of control technology (30% of fleet and 30% NOx reduction efficiency)	Comparison using SCR NOx emission-reduction equipment on heavy-highway sector, assuming modal hp of 100-175 hp and 183 pieces	0.3 tpd (46 tons annually)	\$3.7 million to \$5.3 million	\$80,000 to \$115,000 per ton
Low Emission Diesel Fuel Program	Approved by TNRCC. LED Program begins May 1, 2002; requires diesel fuel produced for delivery and sale; shall not exceed 500 ppm sulfur, less than 10 percent by vol. aromatic HC, and cetane number of 48 or greater	0.31 tpd (47 tons) (7 percent by TNRCC)	*\$2,259,440 Cost range: \$0.04 per gal. - \$0.14 per gal.	*\$48,000 per ton (based on \$0.044 per gal)
Accelerated Purchase Tier 2 Equipment Fleet	Approved by TNRCC Tier 2 equipment fleet 50-100 hp: 25% Tier 2 by end 2004 50% Tier 2 by end 2005 75% Tier 2 by end 2006 100% Tier 2 by end 2007 100-175 hp: 10% Tier 2 by end 2004 20% Tier 2 by end 2005 30% Tier 2 by end 2006 50% Tier 2 by end 2007	**60 percent NOx **40 percent PM	NA	\$8,700 to \$11,700 per ton (based on TNRCC Ch 114 p. 10 preamble)

*NPV cost based on EPA 15 ppm LED lifetime cost per piece in first year, modal hp 100-175, equipment, 610 pieces @ \$3,704 ea. = \$2,259,440, 7 percent reduction for 47 tons reduced = \$48,000/ton

**Based on EPA estimates for entire span of program.

NA – not available

CONCLUSIONS

TNRCC expects an estimated 21 and 13 percent emission reduction from the construction industry through the equipment operating restrictions in HG and DFW, respectively. This reduction will come at a cost to TxDOT and other government agencies as well as to private business. TxDOT may pay $400,000 to $500,000 per ton of NOx reduction as a result of this rule. In comparison, emission control devices cost four to 10 times less. The review and assessment of diesel engine emissions presented herein indicate that implementing after-treatment emission controls would range from $24,000 to $55,000 per ton of NOx reduction across the entire fleet, and $80,000 to $120,000 per ton of NOx reduction if controls are only partially implemented.

Alternative control measures for construction projects, such as diesel engine emission controls, have the potential to allow equipment to operate during normal working hours and still provide NOx emission reductions. The costs of these controls should be carefully evaluated against the anticipated cost increases to TxDOT letting costs in response to the construction shift rule. If using after-treatment emission controls shows a cost savings, perhaps incentives to encourage or accelerate their adoption into the heavy-highway fleet should be developed and assessed. For example, NOx reduction credits could be used as a contracting performance measure in the same way that time and duration contract performance measures are used in construction contracts. Or, funding assistance could be provided to construction equipment owners and contractors that would encourage retrofitting equipment with NOx emission controls sooner than those scheduled in the accelerated purchase rules. Regardless, a host of control measure options should be explored and assessed as alternatives to the construction restriction rule.

Alternative control measures have the potential to offer similar or greater NOx reduction benefits for less money. However, the after-treatment approach to emission control presents challenges of its own such as: the limited commercial availability of NOx after-treatment devices over a broad range of engine horsepower, long-term reliability and maintenance, reduced fuel efficiency, and the evolving nature of emission control technology. The primary benefit of using after-treatment will be the potential to achieve greater NOx reductions sooner. It is also important to note that the emission benefits estimated within this report are calculated only during the construction restriction period. Emission benefits from emission control devices on heavy-highway equipment would actually occur year round, producing even greater reductions. Over the next five to 10 years, the implementation of cleaner diesel fuel and accelerated purchase should achieve significant NOx benefits. In the interim, a variety of control measures should be assessed for effectiveness.

In general, the results of this assessment indicate:

- The cost effectiveness of the LED Program appears to be greater than that of the construction equipment restriction rule. The use of diesel engine emission control devices targeted to reduce NOx emissions are more cost effective than the construction equipment restriction when measured in dollars per ton of NOx reduced.

- The cost of using diesel engine emission control technology (after-treatments and retrofits) is generally less than the cost of the construction equipment restriction rule and provides greater NOx emission reductions.
- The NOx reduction potential is greatest when diesel engine emission control devices are combined with the use of low-sulfur diesel fuel.
- Engine emission control and accelerated purchase are more cost effective than construction equipment restrictions. Even using conservative assumptions, NOx reductions using emission control after-treatment devices range from $25,000 to $55,000 per ton.
- The cost estimate for TxDOT by TNRCC from the impact of a construction equipment restriction rule is of the same order of magnitude as that developed by TTI. Both estimates indicate the cost per ton of NOx reduction to be more than $400,000 per ton.

CHAPTER VII. CONTRIBUTION OF VEHICULAR EMISSIONS CAUSED BY CAPACITY REDUCTION DURING ROADWAY CONSTRUCTION

INTRODUCTION

This chapter examines the impacts of shifting construction schedules, in response to construction equipment restrictions in Houston and Dallas/Fort Worth, with respect to mobile source emissions and delays during peak and off-peak conditions. QUEWZ-98 was selected to perform this evaluation. During the course of the evaluation, however, researchers identified several critical limitations associated with the QUEWZ-98 model with respect to the emissions calculation algorithm. The project staff proceeded by using QUEWZ-98 for delay calculations but developed an alternate method of modeling vehicular emissions. QUEWZ-98 directly calculated delays and road user costs associated with work zones and quantified operational characteristics of traffic flow through work zones. Traffic characteristics in the QUEWZ-98 output served as inputs to the emissions model developed from this work. This model is referred to as the Emissions Workbook and is based on Microsoft® Excel spreadsheets and Visual Basic macros.

The remainder of this chapter is divided into three major sections: QUEWZ-98 Analysis, Emissions Workbook, and Results. The QUEWZ-98 Analysis section details the range of scenarios evaluated, assumptions used, and limitations of QUEWZ-98. The Emissions Workbook section details the need for creating an alternate model for calculating emissions, the procedures to use the Emissions Workbook model developed for this project, and assumptions used in the calculations. The Using the Results section provides two examples of how the results of this study could potentially be used. Appendix B provides a series of tables and graphs summarizing the results of the analyses of the 161 scenarios. These tables and graphs can be utilized to examine the relative impact of various construction schedules and lane closure plans for a facility with a given cross section and level of average annual daily traffic (AADT).

RESEARCH STRATEGY / METHODOLOGY

Initially, the objective was to model actual construction projects in the Houston and Dallas areas in order to compare the mobile source emissions and delays that would be generated as a result of changing the construction schedule to accommodate construction restrictions in these two targeted nonattainment areas. Due to limited availability of traffic control plans for existing projects, researchers modeled an array of general work zone scenarios to reflect a range of project and traffic condition intensity. Variables in the scenarios included facility demand (low, medium, and high AADT), facility cross-section (two to five lanes), number of lanes closed in work zone (one to four lanes), and work zone schedule (seven different schedules modeled). Researchers modeled five alternate work zone schedules in addition to the standard peak and off-peak direction schedules. The alternate schedules accommodated TNRCC's construction restrictions in DFW and HG, and also included an overnight period. The matrix created by the four variables produced a total of 161 scenarios. Table 43 presents this matrix.

Table 43. Matrix of Road Construction Work Zone Scenarios Modeled.

Scenario	**Peak Direction Scenarios (lanes closed)**			**Off-Peak Direction Scenarios (lanes closed)**			
Schedule Name	**Base Schedule**	**Dallas Schedule**	**Houston Schedule**	**Base Schedule**	**Dallas Schedule**	**Houston Schedule**	**Overnight Schedule**
Schedule Hours	**09:00 - 17:00**	**10:00 - 15:00 19:00 - 22:00**	**12:00 - 15:00 19:00 - 24:00**	**07:00 - 15:00**	**10:00 - 18:00**	**12:00 - 20:00**	**21:00 - 05:00**
Low AADT	1 of 2	1 of 2	1 of 2	1 of 2	1 of 2	1 of 2	1 of 2
	1 of 3	1 of 3	1 of 3	1 of 3	1 of 3	1 of 3	1 of 3
	2 of 3	2 of 3	2 of 3	2 of 3	2 of 3	2 of 3	2 of 3
	1 of 4	1 of 4	1 of 4	1 of 4	1 of 4	1 of 4	1 of 4
	2 of 4	2 of 4	2 of 4	2 of 4	2 of 4	2 of 4	2 of 4
	3 of 4	3 of 4	3 of 4	3 of 4	3 of 4	3 of 4	3 of 4
	1 of 5	1 of 5	1 of 5	1 of 5	1 of 5	1 of 5	1 of 5
	2 of 5	2 of 5	2 of 5	2 of 5	2 of 5	2 of 5	2 of 5
	3 of 5	3 of 5	3 of 5	3 of 5	3 of 5	3 of 5	3 of 5
	4 of 5	4 of 5	4 of 5	4 of 5	4 of 5	4 of 5	4 of 5
Medium AADT	1 of 3	1 of 3	1 of 3	1 of 3	1 of 3	1 of 3	1 of 3
	2 of 3	2 of 3	2 of 3	2 of 3	2 of 3	2 of 3	2 of 3
	1 of 4	1 of 4	1 of 4	1 of 4	1 of 4	1 of 4	1 of 4
	2 of 4	2 of 4	2 of 4	2 of 4	2 of 4	2 of 4	2 of 4
	3 of 4	3 of 4	3 of 4	3 of 4	3 of 4	3 of 4	3 of 4
	1 of 5	1 of 5	1 of 5	1 of 5	1 of 5	1 of 5	1 of 5
	2 of 5	2 of 5	2 of 5	2 of 5	2 of 5	2 of 5	2 of 5
	3 of 5	3 of 5	3 of 5	3 of 5	3 of 5	3 of 5	3 of 5
	4 of 5	4 of 5	4 of 5	4 of 5	4 of 5	4 of 5	4 of 5
High AADT	1 of 5	1 of 5	1 of 5	1 of 5	1 of 5	1 of 5	1 of 5
	2 of 5	2 of 5	2 of 5	2 of 5	2 of 5	2 of 5	2 of 5
	3 of 5	3 of 5	3 of 5	3 of 5	3 of 5	3 of 5	3 of 5
	4 of 5	4 of 5	4 of 5	4 of 5	4 of 5	4 of 5	4 of 5

QUEWZ-98 Analysis

QUEWZ-98 is a microcomputer program developed to evaluate freeway work zone lane closures. The program simulates traffic flows through a freeway segment with and without a work zone in place. The user specifies the lane closure schedule and configuration, and the program outputs the resulting impact of the work zone with respect to road user costs, queues, and emissions. QUEWZ-98 can also be used to identify lane closure schedules that minimize work zone related delay. The model can analyze 24 consecutive hours of operation on freeway/multi-lane divided highways, with up to six lanes in each direction and work zones in one or both directions.

QUEWZ-98 Input Data

The input data required to set up a QUEWZ-98 simulation file include data on the lane closure configuration and schedule, traffic volumes approaching the freeway segment, and adjustments to model defaults.

Lane Closure Configuration. Lane closure configuration data include the number of directional roadways closed (one or both directions), the total number of lanes in each direction, the number of lanes open in each direction through the work zone, the distance of the lane closure, and the capacity of the work zone. The assumptions used in simulations for this project include:

- work zone on one side of the freeway only,
- number of lanes in the freeway segment varied between two and five,
- number of lanes closed in work zone varied between one and four lanes, and
- length of work zone equal to 1 mile.

Lane Closure Schedule. Lane closure schedule data include the hours the lane closure begins and ends and the hours work activity begins and ends. It was assumed in these simulations that lane closure and work activity times coincided. Table 44 presents the seven construction schedules evaluated. Two base condition schedules simulated typical construction schedules, 09:00 – 17:00 when the work zone is located in the a.m. peak direction of flow, or 07:00 – 15:00 when the work zone is located in the a.m. off-peak direction of flow. These schedules are derived from current practices prohibiting lane closures in the peak direction of travel during the peak period. Peak and off-peak Dallas schedules simulated the impact of TNRCC's construction equipment restrictions in Dallas, which would ban heavy-duty diesel construction activity prior to 10:00. Peak and off-peak Houston schedules simulate the impact of TNRCC's construction equipment restrictions in Houston, which would ban heavy-duty diesel construction activity prior to 12:00. The final construction schedule simulated overnight work.

Table 44. Construction Schedules Simulated in Evaluation.

Schedule Name	Direction of Flow	Lane Closure Schedule
Base	a.m. peak direction	09:00 – 17:00
	a.m. off-peak direction	07:00 – 15:00
Dallas	p.m. peak direction	10:00 – 15:00, 19:00 – 22:00
	p.m. off-peak direction	10:00 – 18:00
Houston	p.m. peak direction	12:00 – 15:00, 19:00 – 24:00
	p.m. off-peak direction	12:00 – 20:00
Overnight	off-peak direction	21:00 – 05:00

Traffic Volumes. TxDOT provided researchers with 1999 Harris County freeway and interstate AADTs. Researchers ranked the AADTs from highest to lowest and selected three levels of AADT to simulate roadways with low, medium, and high traffic volumes. The 85th percentile AADT represents high-demand facilities and corresponds to 180,000 vehicles per day. The 50th percentile AADT represents medium-demand facilities and corresponds to 110,000 vehicles per day. The 30th percentile AADT represents low-demand facilities and corresponds to 56,000 vehicles per day. QUEWZ-98 distributes the AADT value for a 24-hour period using adjustment factors to account for rural/urban environment and day of week (weekday, Saturday, or Sunday). These adjustment factors were computed at the time QUEWZ-98 was developed based on automatic traffic recorder station data on interstate highways in Texas in October 1985 (37 urban stations and 13 rural stations) (22).

Adjustments to Model Defaults. The final input values are user-specified alternatives to default values of:

- cost update factor,
- percent trucks,
- speed-volume-capacity relationships,
- work zone capacity,
- definition of excessive queuing, and
- emission rates.

All simulations used a cost update factor of 1.3. This factor converts road user costs to year 2000 dollars (current year consumer price index [CPI] divided by year 1990 CPI of 130.7). The default value in QUEWZ-98 for percentage of trucks in the traffic stream is 8 percent. The AADT data from TxDOT revealed an average percentage of trucks on Harris County freeways and interstates of 7.9 percent, justifying the model default of 8 percent. The default speed-volume-capacity relationships in QUEWZ-98 are based on the 1985 *Highway Capacity Manual*. These default values were used in all simulations. The ideal capacity of a work zone is assumed by QUEWZ-98 to be 1600 vehicles per hour per lane (vphpl). This capacity is reduced to 1515 vphpl when factoring in an adjustment for heavy vehicles and was used in all simulations.

Effects of excessive queuing is an option in QUEWZ-98 to allow for the diversion of vehicles within the simulation. Excessive queuing can be defined as a maximum queue length in miles or a maximum delay in minutes, which will influence drivers' decisions to divert to parallel routes. QUEWZ-98 uses the diversion algorithm to calculate the diversion volume to avoid excessive queuing. The default value for the critical length of queue is 2 miles, based on average ramp spacing of 0.4 miles and a maximum of five ramps being engulfed in the queue. These averages are based on diversion studies at temporary freeway work zone lane closures on urban freeways with continuous frontage roads in Texas (22). The diversion algorithm engaged in all simulations when a critical length of queue exceeded 2 miles.

Analyses used the default pollutant emission rates contained in QUEWZ-98 for cars and trucks for HC, CO, and NOx. These values were estimated in the summer of 1998 using data from San Antonio, Texas, and EPA's emissions factor modeling program MOBILE5a (22). See the Limitations of the QUEWZ-98 Model section for more information on emission calculations.

QUEWZ-98 Output Data

A QUEWZ-98 output file consists of three to four pages of data depending on the geometrics and/or traffic volumes in the scenario. Page one of the output file provides an echo of some of the input data, as shown in Figure 8. These data include the number of lanes in the section, number of lanes closed, length of work zone, normal and restricted capacities, AADT, parameters used to calculate hourly volumes from the AADT (weekday and urban environment adjustment factors engaged), scheduled hours of the work zone, and idle emission rates for HC, CO, and NOx.

The second page of the QUEWZ-98 output file contains the road user cost table shown in Figure 9. Road user costs are shown on an hourly basis and totaled at the bottom of the table. Road user costs are estimated for a work zone by taking the difference between road user costs with and without the work zone in place. The road user cost includes a vehicle operating cost component and a travel time cost component. The value of time assumed by QUEWZ-98, based on 1990 dollars, is $12.64 per hour for passenger cars (average occupancy 1.3 persons per vehicle) and $23.09 per hour for trucks (*1*). This value of time was updated to 2000 dollars using a cost update factor of 1.3 (CPI year 2000 divided by CPI year 1990).

Total road user cost calculations include road user costs for diverting vehicles in the event of vehicle diversion by the excessive queuing algorithm. The assumptions built into QUEWZ-98 for vehicle diversion are:

- the length of the alternate route equals the length of the work zone plus the critical length of queue,
- the travel time for diverting vehicles is equal to the time required for a vehicle at the end of the queue to travel through the queue and work zone,

- diverting traffic maintains a uniform speed equal to the length of the alternative route divided by the travel time, and
- trucks do not divert.

```
INPUT DATA SUMMARY: ROAD USER COST OUTPUT            PAGE 1 OF 4
HD5L2CP1.DAT                                            QUEWZ-98
----------------------------------------------------------------
      LANE CLOSURE CONFIGURATION:

        TOTAL NUMBER OF LANES
          INBOUND                                5
          OUTBOUND                               5

        NUMBER OF OPEN LANES
          INBOUND                                3
          OUTBOUND                               5

        LENGTH OF WORK ZONE                      1.00 MILES

        INBOUND  CAPACITY
          NORMAL                             10000. (VPH)
          RESTRICTED                          5400. (VPH)
          WORKING HOURS                       4545. (VPH)

      TRAFFIC PARa.m. ETERS:

        PARa.m. ETERS TO CALCULATE
        HOURLY TRAFFIC VOLUMES
          DAY OF WEEK                     MONDAY
          MONTH                          OCTOBER
          DISTRICT                            99
          LOCATION                      URBAN IN
          AADT (THOUS.)                      180.0

        PERCENTAGE TRUCK                         8.

      SCHEDULE OF WORK ACTIVITY:

        HOURS OF RESTRICTED CAPACITY
          BEGINNING                             10
          ENDING                                15

        HOURS OF WORK ZONE ACTIVITY
          BEGINNING                             10
          ENDING                                15
----------------------------------------------------------------
   IDLE HC CAR     34.9 (g/hr)     IDLE HC TRUCK    12.6 (g/hr)
   IDLE CO CAR    218.5 (g/hr)     IDLE CO TRUCK    94.6 (g/hr)
   IDLE NOX CAR     4.7 (g/hr)     IDLE NOX TRUCK   53.1 (g/hr)
```

Figure 8. Input Echo - Page 1 of QUEWZ-98 Output File.

```
SUMMARY OF ADDITIONAL ROAD USER COSTS                  PAGE 2 OF 4
HD5L2CP1.DAT                                              QUEWZ-98
-------------------------------------------------------------------
ADDITIONAL ROAD USER COSTS ($)
HOUR                 INBOUND              OUTBOUND           TOTAL
-------------------------------------------------------------------
 0- 1                     0.                    0.              0.
 1- 2                     0.                    0.              0.
 2- 3                     0.                    0.              0.
 3- 4                     0.                    0.              0.
 4- 5                     0.                    0.              0.
 5- 6                     0.                    0.              0.
 6- 7                     0.                    0.              0.
 7- 8                     0.                    0.              0.
 8- 9                     0.                    0.              0.
 9-10                     0.                    0.              0.
10-11                  5522.                    0.           5522.
11-12                 11660.                    0.          11660.
12-13                 19516.                    0.          19516.
13-14                 26893.                    0.          26893.
14-15                 30297.                    0.          30297.
15-16                  4378.                    0.           4378.
16-17                     0.                    0.              0.
17-18                     0.                    0.              0.
18-19                     0.                    0.              0.
19-20                     0.                    0.              0.
20-21                     0.                    0.              0.
21-22                     0.                    0.              0.
22-23                     0.                    0.              0.
23-24                     0.                    0.              0.
-------------------------------------------------------------------
TOTAL                 98267.                    0.          98267
-------------------------------------------------------------------
NOTE: LANE CLOSURE ONLY IN INBOUND DIRECTION
```

Figure 9. Road User Costs - Page 2 of QUEWZ-98 Output File.

Page three of the output file, shown in Figure 10, provides a summary of hourly traffic flow characteristics. Traffic conditions reported on an hourly basis include the approach volume, work zone capacity, approach speed, work zone speed, and length of queue. This page provides the majority of input data for the Emissions Workbook. Although QUEWZ-98 distributes AADT over the full 24-hour period, the output reflects only data during the time period in which the work zone is in place. This limited time period is due to the intended use of QUEWZ-98 to determine the differences between delay and emissions when a work zone is and is not in place. Since there is no differential delay or emissions during periods of time when the work zone is not in place, QUEWZ-98 omits those data from the output file. The only exception is when a queue exists at the end of the work zone schedule, in which case QUEWZ-98 will continue the simulation until the queue is dissipated.

Page four of the QUEWZ-98 output file is shown in Figure 11. This page provides a table summarizing hourly diversion volumes for time periods where the queue reaches the critical queue length of 2 miles (queue length shown on page three of output file). A summary of emissions calculations follows the diversion summary on page four of the output file.

Limitations of the QUEWZ-98 Model

The researchers identified a number of limitations with the QUEWZ-98 model during its application for this project. To some extent the model was not designed to handle some of the aspects of this evaluation. The primary limitations of the QUEWZ-98 model for this project concern the emissions algorithm. QUEWZ-98 has an algorithm to estimate the number of vehicles that would divert from a work zone facility once a critical length of queue or a critical delay in queue is reached. While QUEWZ-98 includes the delays associated with diverting vehicles in its road user cost algorithm, it ignores all emissions associated with diverting vehicles. Thus, QUEWZ-98 would underestimate the emissions associated with work zones on high-volume facilities or during high-volume time periods, where vehicular diversion would be expected to occur.

In some of the scenarios, the work zone had enough impact to cause a reduction in vehicle speeds but did not have a large enough impact to cause queue formation. As long as there is no queue associated with a work zone, QUEWZ-98 ignores emissions of all vehicles traveling through the work zone regardless of their speed. Thus, QUEWZ-98 underestimates HC and CO, and overestimates NOx when vehicle speeds are reduced due to a work zone, but no queue is formed.

The Dallas peak and Houston peak schedule scenarios modeled construction work zones set up before a peak period, removed during the peak period, then reestablished after the peak period. One limitation of QUEWZ-98 is that only a single work zone closure can be simulated during a 24-hour period. In order to simulate two work zone closures during a 24-hour period, two QUEWZ-98 files needed to be created. Each file contained 12 hours of volumes and one work zone closure, i.e., creating two separate files did not double the 24-hour volume. Combining the two output files then produced the results for those scenarios.

```
SUMMARY OF TRAFFIC CONDITIONS--INBOUND DIRECTION     PAGE 3 OF 4
HD5L2CP1.DAT                                            QUEWZ-98
----------------------------------------------------------------
HOUR        APPROACH    CAPACITY    APPROACH    WORK ZONE   QUEUE
             VOLUME      (VPH)       SPEED       SPEED     LENGTH
             (VPH)                   (MPH)       (MPH)    (MILES)
----------------------------------------------------------------
 0- 1
 1- 2
 2- 3
 3- 4
 4- 5
 5- 6
 6- 7
 7- 8
 8- 9
 9-10
10-11         4820.       4545.       53.         30.         0.2
11-12         4923.       4545.       53.         30.         0.7
12-13         5004.       4545.       52.         30.         1.3
13-14         5076.       4545.       52.         30.         1.8
14-15         5204.       4545.       52.         30.         2.0
15-16         5639.      10000.       51.         45.         1.0
16-17
17-18
18-19
19-20
20-21
21-22
22-23
23-24

----------------------------------------------------------------
NOTE: TRAFFIC DIVERSION IS PREDICTED, SEE SUMMARY OF TRAFFIC VOLUMES
```

Figure 10. Summary of Traffic Conditions - Page 3 of QUEWZ-98 Output File.

```
SUMMARY OF TRAFFIC VOLUMES--INBOUND DIRECTION        PAGE 4 OF 4
HD5L2CP1.DAT                                             QUEWZ-98
-----------------------------------------------------------------
HOUR              APPROACH           VOLUME            VOLUME
                   VOLUME        REMAINING ON     DIVERTING FROM
                   (VPH)        FREEWAY (VPH)      FREEWAY (VPH)
-----------------------------------------------------------------
 0- 1               890.              890.                 0.
 1- 2               600.              600.                 0.
 2- 3               512.              512.                 0.
 3- 4               468.              468.                 0.
 4- 5               683.              683.                 0.
 5- 6              1836.             1836.                 0.
 6- 7              6209.             6209.                 0.
 7- 8              8993.             8993.                 0.
 8- 9              6629.             6629.                 0.
 9-10              5161.             5161.                 0.
10-11              4820.             4820.                 0.
11-12              4923.             4923.                 0.
12-13              5004.             5004.                 0.
13-14              5076.             4754.               323.
14-15              5204.             4545.               659.
15-16              5639.             5639.                 0.
16-17              6093.             6093.                 0.
17-18              5868.             5868.                 0.
18-19              4435.             4435.                 0.
19-20              3221.             3221.                 0.
20-21              2341.             2341.                 0.
21-22              2049.             2049.                 0.
22-23              1709.             1709.                 0.
23-24              1183.             1183.                 0.
-----------------------------------------------------------------
NOTE: THESE ESTIMATES ASSUME THAT TRAFFIC WILL DIVERT SUCH THAT QUEUE LENGTHS
NEVER EXCEED 2.00 MILES.
                                  EXCESS EMISSIONS (DIFFERENCE)
                             HC              CO              NOx
                            (Kgs)           (Kgs)           (Kgs)
            Inbound         102.2           700.4           -73.0
            Outbound          0.0             0.0             0.0

                                         BASE EMISSIONS
                             HC              CO              NOx
                            (Kgs)           (Kgs)           (Kgs)
            Inbound          89.4           515.8           187.1
            Outbound          0.0             0.0             0.0

                                  CONSTRUCTION RELATED EMISSIONS
                             HC              CO              NOx
                            (Kgs)           (Kgs)           (Kgs)
            Inbound         191.6          1216.2           114.0
            Outbound          0.0             0.0             0.0
```

Figure 11. Diversion and Emissions Summary - Page 4 of QUEWZ-98 Output File.

Volume data are entered in QUEWZ-98 for a 24-hour period beginning at 0:00 and ending at 23:00. Simulating an overnight schedule such as 21:00 to 5:00 would either require creating two files, one to contain the 21:00 to midnight portion and another to contain the midnight to 5:00 portion, or simply shifting the volumes and corresponding times. Shifting the volume data 20 hours (such that 20:00 corresponded with 0:00 in QUEWZ-98) allowed a single file to be used.

Another limitation of the QUEWZ-98 model concerns the inability to see a complete echo of the coded input. Volumes are entered in QUEWZ-98 using an AADT value (which is automatically distributed by QUEWZ-98) or by manually entering hourly data. Applying the same directional and hourly distribution factors as QUEWZ-98 allowed researchers to calculate the hourly volumes from the AADT. This had to be done for the overnight scenario files where the hourly volumes needed to be shifted and for the Houston and Dallas peak direction schedules where two files needed to be created (each with 12 hours of hourly volumes). While the output file echoes the AADT used in the simulation, only those hourly volumes where the work zone is present or residual queues exist are echoed. Although the manually entered volumes could be verified on screen with the file open in QUEWZ-98, error checking manually entered volumes would be easier if echoed in the output file.

Emissions Workbook

After reviewing the output from the QUEWZ-98 model, researchers determined that the model did not fully describe the emissions generated from work zone lane closures. Results identified two important limitations of the QUEWZ-98 emissions algorithm leading to underestimates of emissions associated with work zones. The first limitation is that QUEWZ-98 ignores all emissions from vehicles diverted from the work zone because of critical queues and/or delays. The second limitation regards QUEWZ-98 ignoring emissions of all vehicles traveling through the work zone at reduced speeds but no queue is formed.

Procedure for Using the Emissions Workbook

A separate model called the Emissions Workbook was developed to address the limitations associated with the QUEWZ-98 emissions algorithm and more accurately quantify emissions associated with construction work zones. The Emissions Workbook is a Microsoft Excel workbook containing a number of spreadsheets and Visual Basic macros. The sheets contained in the Emissions Workbook are the:

- instruction sheet,
- paste sheet,
- QUEWZ-98 intermediate calculations sheet,
- emissions calculations sheet,
- MOBILE5 emissions table sheet,

- percent AADT table sheet, and
- graphics sheet.

Although QUEWZ-98 was not used directly to calculate vehicle emissions for the various geometric and volume scenarios described in Table 43, it was used as a preprocessor to generate input values for the Emissions Workbook. Traffic flow characteristics utilized from QUEWZ-98 output include approach volume, approach speed, work zone speed, queue length, and diverting volumes. MOBILE5a freeway and arterial look-up tables provided the emission rates needed for the Emissions Workbook (*23*).

The following sections describe the process used to calculate vehicle emissions and are based on the sheets contained in the Emissions Workbook. The output files from the QUEWZ-98 simulations serve as the input to the Emissions Workbook. In most cases, the entire output file is cut and pasted into the paste sheet section. The remaining calculations and update of graphs are performed automatically. Figure 12 shows the data flow from the QUEWZ-98 model and through the series of spreadsheets in the workbook. This information serves as documentation of the logic and assumptions used in the emissions calculations.

Instruction Sheet. This sheet gives general instructions on how to copy and paste information from the QUEWZ-98 output file to the Emissions Workbook.

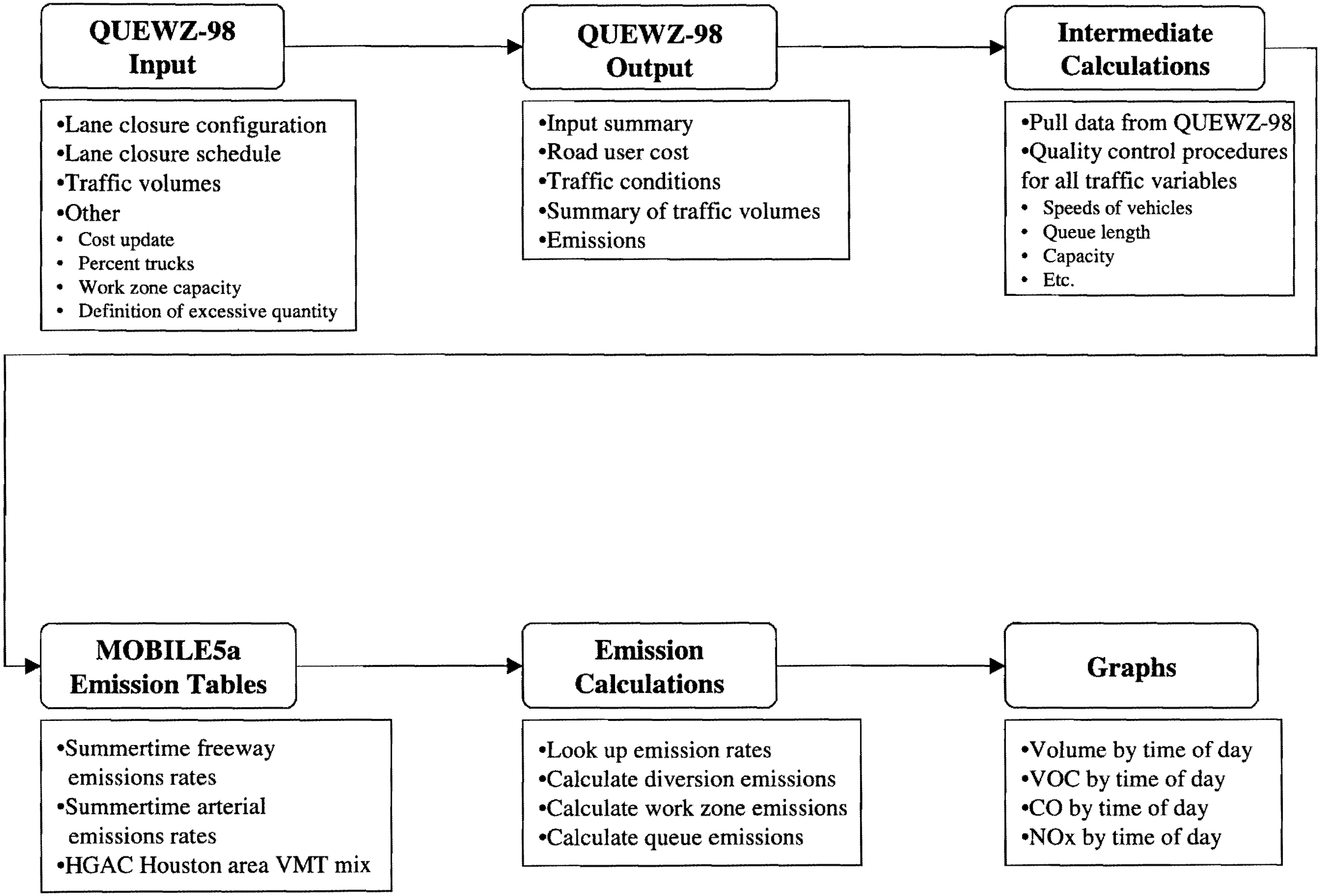


Figure 12. Flow Chart for Work Zone Emissions Calculations.

Paste Sheet. The output from the QUEWZ-98 model serves as input to the emissions calculations. The paste sheet is the location where the QUEWZ-98 output is entered into the Emissions Worksheet. For the majority of the scenarios evaluated (base peak, base off-peak, Dallas off-peak, and Houston off-peak), the entire QUEWZ-98 output file can be cut and pasted into the Emissions Workbook. The process is completed using the following steps:

1. Open Microsoft Excel and then open the desired QUEWZ-98 output file.
2. Import the output from QUEWZ-98 into Excel. Parse the file using the delimited radio button, and check the tab and space boxes. Click Next and then Finish.
3. Highlight the entire sheet (an easy way to do this is to start in cell A1 and then press the Shift, Ctrl, and End keys). Copy the selection by using Ctrl+C.
4. Open the Emission Workbook, making sure the paste sheet is open, click in cell A1, and paste by using Ctrl+V.

Slightly modified procedures were used with the remaining scenarios to pull the QUEWZ-98 output into the paste sheet; however, the calculations performed within the Emissions Workbook are identical. The Dallas peak and Houston peak schedule scenarios modeled construction work zones set up before a peak period, removed during the peak period, then reestablished after the peak period. One limitation of QUEWZ-98 is that only a single work zone closure can be simulated during a 24-hour period. In order to simulate two work zone closures during a 24-hour period, two QUEWZ-98 files needed to be created. Each file contained 12 hours of volumes and one work zone closure, i.e., creating two separate files did not double the 24-hour volume. Combining the two halves of the output files then produced the results for those scenarios.

The overnight scenarios also required a modified procedure. Another limitation of QUEWZ-98 is that volume data are entered for a 24-hour period beginning at 0:00 and ending at 23:00. Simulating an overnight schedule such as 21:00 to 05:00 would either require creating two files, one to contain the 21:00 to 00:00 portion and another to contain the 00:00 to 05:00 portion, or simply shifting the corresponding volumes and times. Shifting the volume data by 20 hours such that 20:00 corresponded with 0:00 created a single file for each overnight scenario in QUEWZ-98. Another limitation of QUEWZ-98 is that it does not echo the hourly volumes in the output of scenarios where no queues form, resulting in a three-page output rather than four pages. As this was the case in all overnight scenarios due to low volumes, the hourly volumes were entered manually into the intermediate calculations spreadsheet.

Hourly volumes were manually entered into cells Y5:Y29 of the intermediate calculations sheet for the overnight scenario files. The user can open the QUEWZ-98 output files as above, but before the information is copied, eight rows need to be inserted (start at row 38 and highlight to row 45; right click the mouse, and insert the rows). The user can then follow steps three and four as above. This procedure aligns the input file so that the worksheet will look up the proper values.

The next types of data required in the paste sheet are vehicle speeds and queue lengths. These two variables came from the QUEWZ-98 model. If QUEWZ-98 did not generate a speed or a queue, it was assumed that the vehicles were traveling at free-flow speed and that no queue was present (these are conditions where QUEWZ-98 does not echo data in the output file). Once all the variables are determined, the rest of the procedure is fairly straightforward.

Once the QUEWZ-98 output is in the workbook, the program performs the emission calculations. In addition to the tables generated by this workbook, a series of graphs is also generated, which serves as a means of quality control to check the output from the QUEWZ-98 model. The following sections document these steps.

QUEWZ-98 Intermediate Calculations. Many problems in calculating the emissions result from the QUEWZ-98 model not reporting all the traffic volumes. If no delay is incurred during a time period, then the traffic volume for that time period is not reported in the output. Much of the logic in the workbook is checking to see if a number is present in the QUEWZ-98 output and, if not, inserting a computed number or default number.

The QUEWZ-98 intermediate calculations sheet serves as a preprocessor to get the correct volume and speed numbers from the QUEWZ-98 output. A lot of the assumptions on the speed and volumes are contained in the next two sheets (QUEWZ-98 intermediate calculations and emissions calculations). Some of the information is pulled from the QUEWZ-98 output, the user enters some, and some is calculated.

A series of colors is used to aid in the discussion and to allow the user to determine how the data flow from one sheet to another. Yellow indicates cells for which the user must enter information. The cells highlighted in blue contain information pulled from the QUEWZ-98 output. All calculated numbers are represented by green cells.

First, the user must enter information into the yellow cells. The length of the diversion is entered in miles in cell E3 (3 miles). Next, the assumed free-flow speed of the vehicles on the freeway (60 mph) is entered into cell I4. The last item the user must enter is the average speed on the diversion route (20 mph), placed in cells N9:N32.

Blue cells designate information pulled from the QUEWZ-98 output. In some cases, the QUEWZ-98 model did not output a fourth page, "Summary of Traffic Volumes." In such instances, the traffic volumes were regenerated using the same directional and hourly distributions as QUEWZ-98. The AADT from the QUEWZ-98 output (paste sheet D29) is multiplied by columns D and G from the percent AADT and directional distribution sheet. The capacity of the facility is given in the QUEWZ-98 output but is generated using the default lane capacity based on the number of lanes if omitted in the output.

The QUEWZ-98 model provides all other information with the exception of the time spent in the queue. This variable is calculated using the queue length and queue speed, which in heavy queues was less than the work zone speed. Once the time in the queue is determined, it is assumed that 5 percent of that time is spent at a complete stop. This figure is based on analysis of congested peak hour travel time runs in the Houston area (1998 Houston/Galveston Area Council [HGC] Travel Time and Speed Survey) (24). This 5 percent stop time is significant because the emission rates for stopped vehicles are substantially higher than those of slow-moving vehicles.

Emission Calculations Sheet. Calculating emissions required two different sets of emission look-up tables: a freeway table and an arterial table. The following steps describe the emission calculation procedure. The speed for a facility determines the emissions rate, which is looked up from the MOBILE5a emissions table. This emissions rate is multiplied by the traffic volume and length of the affected area. This scenario is complicated by different parts of the affected area having different speeds and lengths. The illustration in Figure 13 will aid in the discussion. The approach is assumed to be free-flowing traffic up to the queue zone (if present). The queue zone, as defined by the QUEWZ-98 model, is based on the assumption that vehicles will start to divert if a queue 2 miles long develops upstream of the work zone. Finally, the work zone is the area where the lane closure and the construction occur. As shown in Figure 13, it is assumed that the diversion route is equal to the length of the combined queue zone and the work zone. This is the same assumption that the QUEWZ-98 model uses for the road user cost estimations.

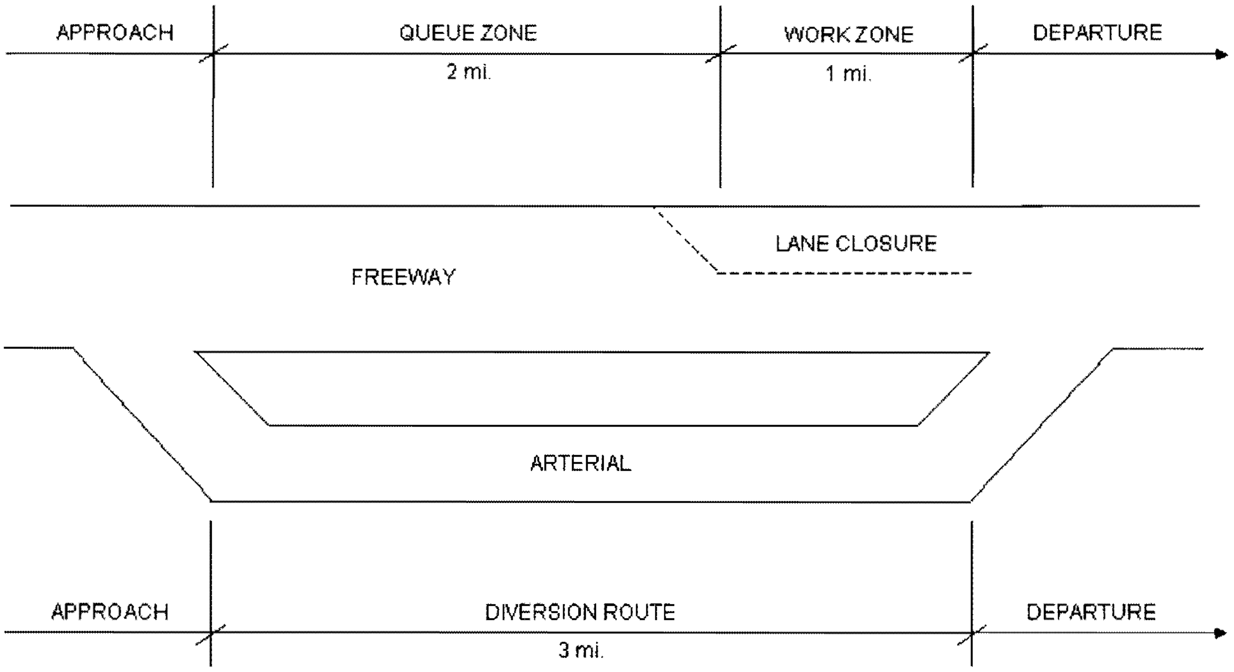


Figure 13. Illustration of Assumed Diversion Route Length.

Assumptions made when calculating the vehicle emissions on the freeway and on the diversion route include:

- The diversion route is equal to the combined length of the work zone and queue zone.
- Vehicles will divert to an alternate route if a queue extends more than 2 miles.
- Vehicles on the diversion route will average 20 mph.[19]
- Work zone speed is 30 mph.[20]
- Queue zone speeds vary based on the QUEWZ-98 model output.
- Traffic is assumed to be traveling at a free-flow speed of 60 mph if the QUEWZ-98 model provides no vehicle speed.
- Vehicles in the queue zone will be stopped 5 percent of the time based on a sample of Houston area freeway segments (24).

MOBILE5a Emissions Table Sheet. This sheet contains the MOBILE5a emission rates for eight different vehicle classifications in the Houston area. These rates are provided for speeds from 3 mph to 65 mph for summertime conditions. The idle emissions (g/hour) were calculated using a per hour emissions rate (multiplying the 3 mph rate by three). The pollutants modeled in the Emission Workbook include:

VOC	Volatile Organic Compounds (g/mile)
CO	Carbon Monoxide (g/mile)
NOx	Oxides of Nitrogen (g/mile)

The vehicle types included in the emission tables are:

LDGV	Light-Duty Gas Vehicle
LDGT1	Light-Duty Gas Truck 1
LDGT2	Light-Duty Gas Truck 2
HDGV	Heavy-Duty Gas Vehicle
LDDV	Light-Duty Diesel Vehicle
LDDT	Light-Duty Diesel Truck
HDDV	Heavy-Duty Diesel Vehicle
MC	Motorcycle

The two sets of composite emission rate tables were created using HGC VMT mix data for Houston area arterials and freeways. Table 45 presents the arterial and freeway vehicle mixes used in the composite emission rate tables. The definitions for the abbreviated vehicle types in the table are listed above.

---

[19] Based on Houston area arterial travel time data.

[20] Queue zone speeds may be considerably lower.

Table 45. Percentage of Vehicles Used in HGC Emission Rate Tables.

	LDGV	LDGT1	LDGT2	HDGV	LDDV	LDDT	HDDV	MC
HGC 1997-1999 Arterial VMT Mix	69.857	16.9978	5.0277	2.1106	0.2028	0.2111	5.4932	0.100
HGC 1997-1999 Freeway VMT Mix	74.3923	13.0695	3.9575	1.9477	0.2159	0.1623	6.1548	0.100

RESULTS

This section provides information on potential uses of the QUEWZ results. Researchers evaluated the impact of construction projects with respect to road user costs, NOx, CO, and VOC. The range of work zone scenarios in this evaluation simulated various lane closure configurations, traffic demand, and work zone schedules. The number of lanes in the section of roadway varied from two to five lanes. The number of lanes closed due to the work zone varied from one to four lanes. Three levels of traffic demand were simulated using AADT data from Houston freeways and interstates. Finally, the simulations incorporated seven different construction schedules.

The seven schedules can be grouped into three categories: schedules that encompass a peak-direction peak-period (referred to as peak schedules), schedules that do not encompass a peak-direction peak-period (referred to as off-peak schedules), and an overnight schedule. The times associated with these seven construction schedules are presented in Table 43. Three peak schedules evaluated included: base peak schedule (typical schedule without construction restrictions), a Dallas peak schedule (construction delayed until 10:00), and a Houston peak schedule (construction delayed until 12:00). Three off-peak schedules evaluated included: base off-peak schedule (typical schedule without construction restrictions), a Dallas off-peak schedule (construction delayed until 10:00), and a Houston off-peak schedule (construction delayed until 12:00).

Tables and Graphs

The road user cost information was pulled from the original QUEWZ-98 output file (one for each of the 161 scenarios), and the emissions information was pulled from the Emissions Workbook file. Consolidating this information into a large matrix table allowed researchers to create a series of graphs for each geometric/volume scenario with a series of curves representing the different road closure scenarios. These graphs provide the user a means of comparing the impact of different road closure scenarios. The impact of schedule and number of lanes closed are presented in road user cost, NOx, CO, and VOC graphs for the following scenarios:

three-lane section:
- low volume, and
- medium volume;

four-lane section:
- low volume, and
- medium volume;

five-lane section:
- low volume,
- medium volume, and
- high volume.

To illustrate the use of these graphs, refer to Figures 14-17. Figure 14 details the road user costs associated with the seven different construction schedules and the number of lanes closed in the work zone for a medium volume, four-lane section. In order to combine the data from various scenarios (one of four lanes closed, two of four lanes closed, and three of four lanes closed), volume per lane is used as the common x-axis. The AADT used in all medium volume scenarios was 110,000 vehicles per day, which corresponds to 55,000 vehicles per day per direction, assuming a 50/50 directional split.

The three data points on each trend line in Figure 14, moving from left to right, indicate the associated road user cost for one of four lanes closed (corresponds to approximately 18,500 vehicles per day per lane [vpdpl]), two of four lanes closed (corresponds to approximately 27,500 vpdpl), and three of four lanes closed (corresponds to approximately 55,000 vpdpl). Thus, the road user cost associated with closing one lane (first data point on trend line) on a medium volume, four-lane section using the base schedule (top trend line) would be approximately $30,000 per day. Similarly, the road user cost associated with closing two lanes (second data point on trend line) on a medium volume, four-lane section using the Dallas off-peak schedule would be approximately $69,000 per day. Similarly, Figures 15, 16, and 17 show the impacts of schedule and number of lanes closed for VOC, NOx, and CO, respectively.

Appendix B contains the complete series of tables and graphs to document the results of this evaluation. No graphs are included for the scenarios involving a one-lane closure of a two-lane section, as they would only involve a single data point for each schedule. The results of these scenarios are presented in Table B-1. The following sample problems are provided to show potential uses of the results of this evaluation.

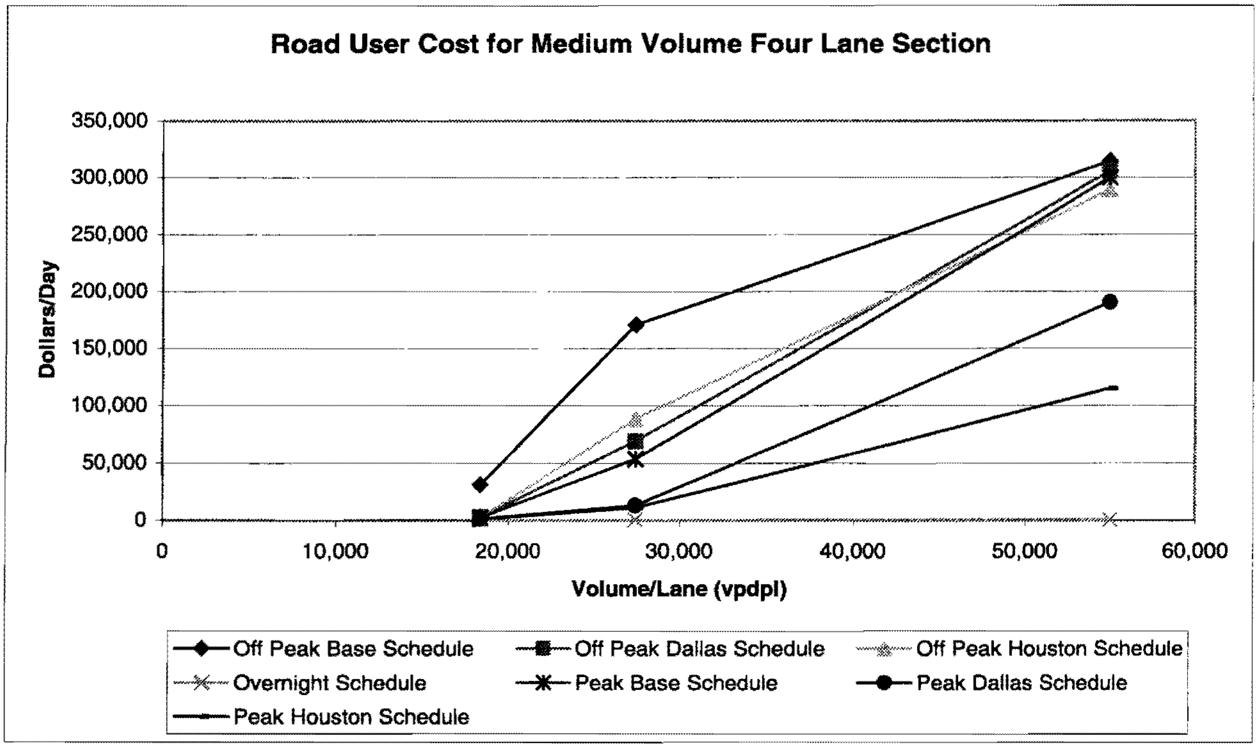


Figure 14. Example of Road User Cost for Medium Volume Four-Lane Section.

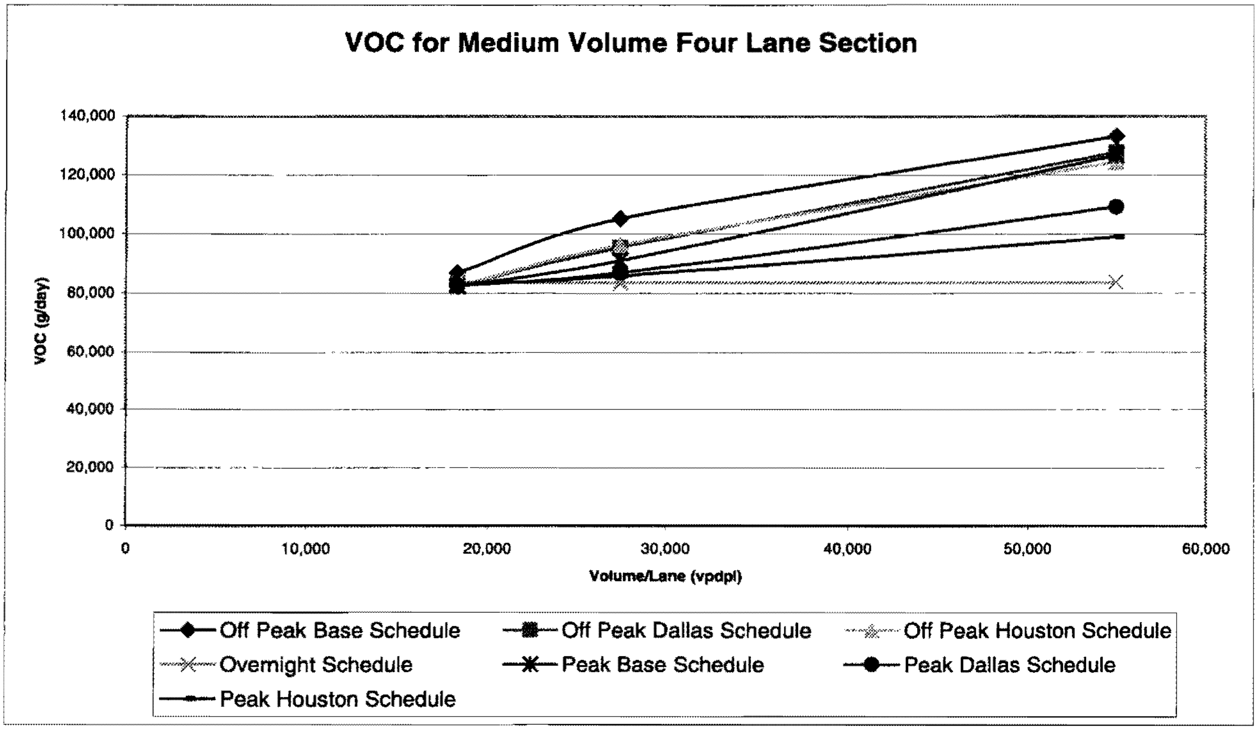


Figure 15. Example of VOC for Medium Volume Four-Lane Section.

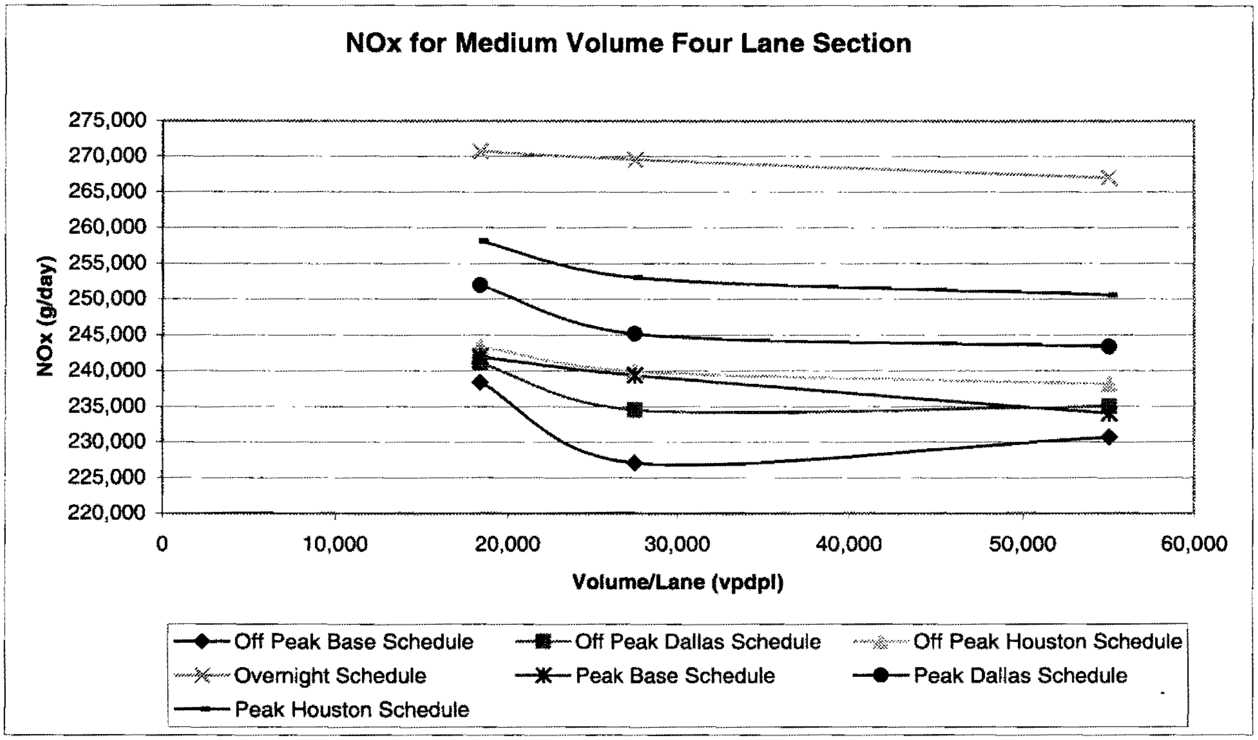


Figure 16. Example of NOx for Medium Volume Four-Lane Section.

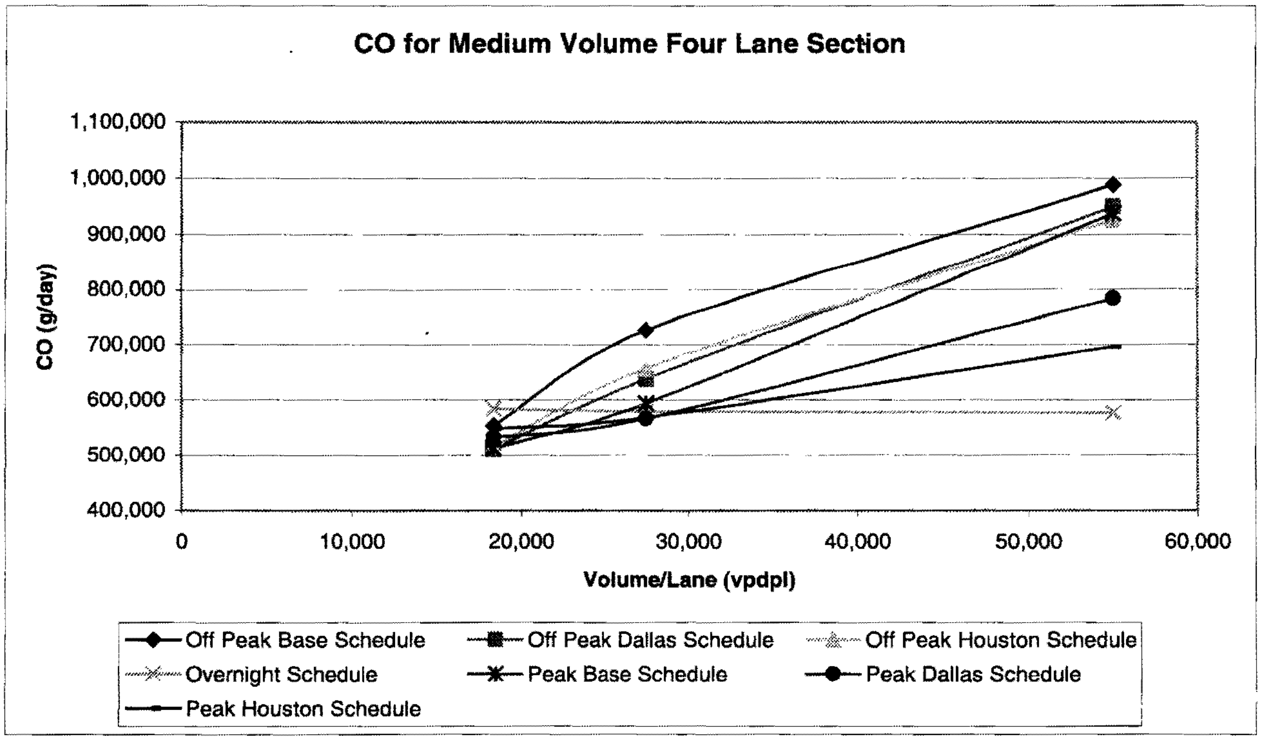


Figure 17. Example of CO for Medium Volume Four-Lane Section.

Sample Problem 1 – Impact of Increased Project Duration Due to Schedule Shift

The information derived in this project can be used to show the impacts of construction shifts with respect to road user costs and emissions. Changes in these values occur as a result of an increase or decrease of daily values as well as a lengthening of project duration due to the schedule shift. A portion of this project evaluated the effect of various construction schedules with respect to project duration (*21*). A brief summary of the results from HG previously reported in Chapter V and used for this problem are shown in Table 46.

Table 46. Average Impacts in Project Duration Estimated by Houston Contractors.

Work Schedule Alternative	Sample Hours	Contractor Estimated Increase (%)
(Full) delayed, continuous operation	12:00 to 20:00	5
Partially delayed, continuous operation	10:00 to 18:00	10
Delayed, non-continuous operation	12:00 to 15:00 19:00 to 24:00	19
Continuous nighttime operation	21:00 to 05:00	12

To demonstrate the impact of work schedule shifts with respect to road user costs and emissions, the following sample project can be considered. Suppose a project is normally scheduled to take three months to complete. The project requires one lane in a three-lane section to be closed for a 1-mile work zone. The facility serves a medium level AADT. The impacts of the alternative schedules are presented with respect to road user costs and NOx in Tables 47 and 48, respectively. These tables use contractor estimates of project duration increases and results of simulations from QUEWZ-98 and the Emissions Workbook. These increases (last column) are solely due to project lengthening associated with each schedule and do not include other costs that may be incurred with some of the schedules. For example, overnight schedules may incur higher equipment costs to provide lighting and higher labor costs. Similarly the non-continuous schedule requires more worker time to be spent setting up and taking down the work zone, i.e., workers set up the work zone, remove it for the peak period, then reestablish it.

The results of this example show that the road user costs decrease as the construction schedule is moved out of the peak period. However, this also increases vehicle speeds, which in turn increase the NOx emissions generated by the respective work zone schedules. From Figure 18, the partial delayed and full delayed continuous schedules offer the greatest benefits for NOx reduction under construction restrictions. These schedules were preferred over non-continuous and nighttime schedules.

Table 47. Sample of Estimated Impacts from Increased Project Duration on Road User Costs.

Construction Schedule	Percent Increase	Duration of Project	Days Increased	Daily Road User Cost (2)	Total Road User Cost ($)	Differential Cost ($)
Base	0	60	0.0	132,225	7,933,500	
Full delayed, continuous	5	60	3.0	73,345	4,620,735	(3,312,765)
Partial delayed, continuous	10	60	6.0	61,533	4,061,178	(3,872,322)
Non-continuous	19	60	11.4	11,268	804,535	(7,128,965)
Nighttime	12	60	7.2	161	10,819	(7,922,681)

Table 48. Sample of Estimated Impacts from Increased Project Duration on On-Road Mobile Source NOx Emissions.

Construction Schedule	Percent Increase	Duration of Project	Days Increased	Daily NOx (kg)	Total NOx (kg)	Differential NOx (kg)
Base	0	60	0.0	226	13,574	
Full delayed, continuous	5	60	3.0	238	15,018	1444
Partial delayed, continuous	10	60	6.0	227	14,987	1413
Non-continuous	19	60	11.4	231	16,472	2898
Nighttime	12	60	7.2	244	16,375	2801

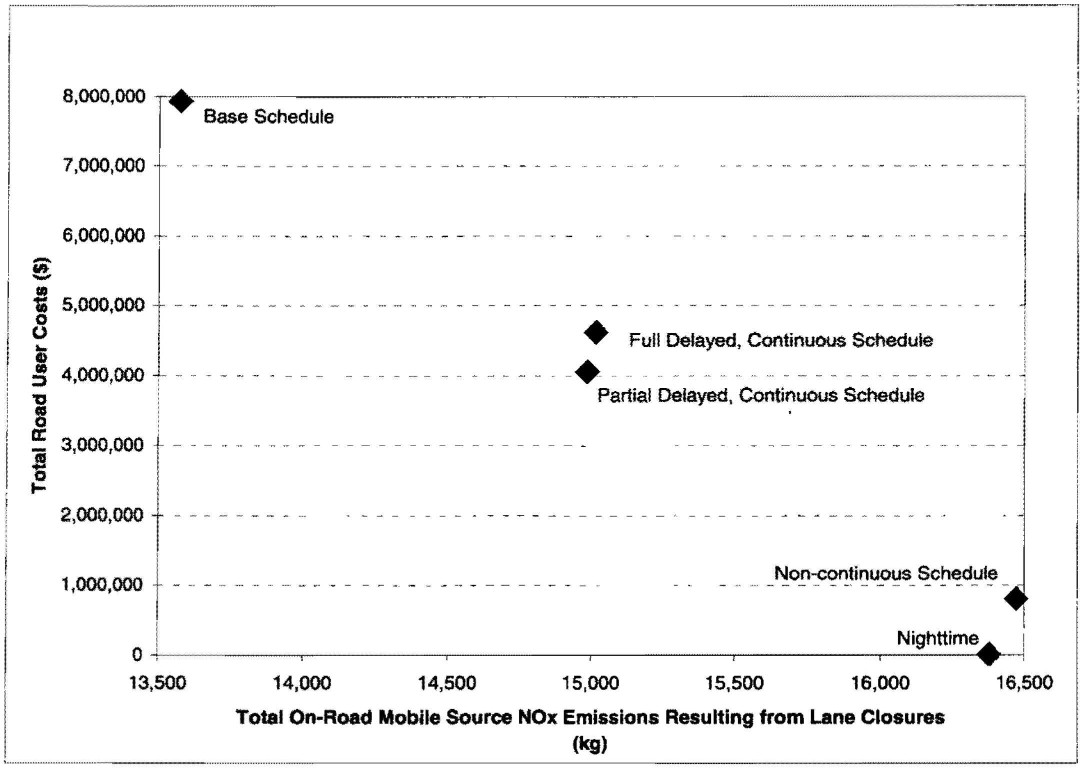


Figure 18. Sample of a Road User Cost vs. On-Road Mobile Source NOx Emission Comparison for Evaluating Alternative Work Schedules to Comply with Construction Equipment Restrictions.

Sample Problem 2 - Impact of Schedule or Number of Lanes Closed in Work Zone

Another application of the results of this project may be to make comparisons of the relative impact of schedule alternatives or number of lanes closed in the work zone with respect to road user cost and emissions. For this example, consider a project in Dallas involving a medium volume, four-lane section roadway. Suppose the construction work will require two lanes of the four-lane section to be closed for the work zone. Figure 14 can be utilized to determine the approximate road user costs associated with each of the construction schedules. Figures 15 through 17 can be utilized to determine the impact on emissions. The results of the comparison between several schedules (base, Dallas [construction delayed until 10:00], and overnight) are summarized in Table 49. With respect to road user cost, the overnight schedule incurs the lowest cost due to the low volumes associated with nighttime and early morning conditions, while the Dallas and base schedules incur higher costs, as the work zone impacts more vehicles.

Table 49. Sample of Work Schedule Impacts on Daily Road User Cost and On-Road Mobile Source NOx Emissions in DFW.

Measure	Schedule		
	Base (Off-Peak)	Dallas (Off-Peak)	Overnight
Road user cost ($/day)	170,805	69,189	175
CO (g/day)	725,485	638,235	579,216
VOC (g/day)	105,231	95,410	83,565
NOx (g/day)	227,074	234,519	269,565

CONCLUSIONS

QUEWZ-98 and a post-processing procedure were used to estimate road user costs, HC, CO, and NOx emissions impacts from various lane closure/work schedule combinations. The post-processing procedure, coded in common spreadsheet software, overcame limitations (treatment of diverted traffic and speed reductions with no queuing) of QUEWZ-98's current emissions module. Other limitations were instructions for evaluating overnight lane closures and a lack of comprehensive input echo to the user.

The many tables and graphs developed from this evaluation will be useful to TxDOT construction staff in the DFW and HG nonattainment areas. These tools can be used to generalize impacts of lane closures with work schedules. If specific cases require analysis, QUEWZ-98 and the post-processing procedure can be used for the evaluation.

CHAPTER VIII. CONCLUSIONS

Air quality in Texas' two largest nonattainment areas, Dallas/Fort Worth (DFW) and Houston/Galveston (HG), has worsened in recent years. Regulators' concerns with meeting national ozone standards first focused on aggressive control of volatile organic compounds (VOCs). Advances in atmospheric science and past success of VOC reductions now show that oxides of nitrogen (NOx) is a greater concern for controlling ozone formation. In addition, demonstration of air quality progress often hinges on a couple of tons or less of pollutant. As a result of this shift to NOx control, pollution sources not previously targeted for controls are now under review, including off-road sources such as emissions from the construction industry. As these sources come under the scrutiny of regulators and controls are proposed, opposition from within the affected industry rises.

TEXAS IS LEADING THE COUNTRY

Texas Natural Resource Conservation Commission (TNRCC) is the first state environmental agency in the country to adopt construction equipment restrictions within the State Implementation Plan (SIP). TNRCC approved SIP measures in both DFW and HG restricting the use of diesel-powered construction equipment ≥50 hp in the morning hours (6:00 a.m. to 10:00 a.m. in DFW and 6:00 a.m. to noon in HG). Among the exemptions allowed under this SIP rule is a process to petition for an exemption if equivalent emission reductions result from that plan.

The construction equipment restriction rules will attempt to control 3 to 14 percent of a region's NOx contributions to yield several tons in overall reduction. TNRCC expects an estimated 21 and 13 percent reduction from the construction industry in HG and DFW, respectively. No similar SIP rules are in use, nor under consideration outside of Texas, although several equipment upgrade incentive programs and project-specific restrictions were found in other states.

Prior to the rule placing controls on the construction industry, TNRCC contracted with a consultant to develop construction equipment inventories and activity data specific to HG. This inventory from HG was also extrapolated to DFW. Within HG, TNRCC's consultant proved that the U.S. Environmental Protection Agency's (EPA's) NONROAD emission model for off-road equipment overestimated both the construction fleet (by as much as 50 percent) and their activity. As a result, EPA's NONROAD model overestimated emissions from this group by as much as three times because the default equipment populations and activity data were inflated. TNRCC's efforts prevented much more serious controls from being proposed to control construction industry emissions. The controls adopted by TNRCC's commission remain stringent and burdensome to both public agencies and private contractors.

Estimations of the Texas Department of Transportation's (TxDOT's) construction emissions were greatly overstated from TNRCC's estimates using empirical equipment inventory and activity data. The information gathered through TxDOT Research Project 0-1745 and extrapolated to each nonattainment area resulted in a 26 to 98 percent overestimate from TNRCC's improved NONROAD model estimates.

INCREASED PROJECT COSTS AND LENGTHENED PROJECT SCHEDULES

The construction equipment restrictions imposed by TNRCC to reduce NOx emissions will have a significant impact on TxDOT. As a result of TNRCC's construction equipment restriction rule, TxDOT construction project costs are expected to increase, and project durations will lengthen. These effects are a direct result of contractors not being able to use diesel-powered equipment ≥50 hp during the restriction. Gasoline-powered and smaller diesel-powered equipment, and laborers can continue to be productive during the restricted hours, but to what degree? Typical road construction work requires the use of the higher horsepower equipment because it is more efficient and productive. Unfortunately, one alternative is to increase the use of smaller equipment and laborers with hand tools as a substitute for state-idled equipment.

After interviews with select contractors and TxDOT staff in both targeted nonattainment areas, several conclusions were developed. These conclusions include:

- increased project costs to TxDOT,
- TxDOT's cost per ton NOx reduced, and
- schedule impacts.

As initially suspected, the contractors indicated that the direct labor costs would be affected the most. When TNRCC's construction restriction rule takes effect in 2005, project costs are expected to increase by:

- 8 to 16 percent in HG, and
- 4 to 32 percent in DFW.

TNRCC initially estimated a 15 to 20 percent increase in project costs within HG. The cost of this rule to TxDOT, using data collected from this project, is estimated to be:

- $116 million annually, or
- approximately $350,000 to $550,000 per ton NOx reduced.

This cost estimate, using results from the project surveys, is 6 percent lower than the initial cost estimate of $124 million annually, using TNRCC estimates. The $116 million annual cost to TxDOT is equivalent to:

- 72.5 million gallons of gasoline at $1.60 per gallon,
- fueling TxDOT's entire on-road and off-road fleet for 8.3 years,[21]

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[21] 2000 TxDOT fleet expenditures for gasoline, diesel, and propane/natural gas totaled $13,934,318.

- 8th largest district in FY 00 construction expenditures, or
- nearly equivalent to the FY 00 construction expenditures for Brownwood, San Angelo, and Abilene Districts combined.

The rule prevents the use of diesel-powered equipment greater than 50 hp in the morning hours (6:00 a.m. to 10:00 a.m. in DFW and 6:00 a.m. to noon in HG). Contractors expressed a preference for schedules that allow continuous operations over schedules that divide working hours because of lane closure issues during the p.m. peak period. Since equipment cannot be used during these restricted hours, project milestones will be pushed back. Project schedules are expected to be lengthened 6 to 12 percent in HG and 5 to 28 percent in DFW when TNRCC's construction restriction rule takes effect in 2005. For a three-year project, this may add 38 to 210 days to the project.

LONGER PROJECTS YIELD SLIGHTLY MORE ON-ROAD NOx EMISSIONS

The frequency of work zone lane closures will increase as major multi-million dollar, multi-year projects' durations within the two large nonattainment areas increase. The incremental on-road mobile source emission impacts of additional work zone lane closures can be approximated using the series of tables and graphs developed from this project. The daily NOx impact resulting from the work zone lane closures is nearly insignificant. In fact, NOx emissions tend to increase when lane closures occur outside of the construction equipment restriction hours due to lower facility demand and higher vehicle speeds. Ironically, work zone lane closures help to lower NOx emissions by reducing vehicle speeds.

TURNING ATTENTION TO ALTERNATIVE CONTROL TECHNOLOGIES

Alternative emission control technology is available for construction equipment affected by TNRCC's construction equipment restriction rule. Emission controls can reduce both NOx and particulate matter (PM) emissions from equipment. To achieve meaningful NOx reductions, the control technologies rely on the use of low-emission diesel fuel (LED). Without LED, the control technologies are much less effective in reducing emissions.

One particular technology, selective catalytic reduction (SCR), shows potential for providing emission benefits. SCR is one of the few commercially available technologies at this time with demonstrated NOx reduction results. Though this technology has been traditionally used on stationary engines, SCR is being applied to trucks, buses, and lower horsepower engines in the range of common construction equipment horsepower. Though not widely applied to construction equipment, if the SCR technology were retrofitted on the heavy-highway construction equipment fleets, the following are estimated:

- When fully implemented on the affected construction fleets in the two nonattainment areas, the estimated cost per ton NOx reduced would be \$35,000 in DFW and \$55,000 in HG. These costs are 84 percent and 93 percent lower than the estimated cost to TxDOT of the enforced construction restriction rule for HG and DFW, respectively.

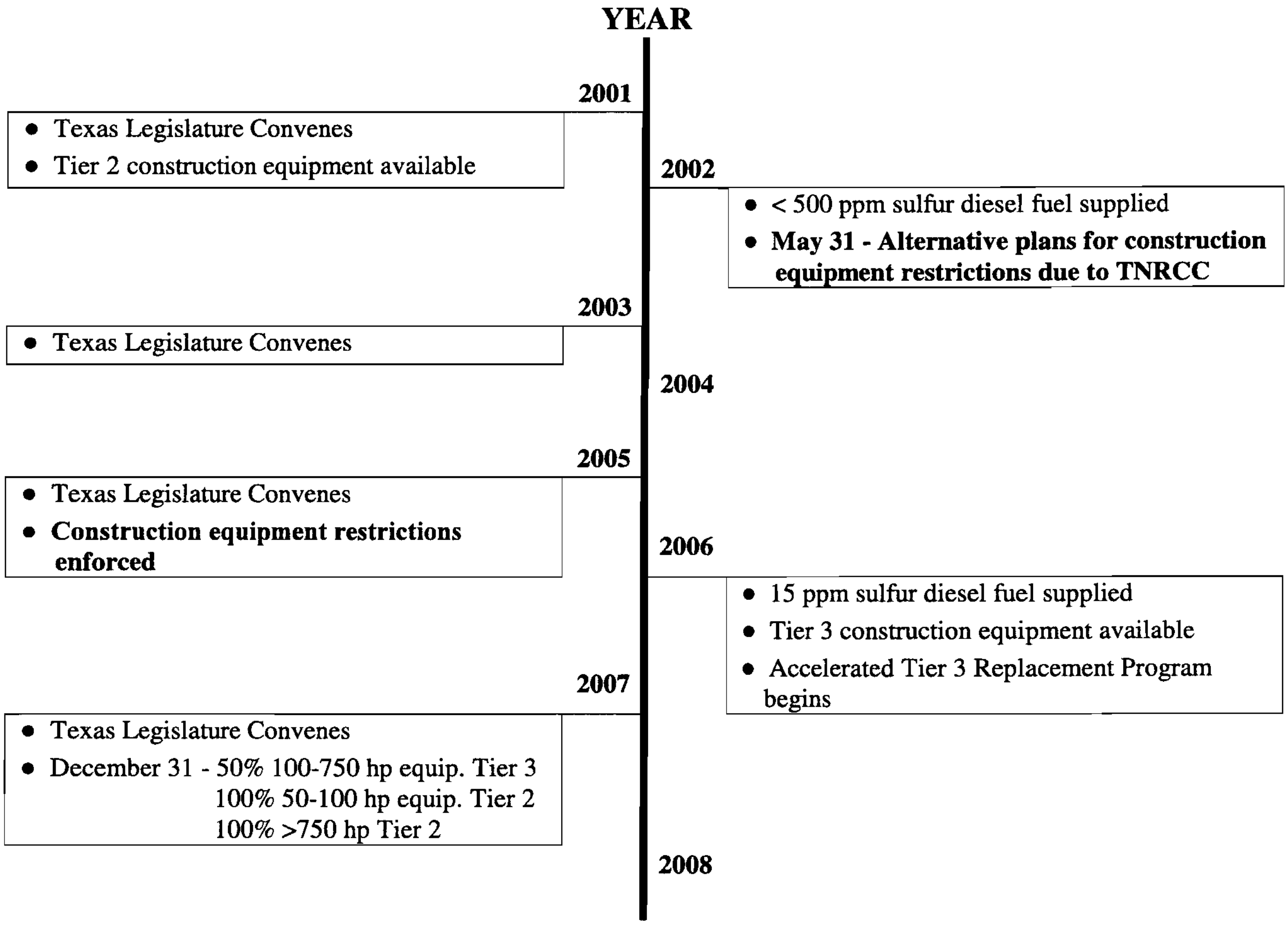
- If a partial implementation of this control technology was used on 30 percent of the construction fleet in the two nonattainment areas with only 30 percent efficiency, the estimated costs per ton NOx reduced are $121,000 and $115,000 for HG and DFW, respectively. These costs are 64 percent and 78 percent lower than the estimated cost to TxDOT of the enforced construction restriction rule for HG and DFW, respectively.

The Carl Moyer Program in California is an incentive program to promote the repower, retrofit, and purchase of off-road equipment so that they operate cleaner and reduce emissions. The program pays for the incremental costs of these activities if they meet a specified cost-effectiveness level for NOx reductions. The first-year results of this program in California would have yielded more than half of the estimated NOx reduction of the construction equipment restriction in HG (4 tpd vs. 6.7 tpd). Additionally, the benefits of this program are realized year round as opposed to only during the ozone season. Equipment upgrades will lower particulates and other pollutants. Particulate matter is expected to be the next major air quality concern when EPA's proposed stricter standards are adopted.

REGULATORY TIMELINE

TxDOT will be required to respond immediately, efficiently, and successfully in order to minimize the potential adverse affects of TNRCC's construction equipment restriction rule. Private enterprises and other public agencies must also respond in kind to TNRCC so that delays to their projects are minimized. The timeline in Figure 19 shows key regulatory milestones for the construction equipment restriction rule, low-emission diesel fuel, and Tier 2/Tier 3 engines. An aggressive approach is needed to prepare exemptions to the rule.

Because this rule has the potential to delay the completion of public works projects, whether these projects are transportation, wastewater, public water supply, or other important and/or critical projects, the public will be adversely affected at the expense of slightly cleaner air. Overwhelming growth within large metropolitan areas has contributed to our air quality health problem. Ironically, the rule's approach to improve air quality effectively cripples the productivity of construction crews both rehabilitating inadequate infrastructure and providing additional infrastructure to meet ever-growing demands.



Note:
Tier 2/Tier 3 applies to compression-ignition engines ≥50 hp
Construction equipment restrictions apply to diesel-powered equipment >50 hp

Figure 19. Timeline of Significant Future Events.

CHAPTER IX. RECOMMENDATIONS

The potential for using alternative control measures at TxDOT construction sites to allow equipment to operate during normal working hours is an important consideration. The costs of these controls should be carefully evaluated against the anticipated increases to TxDOT construction letting costs in response to the construction equipment restriction rule. If retrofit emission controls show a cost savings, then perhaps mechanisms to encourage or accelerate their adoption into the heavy-highway fleet should be assessed and developed.

The introduction of LED fuel, as outlined in the SIP, is critical to the success of any alternative control program considered in lieu of accepting work delays from the construction restriction rule. The low-sulfur fuels act as an enabler for new engine and aftermarket technologies.

Three specific recommendations are identified below. Each requires additional investigation that was not in the scope of the current project. These recommendations might be implemented separately or as combined programs.

TxDOT should cooperatively work with construction firms to minimize construction schedule delays that may result from the rule.

Schedule delays will be minimized only if exemptions to the construction equipment restriction rule are submitted to TNRCC by May 31, 2002. Contractors will be required to submit the exemption plans to TNRCC. With the assistance from TxDOT, adequate plans may be developed.

Investigate the development of an equipment upgrade incentive program in Texas.

Whether funded from within TxDOT or sought as special funding from the Texas Legislature, this program could provide significant emission reductions from TxDOT construction projects at a cost of nearly $50 million for all affected equipment in the two nonattainment areas. If TxDOT plans to lobby the Texas Legislature for additional funding or special funding, these efforts should be made to the 78th Legislature in 2003, so that funding is secured during FY 2005 when the construction equipment restrictions begins. The program may be phased in over a three-year period, at the conclusion of which the Texas Legislature could review the program's effectiveness. The cost would vary for the different control technologies used to retrofit equipment. For SCR, the cost per ton NOx reduced may be $35,000 to $121,000, depending on both the level of contractor participation and the region.

Investigate providing NOx contract incentives to contractors for operating cleaner-burning equipment.

TxDOT could adopt environmental contract incentives much like current performance-based incentives and penalties that exist in current construction contracts. NOx budgets for construction equipment might be established, much like project schedules are determined, and if the contractors show that they came under budget, they receive a monetary reward. This program would help subsidize the introduction of cleaner equipment in the construction fleet, while placing the risk of investment on the contractors and not the Department. A reward of $10,000 for each ton NOx reduced would represent an extremely significant reduction in costs to the Department (97 - 98 percent lower than the cost of the construction equipment restriction rule and 71 – 82 percent lower than the cost of fully retrofitting the heavy-highway construction fleet in the two nonattainment areas).

Create a database of clean/super-clean construction equipment used on TxDOT projects.

TxDOT's Construction Division could create a database of construction equipment greater than 50 hp that have been retrofitted with emission control technology or are new Tier 2/Tier 3 equipment. Contractors might be encouraged or required to register their equipment with TxDOT and provide certifications to the Department that the equipment has received proper maintenance and is operating correctly. In order for a contractor to receive credit or rewards, they must adopt controls with certified NOx reductions. A reward of $10,000 for each ton NOx reduced would represent an extremely significant reduction in costs to the Department (97 - 98 percent lower than the cost of the construction equipment restriction rule and 71 – 82 percent lower than the cost of fully retrofitting the heavy-highway construction fleet in the two nonattainment areas).

Update the QUEWZ model to address limitations in emission analysis and documentation.

As stated within this report, several deficiencies were found when applying QUEWZ to evaluating mobile source emission impacts of work zone lane closures. Specific recommendations for improving QUEWZ include the following:

- Provide instruction within the documentation for evaluating overnight operations.
- Improve the emissions module so that emissions from diverted vehicles are included in the evaluations summary.
- Improve the emissions module so that emissions are calculated for scenarios where there are speed reductions, but no queues are formed.
- Modify the model to run within the Microsoft Windows platform so that modules can be included to provide better, more informational graphical output.

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APPENDIX A: DIESEL GLOSSARY[22]

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[22] Glossary taken from: Reduction Plan to Reduce PM Emission from Diesel-Fueled Engines and Vehicles. California Air Resources Board, Stationary Source Division, Mobile Source Control Division. October 2000.

Aftercooling / Intercooling - Cooling the engine intake air after the turbocharger and prior to introduction into the cylinder. Aftercooling increases engine power and lowers NOx emissions.

After-treatment Devices - Devices that remove pollutants from exhaust gases after the gas leaves combustion chamber (e.g., catalytic converters or diesel particulate filters). The term "exhaust gas after-treatment" is considered derogatory by the emission control industry, but there is no consensus on the use of such alternatives as "post-combustion treatment" or "exhaust emission control."

Alternative Fuel - Fuel other than petroleum diesel or gasoline.

Bi-Fueled Vehicle - A vehicle with two separated fuel systems designed to run on either conventional fuel or an alternative fuel using only one fuel at a time.

Biodiesel - The mono alkyl esters of long chain fatty acids derived from renewable lipid feedstocks, such as vegetable oils and animal fats, for use in compression ignition (diesel) engines. Manufactured by transestrification of the organic feedstock by methanol.

Brake Mean Effective Pressure (BMEP) - The work accomplished during one engine cycle divided by the engine swept volume. It is essentially the engine torque normalized by the engine displacement. The word "brake" denotes the actual torque/power available at the engine flywheel as measured on a dynamometer. Thus, BMEP is a measure of the useful power output of the engine.

California Air Resources Board (CARB) - A state regulatory agency charged with regulating the air quality in California.

Carbon Dioxide (CO_2) - A colorless, odorless, non-toxic gas. It is one of main products of fossil-fuel combustion. CO_2 is a greenhouse gas that contributes to the potential for global warming.

Carbon Monoxide (CO) - A colorless, odorless, and toxic gas. It blocks the lungs' ability to obtain oxygen. CO is produced by incomplete combustion of fossil fuels and is a major part of air pollution. Compression-ignition (diesel) engines generate significantly lower CO emissions than spark-ignited engines.

Catalyst - A substance that influences the rate of a chemical reaction but is not one of the original reactants or final products, i.e., it is not consumed or altered in the reaction. Catalysts are used in many processes in the chemical and petroleum industries. Emission control catalysts are used to promote reactions that change exhaust pollutants from internal combustion engines into harmless substances.

Cetane Index - A calculated value, derived from fuel density and volatility, giving a reasonably close approximation to cetane number.

Cetane Number - A measure of ignition quality of diesel fuel. The higher the cetane number the easier the fuel ignites when injected into an engine. Cetane number is determined by an engine test using two reference fuel blends of known cetane numbers. The reference fuels are prepared by blending normal cetane (n-hexadecane), having a value of 100, with heptamethyl nonane, having a value of 15.

Clean Air Act (CAA) - In the U.S., the fundamental legislation to control air pollution. The original Clean Air Act was signed in 1963. The law set emissions standards for stationary sources, such as factories and power plants. Criteria pollutants included lead, ozone, CO, SO_2, NOx, and PM, as well as air toxins. The CAA was amended several times, most recently in 1990. The Amendments of 1970 introduced motor vehicle emission standards for automobiles and trucks.

Clean-Fuel Vehicle (CFV) - A vehicle that has been certified to meet clean-fuel standards of the Clean Air Act Amendments of 1990.

Cloud Point (CP) - A measure of the ability of a diesel fuel to operate under cold weather conditions. Defined as the temperature at which wax first becomes visible when diesel fuel is cooled under standardized test conditions (ASTM D2500).

Common Rail Injection - A diesel fuel injection system employing a common pressure accumulator, called the rail, which is mounted along the engine block. The rail is fed by a high-pressure fuel pump. Solenoid valves activate the injectors, which are fed from the common rail. The solenoid valves and the fuel pump are electronically controlled. In the common rail injection system the injection pressure is independent from engine speed and load. Therefore, the injection parameters can be freely controlled. Usually a pilot injection is introduced, which allows for reductions in engine noise and NOx emissions.

Compressed Natural Gas (CNG) - Natural gas compressed to a volume and density that is practical as a portable fuel supply.

Compression Ignition (CI) - The form of ignition that initiates combustion in a diesel engine. The rapid compression of air within the cylinders generates the heat required to ignite the fuel as it is injected.

Cordierite - A ceramic material of the formula $2MgO\text{-}2Al_2O_3\text{-}5SiO_2$, which is used for automotive flow-through catalyst substrates and ceramic wall-flow diesel filters.

Diesel Oxidation Catalyst (DOC) - Catalyst promoting oxidation processes in diesel exhaust. Usually designed to reduce emissions of the organic fraction of diesel particulates, gas-phase HC, and CO.

Diesel Particulate Filter (DPF) - A device that physically captures diesel particulates, preventing their discharge from the tailpipe. Collected particulates need to be removed from the filter, usually by continuous or periodic oxidation in a process called "regeneration."

Diesel Particulate Matter (DPM) - Sub-micron size particles found in diesel exhaust. Most emission regulations specify DPM measurement methods in which particulates are sampled on filters from cooled exhaust gas. The cooling causes condensation of vapors in the gas sampling train. Thus, DPM is composed of both solid and liquid particles and is generally classified into three fractions: (1) inorganic carbon (soot), (2) organic fraction (often referred to as SOF or VOF), and (3) sulfate fraction (hydrated sulfuric acid).

Direct Injection (DI) - In diesel engines with direct injection the combustion chamber is not divided, and fuel is injected directly to the cylinder.

Dual-Fuel Vehicle - A vehicle designed to operate on a combination of alternative fuel, such as compressed natural gas (CNG) or liquefied petroleum gas (LPG), and conventional fuel, such as diesel or gasoline. These vehicles have two separate fuel systems, which inject both fuels simultaneously into the engine combustion chamber.

Electronic Control Module (ECM) - A microprocessor that determines the beginning and end of each injection cycle on every cylinder. The ECM determines both fuel metering and injection timing in response to such parameters as engine crankshaft position and rpm, engine coolant and intake air temperature, and absolute intake air boost pressure.

Elemental Carbon (EC) - Inorganic carbon, as opposed to carbon in organic compounds, is sometimes used as a surrogate measure for DPM, especially in occupational health environments. Elemental carbon usually accounts for 40-60 percent of the total DPM mass.

Emission Credit Trading - A program administered by EPA under which low polluters are awarded credits that may be traded on a regulated market and purchased by polluters who are in noncompliance for emissions until compliance can be achieved.

Evaporative Emissions - Hydrocarbon vapors that escape from a fuel storage tank or a vehicle fuel tank or vehicle fuel system.

Flash Point - The temperature at which a combustible liquid gives off just enough vapor to produce a vapor/air mixture that will ignite when a flame is applied. The flash point is measured in a standardized apparatus using standard test methods, such as ASTM D93 or ISO 2719.

Flexible-Fueled Vehicle - A vehicle with the ability to operate on alternative fuels, 100 percent petroleum-based fuels, or a mixture of alternative fuel and petroleum-based fuels.

Fuel Cycle - The processes involved in extracting a fuel in its native form, converting it to a useful product, transporting it to market, and consuming it at its final destination.

Geometric Surface Area (GSA) - In monolith catalyst substrates, the total channel surface area per unit of substrate volume.

Hybrid Electric Vehicle (HEV) - Various types of electric vehicles that use another power source to propel the vehicle or generate power for an electric drive train, or a combination of the two types.

Hydraulic/Electronic Unit Injector (HEUI) - A type of unit injector actuated by engine oil pressure rather than the camshaft. A separate oil pump creates a very high oil pressure (up to 3000 psi). This high pressure is routed to every injector through a gallery. The engine's Electronic Control Module varies the pressure in response to engine speed and other parameters.

Ignition Delay - The length of time or number of degrees of crankshaft rotation between the beginning of injection and ignition of the fuel.

In-Direct Injection (IDI) - In diesel engines with in-direct injection, the fuel is injected to an auxiliary prechamber. Combustion starts in the prechamber and propagates to the cylinder.

Injection Period - The time, measured in degrees of crankshaft rotation, between the beginning and end of injection. On engines with hydromechanical injection systems, it is controlled by the opening and closing of ports in the injector body or by the action of a plunger forcing fuel out of a cup. On electronic injection systems, it is determined directly or indirectly by the action of a solenoid valve.

In-Line Injection Pump - An injection pump with a separate cylinder and plunger for each engine cylinder. Each plunger is rotated by a rack to determine metering via ports in the body of the pump and helical cuts on the pump plungers. The plungers are driven off a camshaft, which usually incorporates a centrifugal or electronically controlled timing advance mechanism.

Lean NOx Catalyst (LNC) - Catalyst designed to reduce nitrogen oxides from diesel or spark-ignited engine exhaust gases under net oxidizing conditions, i.e., in the presence of excessive amount of oxygen.

Liquefied Natural Gas (LNG) - Natural gas that has been refrigerated to cryonic temperatures where the gas condenses into a liquid.

Liquefied Petroleum Gas (LPG) - A mixture of low-boiling HC that exist in a liquid state at ambient temperatures when under moderate pressures (less than 1.5 MPa or 200 psi). LPG is a by-product from the processing of natural gas and from petroleum refining. Major components of LPG are propane (min. 85 percent content in the U.S.), butane, and propylene.

Low Emission Vehicle (LEV) - A vehicle that is certified to meet the LEV emission standards set by CARB.

National Ambient Air Quality Standards (NAAQS) - Ambient standards for six pollutants including ozone, CO, nitrogen dioxide, lead, PM, and oxides of sulfur specifically regulated under the U.S. Clean Air Act of 1990. Urban areas are required to achieve attainment regarding ambient concentrations of these criteria pollutants.

Natural Gas (NG) - Mixture of hydrocarbon compounds and small quantities of various non-hydrocarbon components existing in the gas phase or in solution with crude oil in natural underground reservoirs. The main component of natural gas is methane.

Nitrogen Oxides (NOx) - Several air-polluting gases composed of nitrogen and oxygen that play an important role in the formation of photochemical smog. Nitrogen oxides are collectively referred to as "NOx," where "x" represents a changing proportion of oxygen to nitrogen. Internal combustion engines are significant contributors to the worldwide nitrogen oxide emissions. For the purpose of emission regulations, NOx is composed of colorless nitric oxide (NO), and the reddish-brown, very toxic, and reactive nitrogen dioxide (NO_2). Other nitrogen oxides, such as nitrous oxide N_2O (the anesthetic "laughing gas"), are not regulated emissions.

Nonattainment Area - A region that exceeds the U.S. NAAQS for one or more criteria pollutants. Such regions, or areas, are required to seek modifications to their SIPs, setting forth a reasonable timetable using means that are approved by EPA to achieve attainment of NAAQS by a certain date. Under the Clean Air Act, if a nonattainment area fails to attain NAAQS, EPA may superimpose a Federal Implementation Plan (FIP) with stricter requirements. Also, EPA may impose fines, construction bans, or cutoffs in federal grant revenues until the area achieves applicable NAAQS.

Original Equipment Manufacturer (OEM) - Manufacturers of equipment (such as engines, vehicles, etc.) that provide the original product design and materials for its assembly and manufacture. OEMs are directly responsible for manufacturing and modifying the products, making them commercially available, and providing the warranty.

Overhead Cam - A camshaft used for operating both valves and unit injectors, located on top of or within the cylinder head. Such camshafts are driven by a multi-gear geartrain off the crankshaft. They simplify the design of the cylinder head and eliminate pushrods, allowing for much larger, open intake and exhaust ports, and better breathing.

Oxygenated Fuel - Any fuel substance containing oxygen, such as ethanol, methanol, or biodiesel. Oxygenated fuel tends to give a more complete combustion of its carbon into carbon dioxide (CO_2), thereby reducing emissions of HC and CO. Oxygenated fuels may result in increased nitrogen oxides emissions.

Ozone (O_3) - An oxygen molecule with three oxygen atoms. The stratosphere ozone layer, which is a concentration of ozone molecules located at 10 to 50 kilometers above sea level, is in a state of dynamic equilibrium. Oxygen molecules absorb ultraviolet (UV) light to form ozone that, in turn, decomposes back to oxygen. These processes absorb most of the ultraviolet light from the sun, shielding life from the harmful effects of UV radiation. Ozone is normally present at ground level in low concentrations. In cities where high levels of air pollutants are present, the action of the sun's ultraviolet light can, through a complex series of reactions, produce harmful concentrations of the ground level ozone. The resulting air pollution is known as photochemical smog.

Particulate Matter (PM) - Particles formed by incomplete combustion of fuel. Compression-ignition (diesel) engines generate significantly higher PM emissions than spark-ignited engines. The particles are composed of elemental carbon, heavy hydrocarbons (SOF), and hydrated sulfuric acid ("sulfate particulates").

Polycyclic Organic Matter (POM) - A class of air toxics defined in the U.S. Clean Air Act as compounds with more than one benzene ring and a boiling point of 100 °C and higher. Includes practically all of diesel polynuclear aromatic hydrocarbon (PAH) material.

Polynuclear Aromatic Hydrocarbons (PAH) - Aromatic HC with two or more (up to five or six) benzene rings joined in various, more or less clustered forms.

Precombustion Chamber - A small, auxiliary combustion chamber connected by a narrow orifice with the main chamber. Fuel is injected into the prechamber and ignites there, causing hot gases to expand into the main chamber (cylinder).

Selective Catalytic Reduction (SCR) - Term frequently used as a synonym for catalytic reduction of NOx in diesel exhaust or flue gases by nitrogen-containing compounds, such as ammonia or urea. Such systems are commercially available for stationary applications. Since "selective catalytic reduction" is a generic term also used in regards to other reactions, its use may lead to confusion in some situations.

Soluble Organic Fraction (SOF) - The organic fraction of diesel particulates. SOF includes heavy hydrocarbons derived from the fuel and from the engine lubricating oil. The term "soluble" originates from the analytical method used to measure SOF that is based on extraction of PM samples using organic solvents.

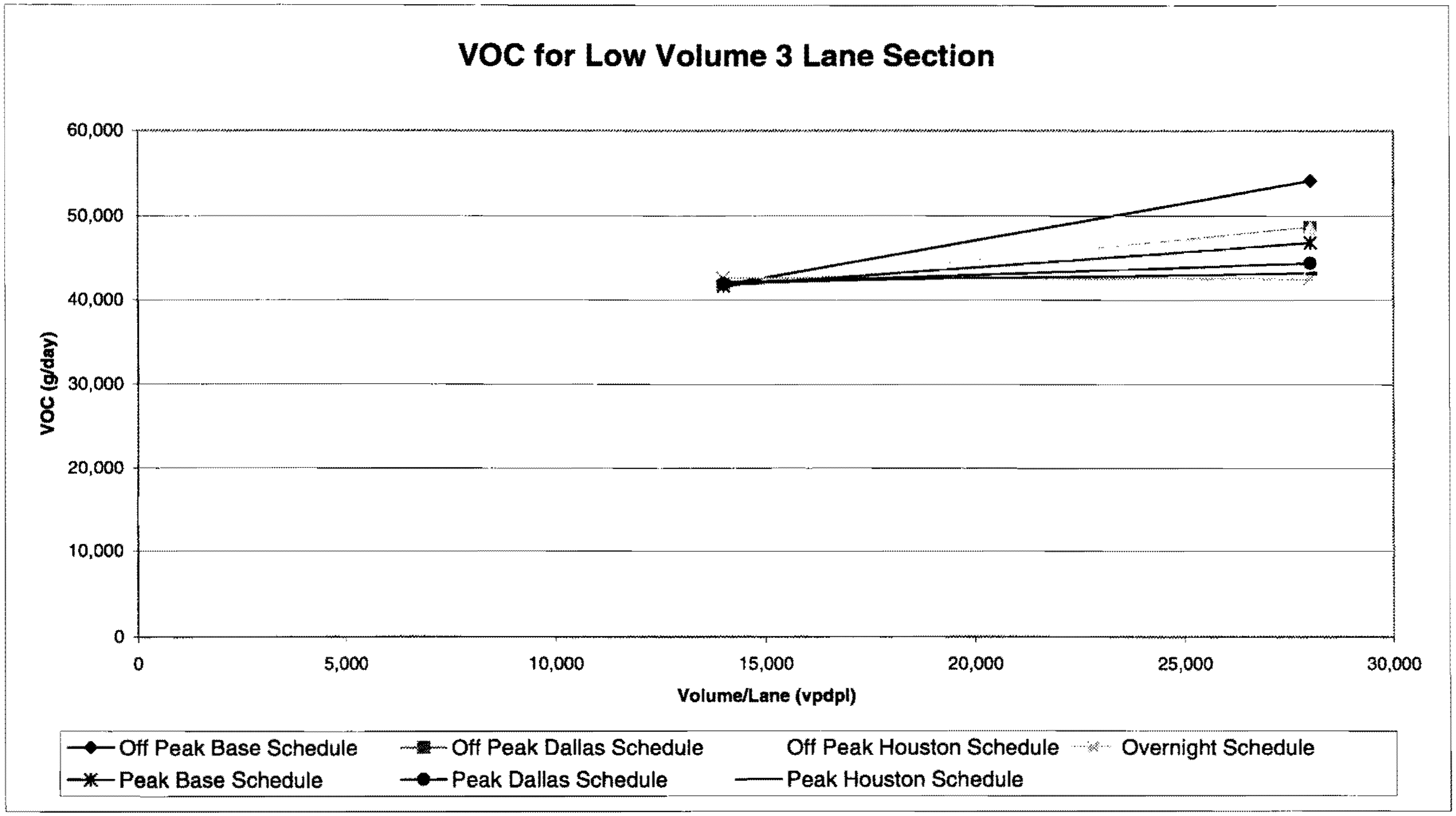
Total Carbon (TC) - The sum of the elemental carbon and organic carbon associated with diesel particulates. Typically amounts to 80-85 percent of the total DPM mass.

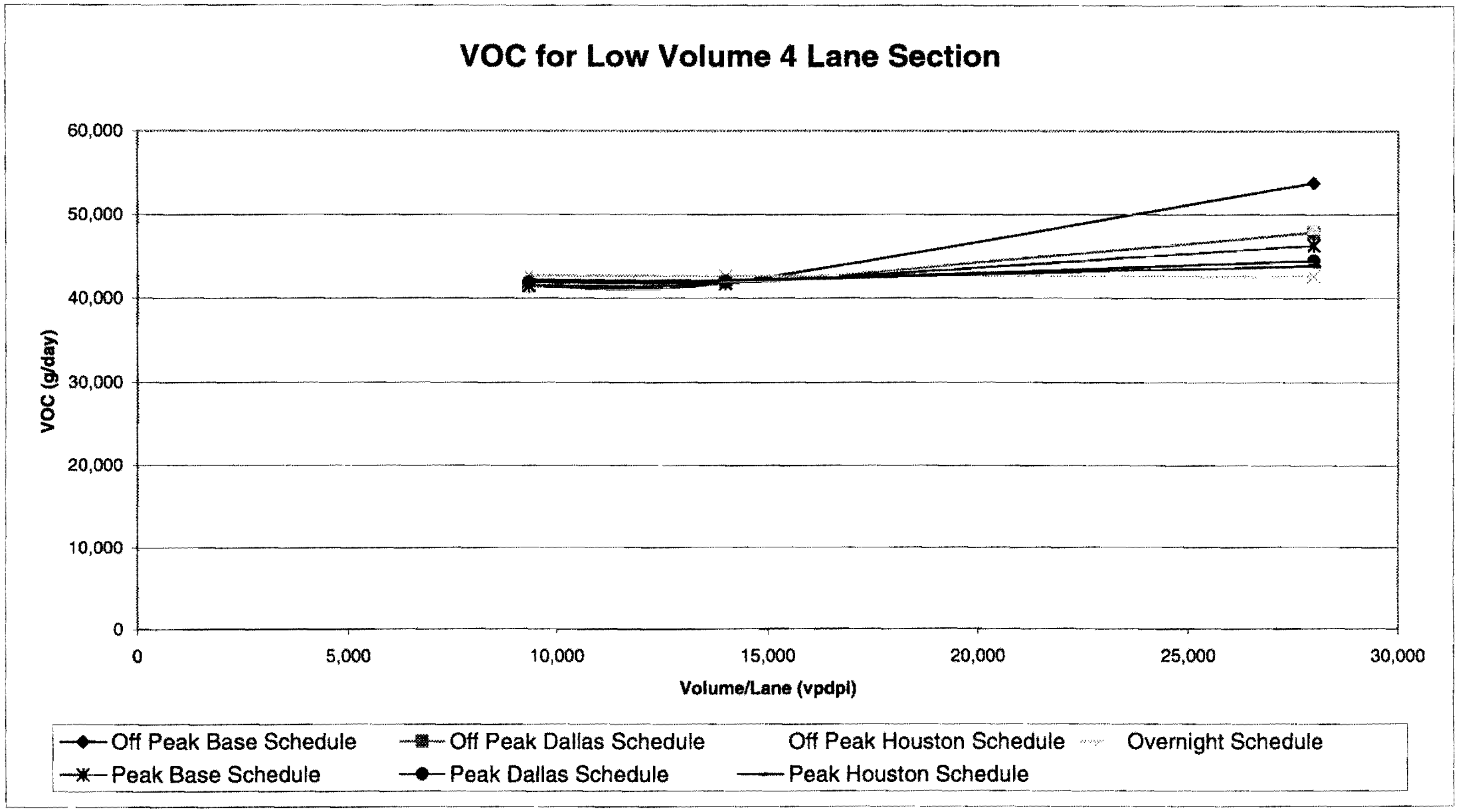
Turbocharging - A process of compressing the engine intake air charge to allow more air and fuel into the cylinder, increasing the engine's power output. An exhaust gas-propelled turbine drives the compressor, called the turbocharger.

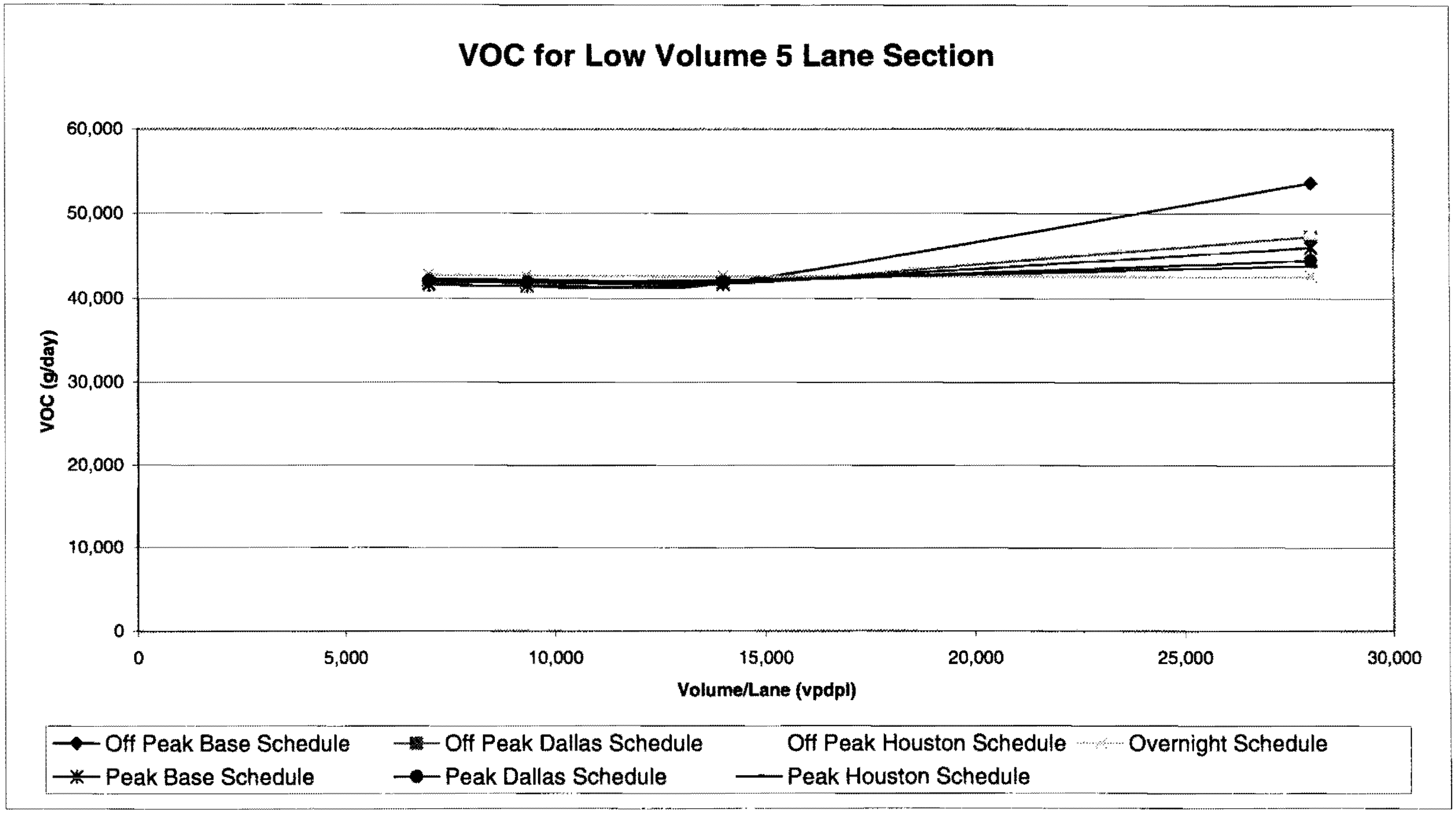
Volatile Organic Compound (VOC) - Hydrocarbon-based emissions released through evaporation or combustion. The term VOC is usually used in regard to stationary emission sources.

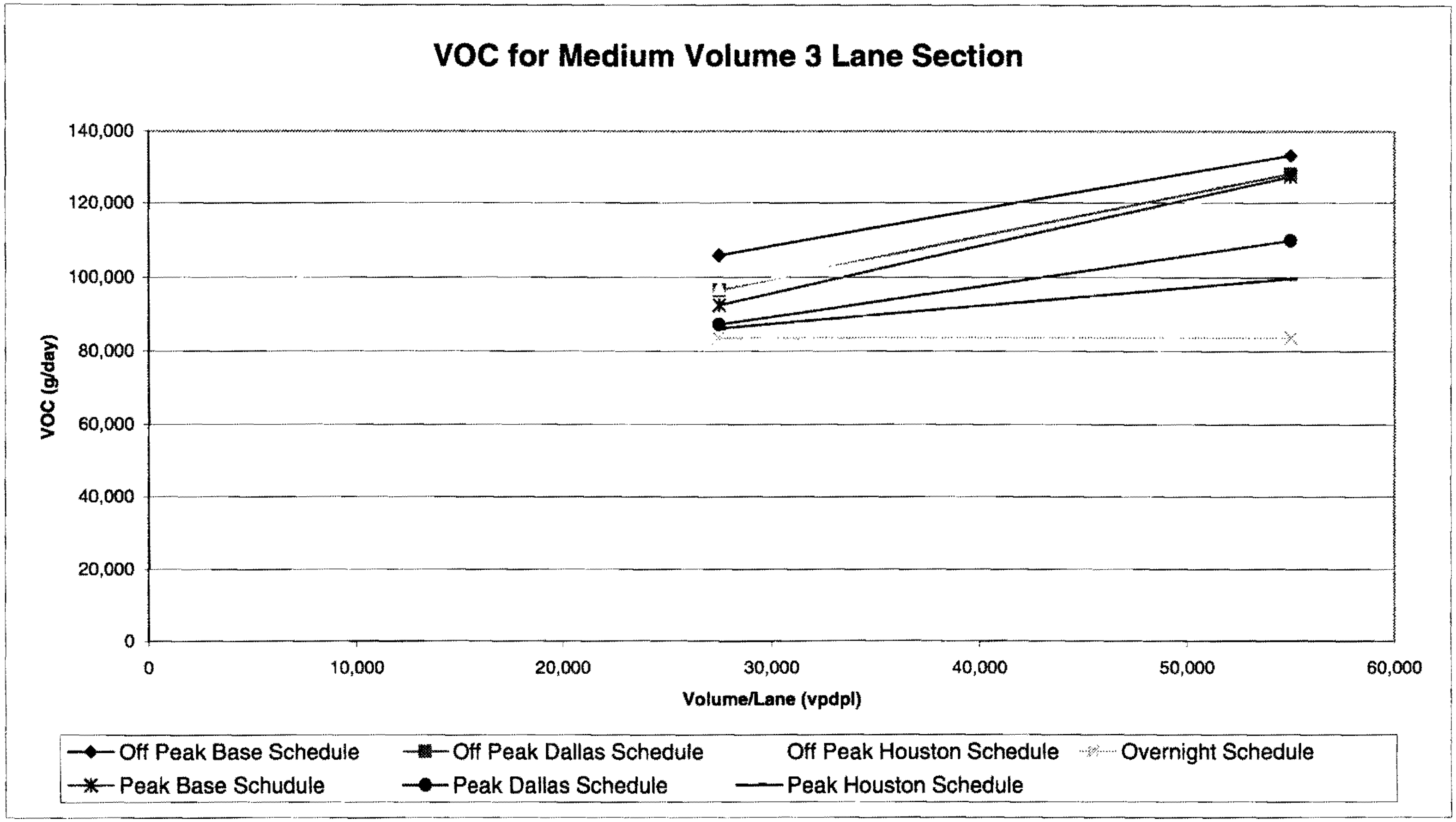
Volatile Organic Fraction (VOF) - The organic fraction of DPM as determined by vacuum evaporation. It may or may not be equivalent to the SOF fraction. Depending on the exact analytical procedure, the VOF may include the organic material (SOF) as well as some of the sulfate particulates which, being composed primarily of hydrated sulfuric acid, are also volatile.

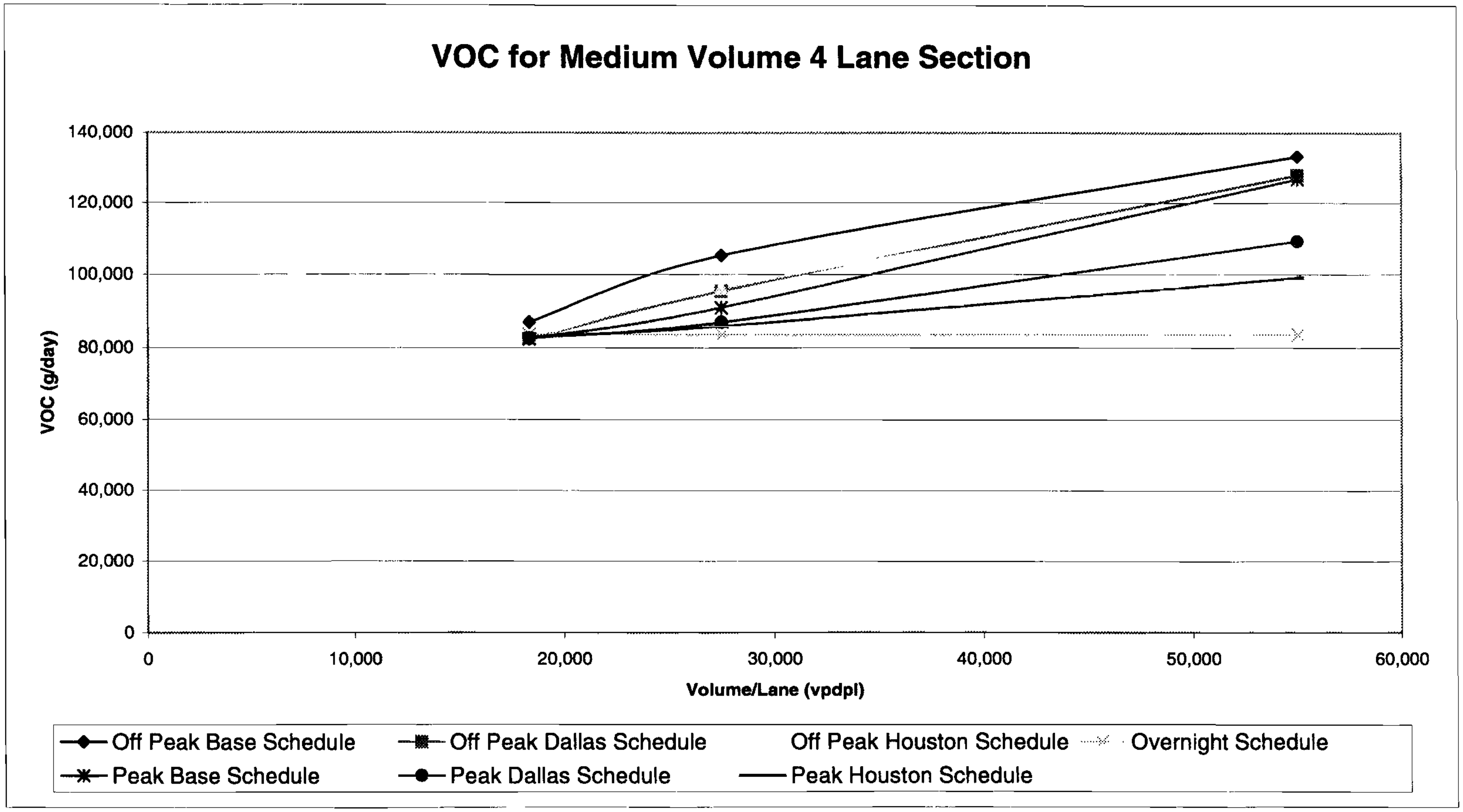
APPENDIX B: EMISSION AND ROAD USER COST TABLES AND GRAPHS

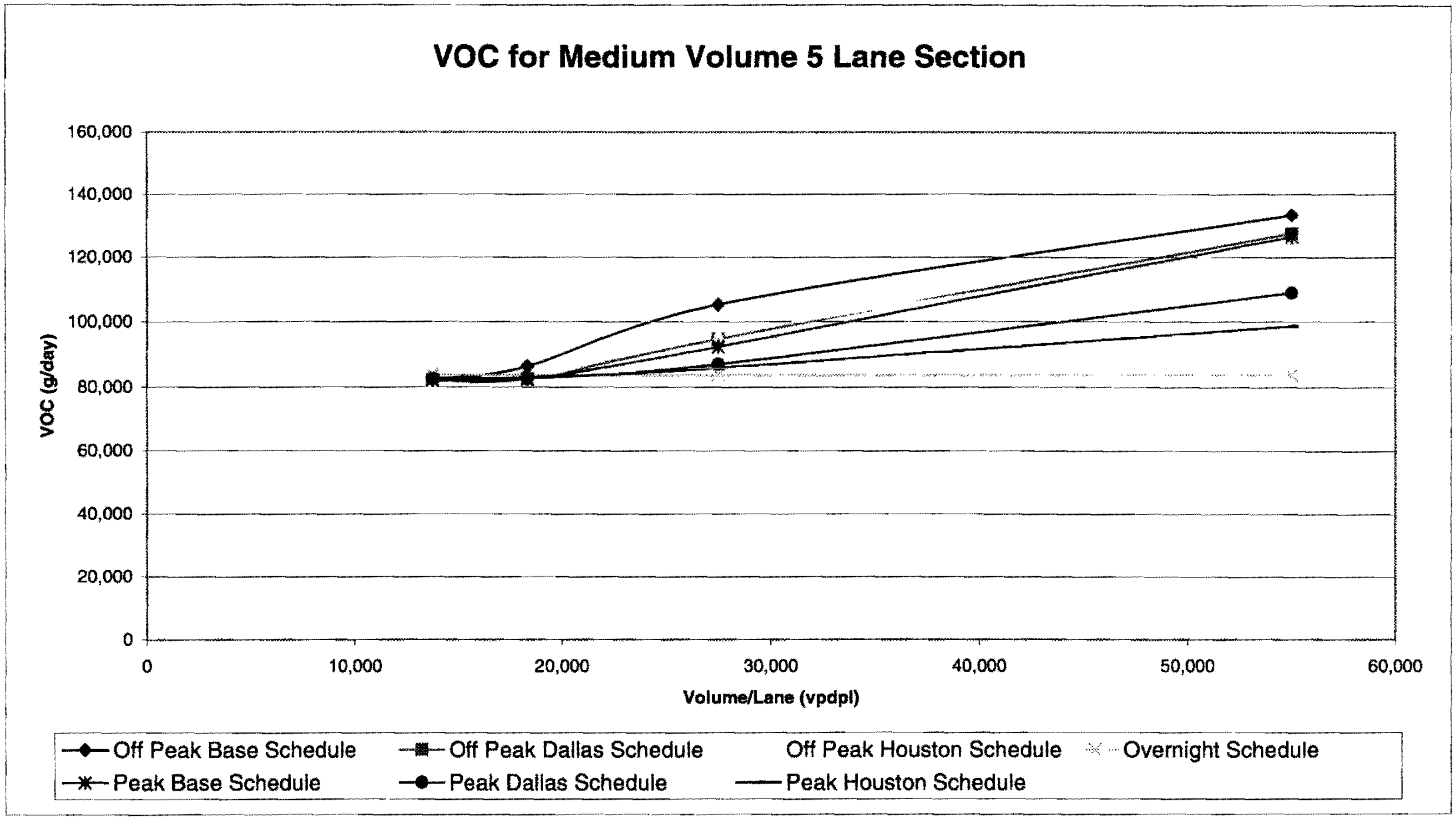

VOC for Low Volume 3 Lane Section
VOC (g/day)
60,000
50,000
40,000
30,000
20,000
10,000
0
0
5,000
10,000
15,000
20,000
25,000
30,000
Volume/Lane (vpdpl)
Off Peak Base Schedule
Off Peak Dallas Schedule
Off Peak Houston Schedule
Overnight Schedule
Peak Base Schedule
Peak Dallas Schedule
Peak Houston Schedule

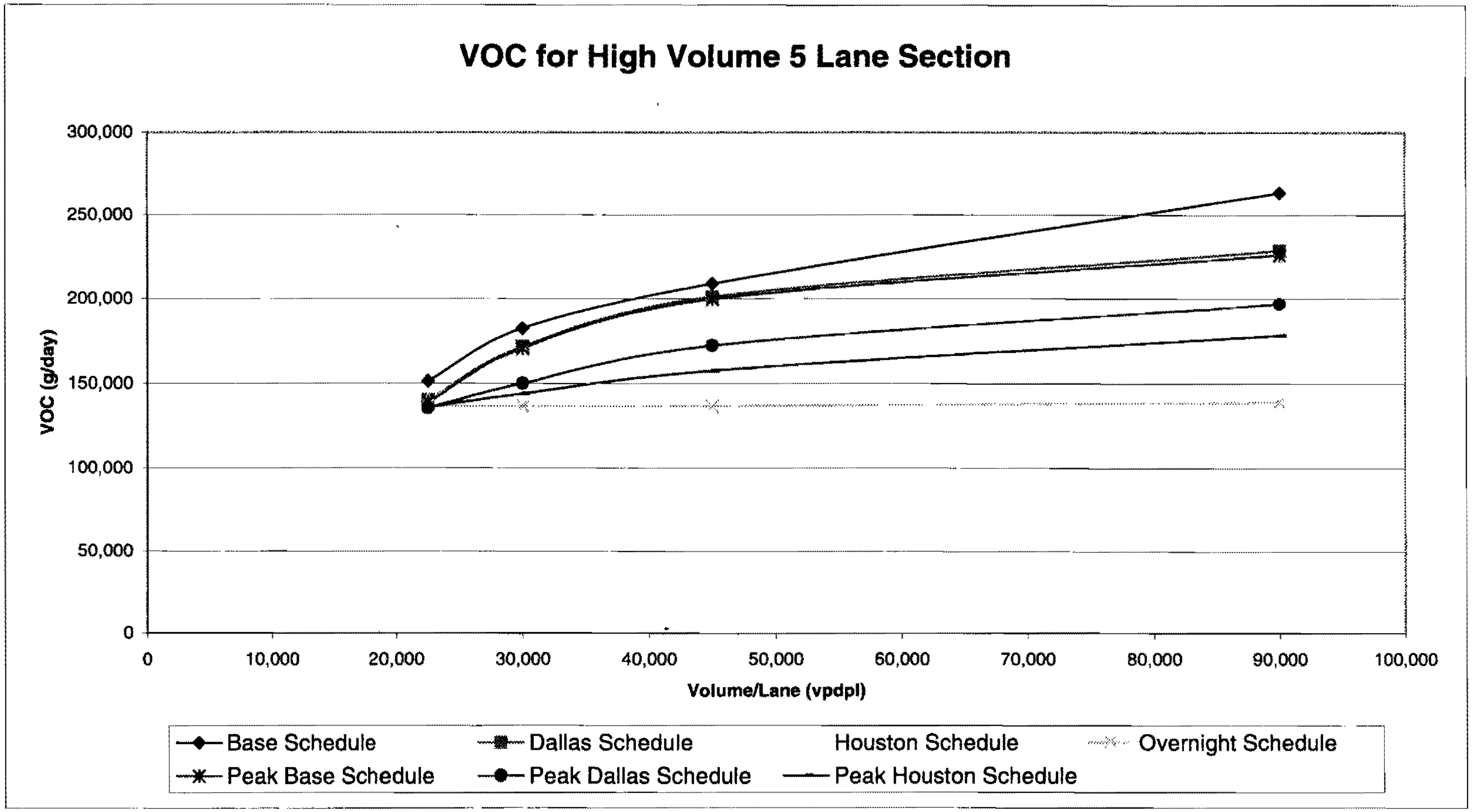

VOC for Low Volume 4 Lane Section
VOC (g/day)
60,000
50,000
40,000
30,000
20,000
10,000
0
0
5,000
10,000
15,000
20,000
25,000
30,000
Volume/Lane (vpdpl)
Off Peak Base Schedule
Off Peak Dallas Schedule
Off Peak Houston Schedule
Overnight Schedule
Peak Base Schedule
Peak Dallas Schedule
Peak Houston Schedule

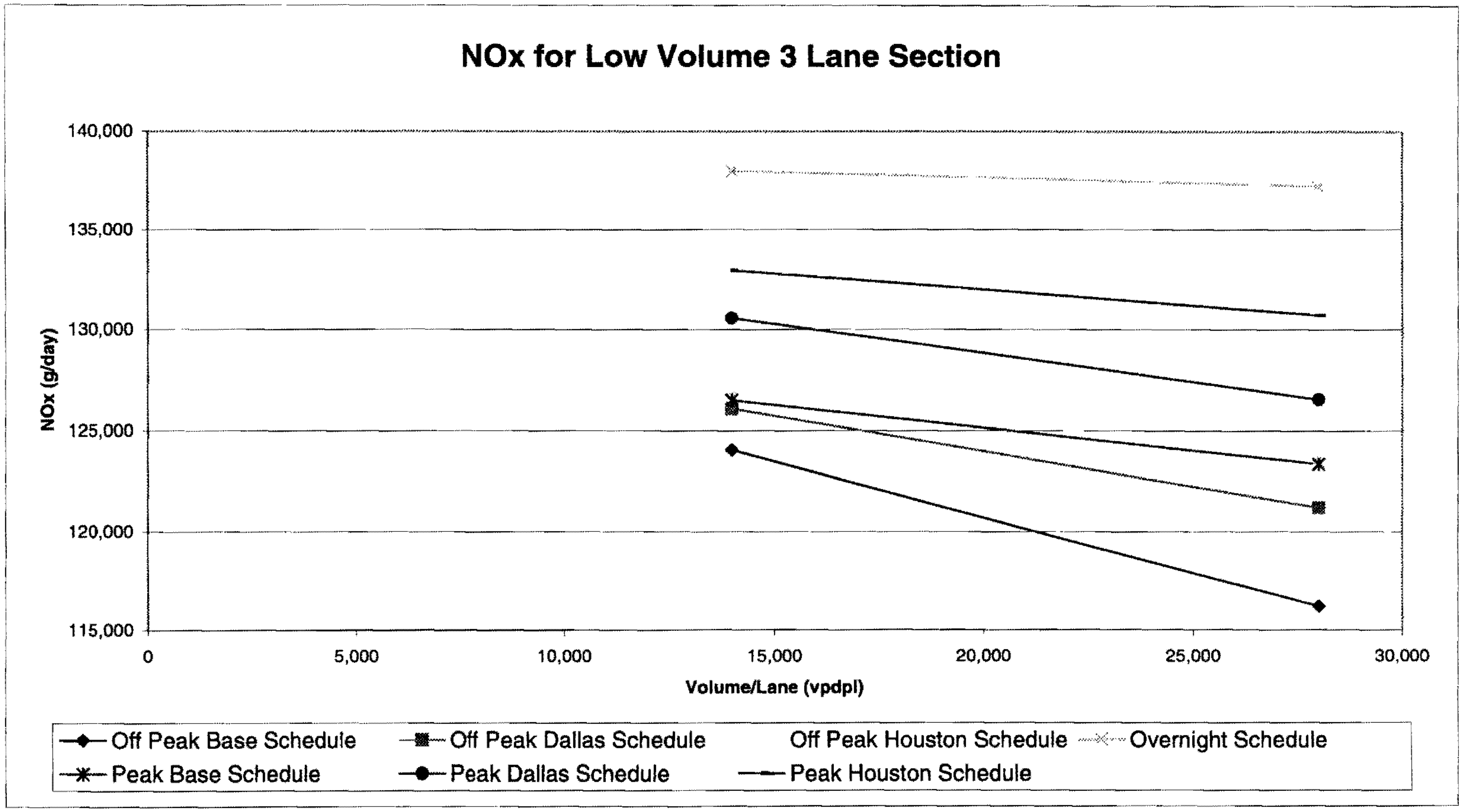

VOC for Low Volume 5 Lane Section
VOC (g/day)
60,000
50,000
40,000
30,000
20,000
10,000
0
0
5,000
10,000
15,000
20,000
25,000
30,000
Volume/Lane (vpdpl)
Off Peak Base Schedule
Off Peak Dallas Schedule
Off Peak Houston Schedule
Overnight Schedule
Peak Base Schedule
Peak Dallas Schedule
Peak Houston Schedule


VOC for Medium Volume 3 Lane Section
VOC (g/day)
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
0
10,000
20,000
30,000
40,000
50,000
60,000
Volume/Lane (vpdpl)
Off Peak Base Schedule
Off Peak Dallas Schedule
Off Peak Houston Schedule
Overnight Schedule
Peak Base Schudule
Peak Dallas Schedule
Peak Houston Schedule

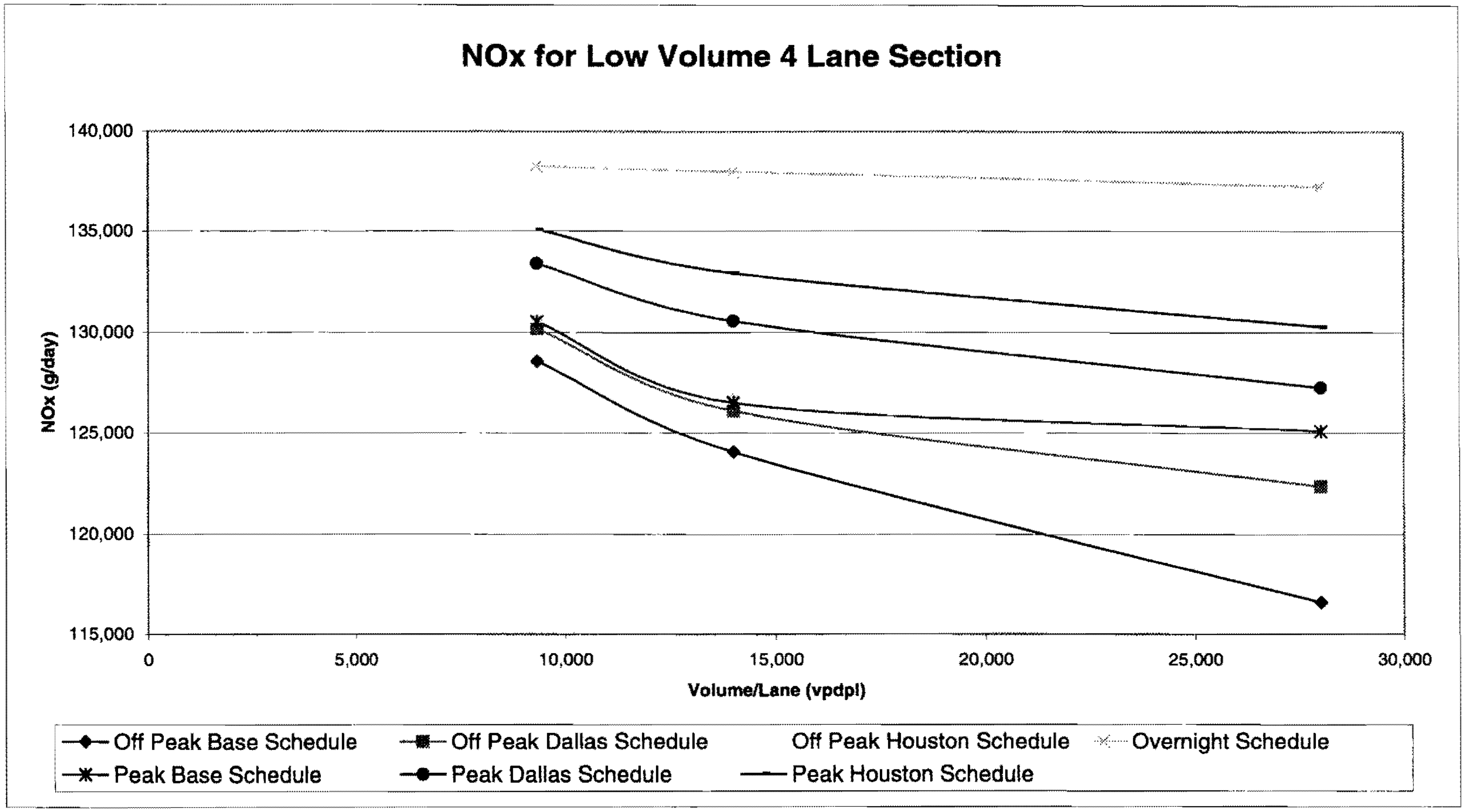

VOC for Medium Volume 4 Lane Section
VOC (g/day)
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
0
10,000
20,000
30,000
40,000
50,000
60,000
Volume/Lane (vpdpl)
Off Peak Base Schedule
Off Peak Dallas Schedule
Off Peak Houston Schedule
Overnight Schedule
Peak Base Schedule
Peak Dallas Schedule
Peak Houston Schedule

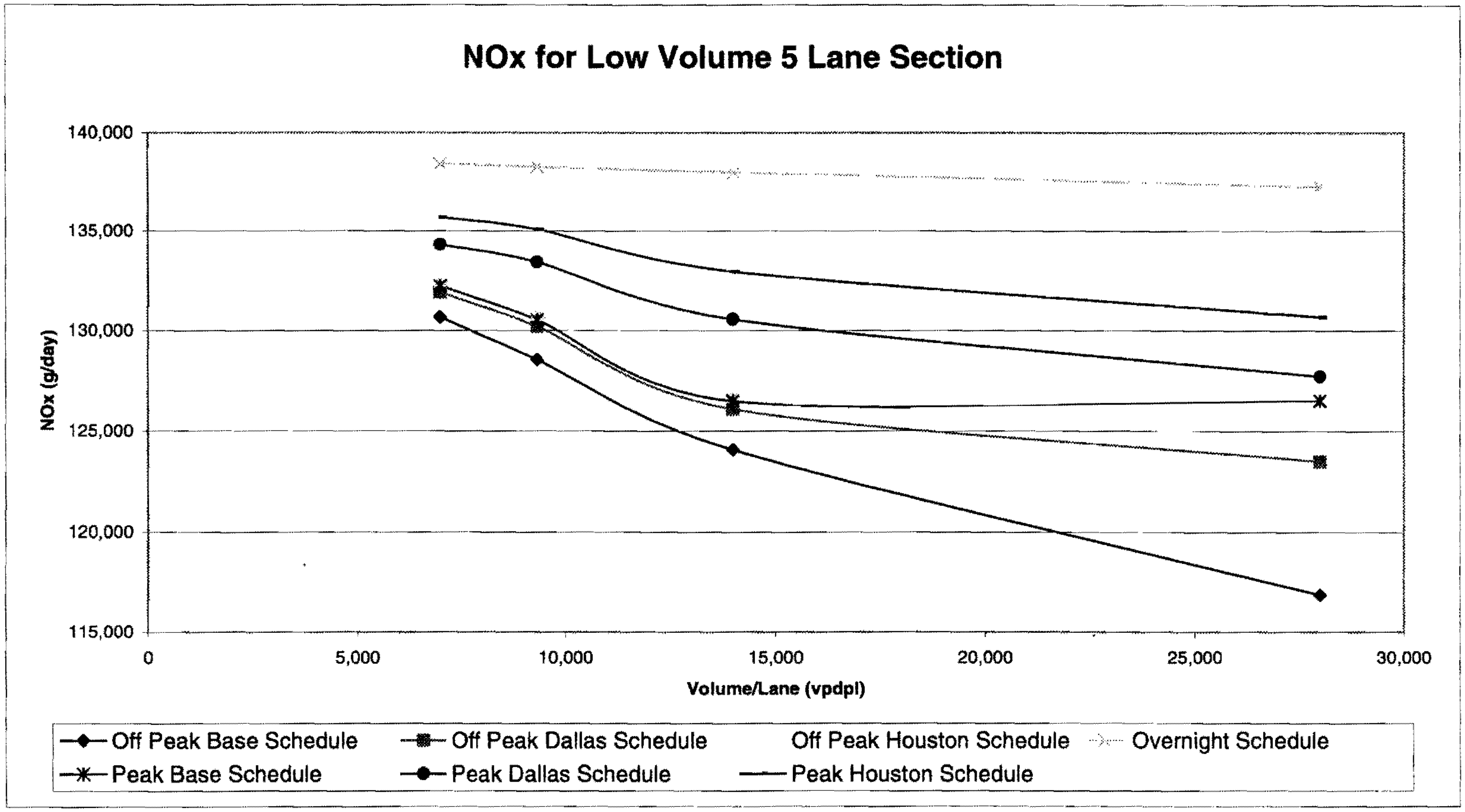

VOC for Medium Volume 5 Lane Section
VOC (g/day)
160,000
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
0
10,000
20,000
30,000
40,000
50,000
60,000
Volume/Lane (vpdpl)
Off Peak Base Schedule
Off Peak Dallas Schedule
Off Peak Houston Schedule
Overnight Schedule
Peak Base Schedule
Peak Dallas Schedule
Peak Houston Schedule

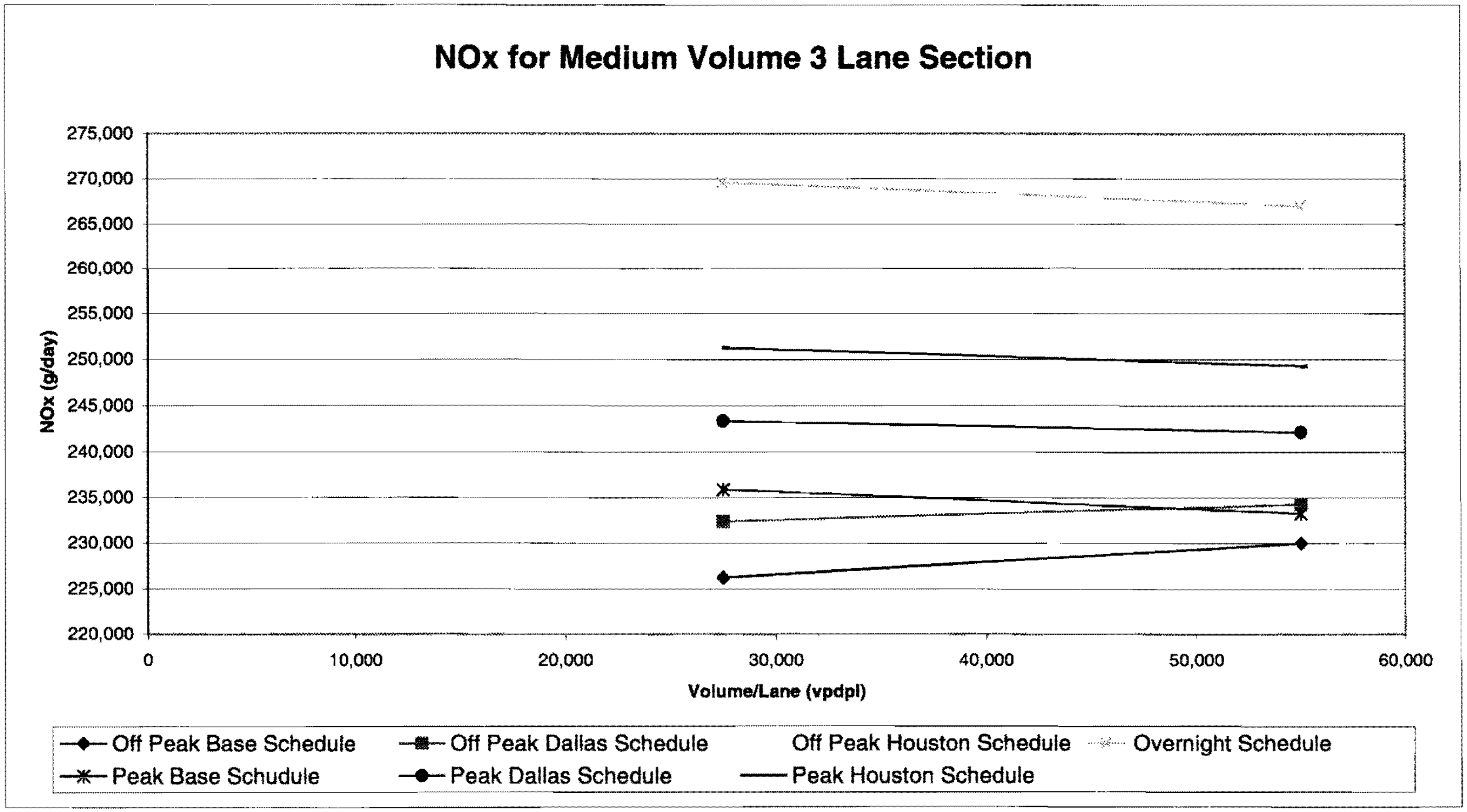

VOC for High Volume 5 Lane Section
VOC (g/day)
300,000
250,000
200,000
150,000
100,000
50,000
0
0
10,000
20,000
30,000
40,000
50,000
60,000
70,000
80,000
90,000
100,000
Volume/Lane (vpdpl)
Base Schedule
Dallas Schedule
Houston Schedule
Overnight Schedule
Peak Base Schedule
Peak Dallas Schedule
Peak Houston Schedule

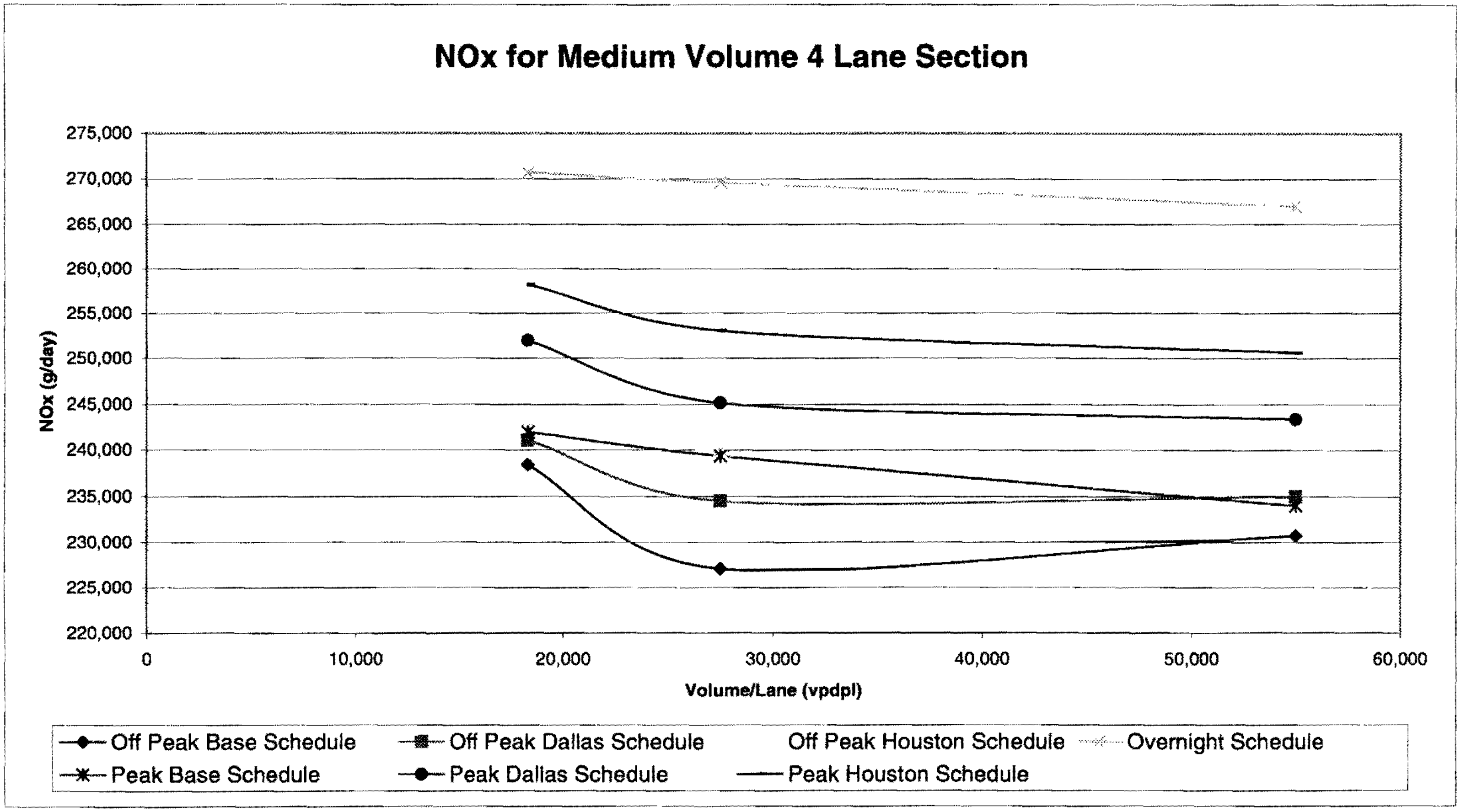


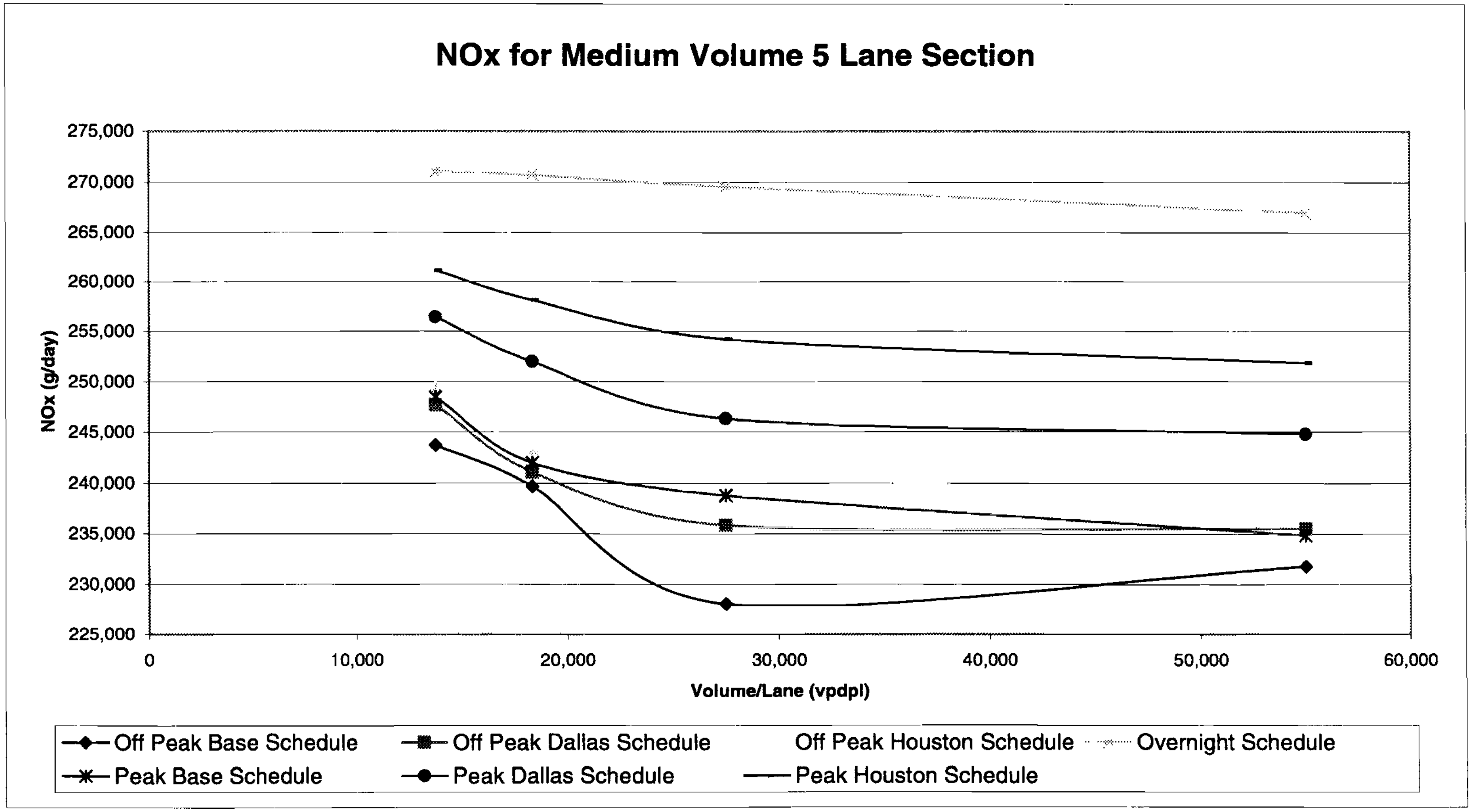
NOx for Low Volume 3 Lane Section
NOx (g/day)
140,000
135,000
130,000
125,000
120,000
115,000
0
5,000
10,000
15,000
20,000
25,000
30,000
Volume/Lane (vpdpl)
Off Peak Base Schedule
Off Peak Dallas Schedule
Off Peak Houston Schedule
Overnight Schedule
Peak Base Schedule
Peak Dallas Schedule
Peak Houston Schedule


NOx for Low Volume 4 Lane Section

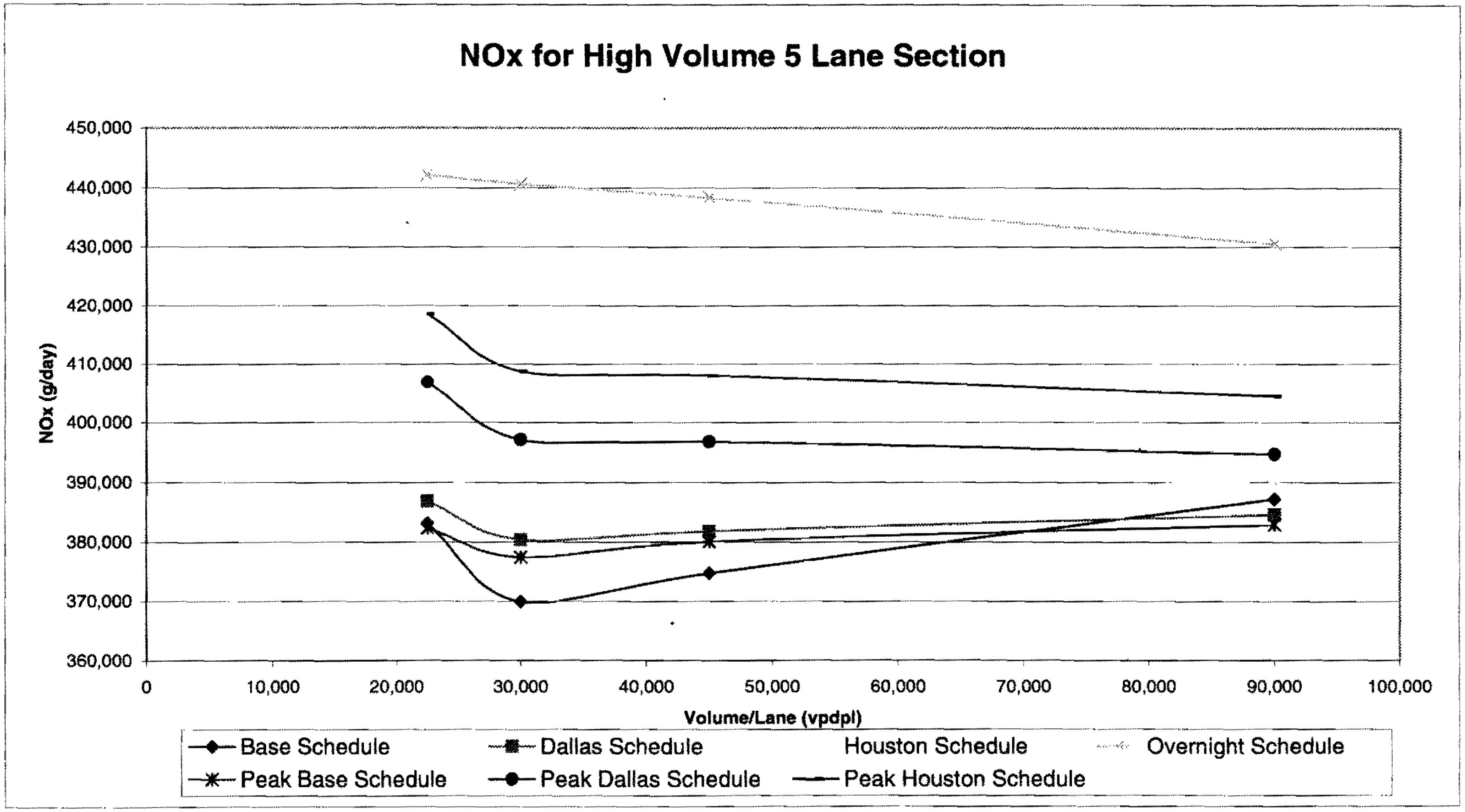

NOx for Low Volume 5 Lane Section
140,000
135,000
130,000
125,000
120,000
115,000
NOx (g/day)
0
5,000
10,000
15,000
20,000
25,000
30,000
Volume/Lane (vpdpl)
Off Peak Base Schedule
Off Peak Dallas Schedule
Off Peak Houston Schedule
Overnight Schedule
Peak Base Schedule
Peak Dallas Schedule
Peak Houston Schedule

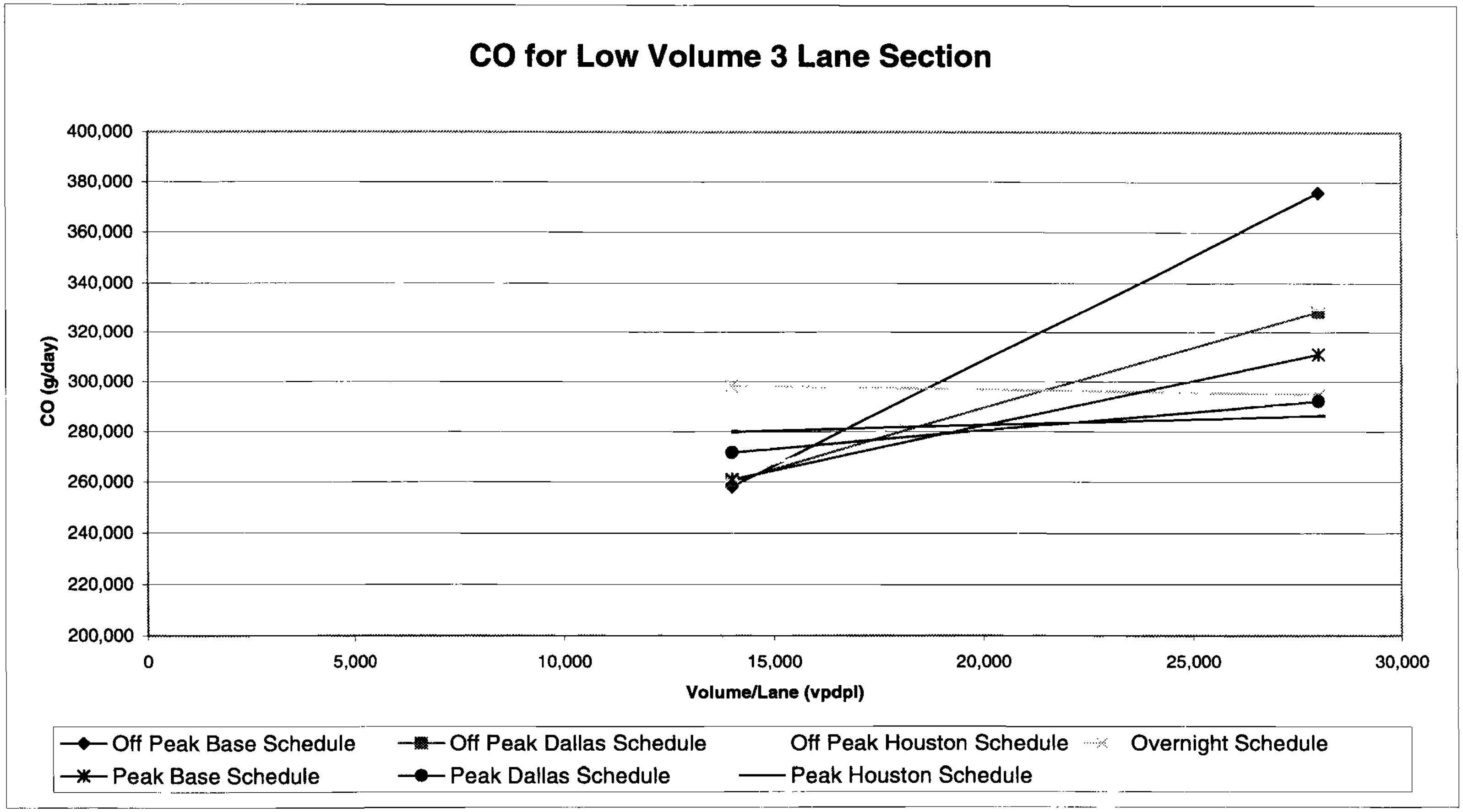

NOx for Medium Volume 3 Lane Section
NOx (g/day)
275,000
270,000
265,000
260,000
255,000
250,000
245,000
240,000
235,000
230,000
225,000
220,000
0
10,000
20,000
30,000
40,000
50,000
60,000
Volume/Lane (vpdpl)
Off Peak Base Schedule
Off Peak Dallas Schedule
Off Peak Houston Schedule
Overnight Schedule
Peak Base Schudule
Peak Dallas Schedule
Peak Houston Schedule

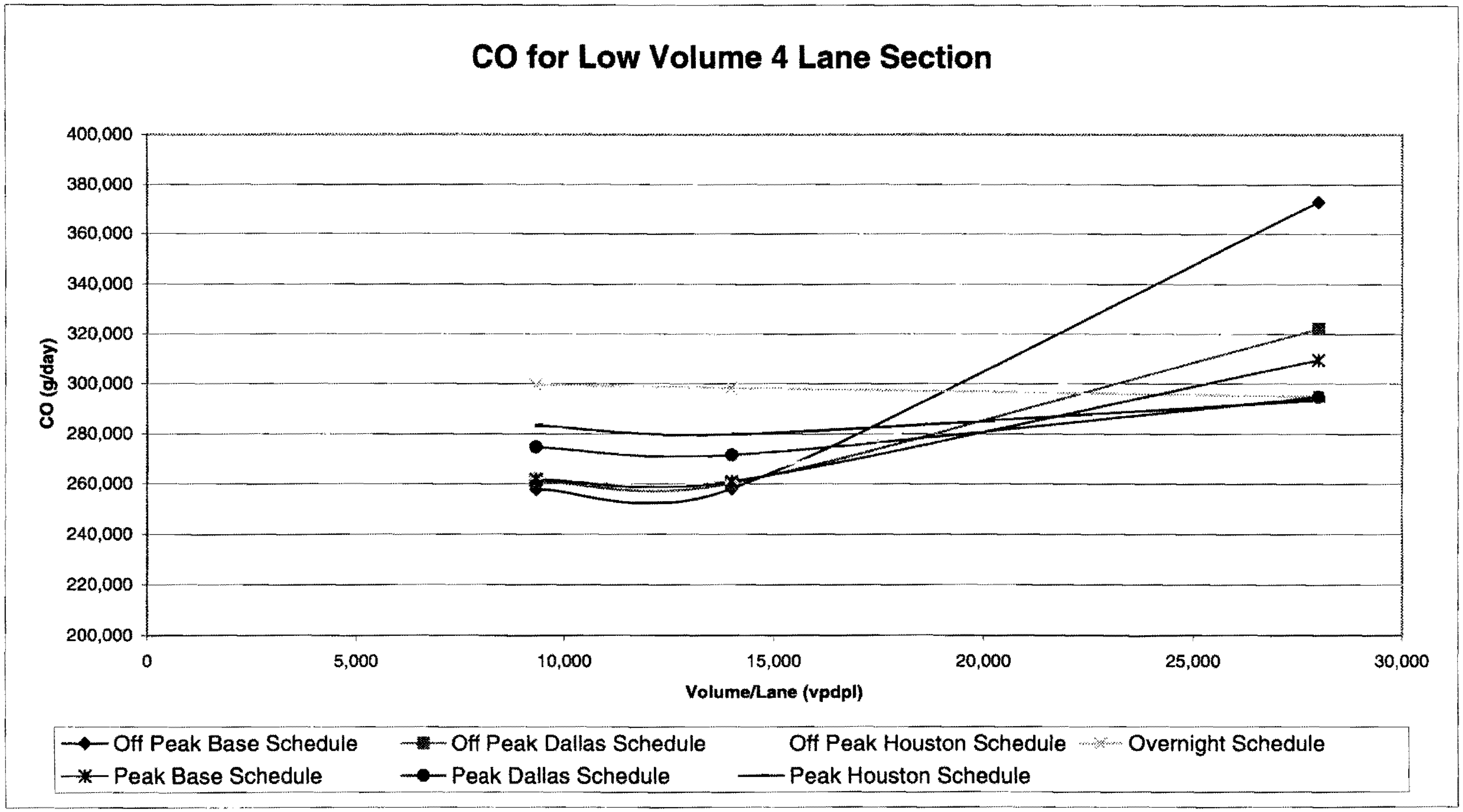

NOx for Medium Volume 4 Lane Section
NOx (g/day)
275,000
270,000
265,000
260,000
255,000
250,000
245,000
240,000
235,000
230,000
225,000
220,000
0
10,000
20,000
30,000
40,000
50,000
60,000
Volume/Lane (vpdpl)
Off Peak Base Schedule
Off Peak Dallas Schedule
Off Peak Houston Schedule
Overnight Schedule
Peak Base Schedule
Peak Dallas Schedule
Peak Houston Schedule

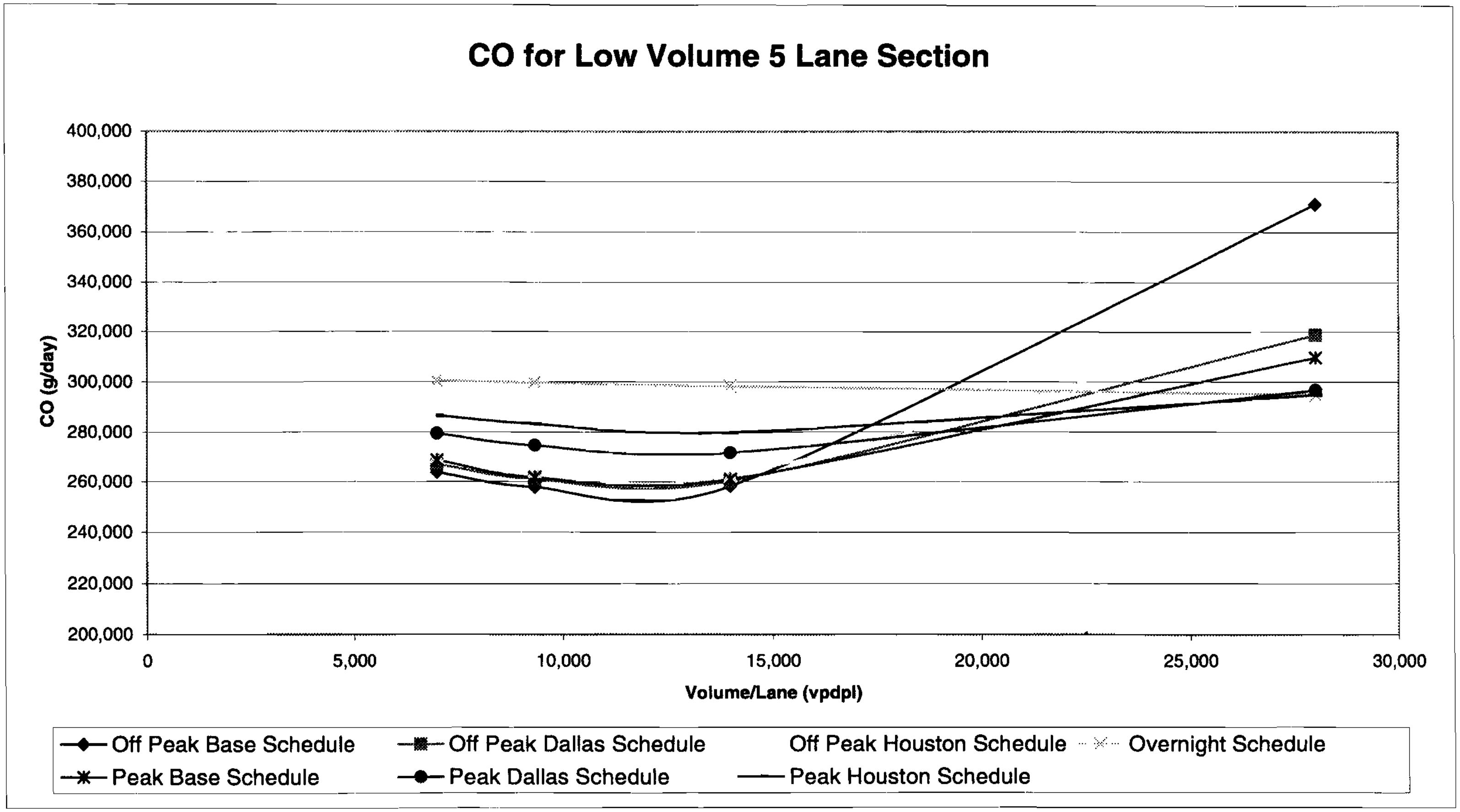


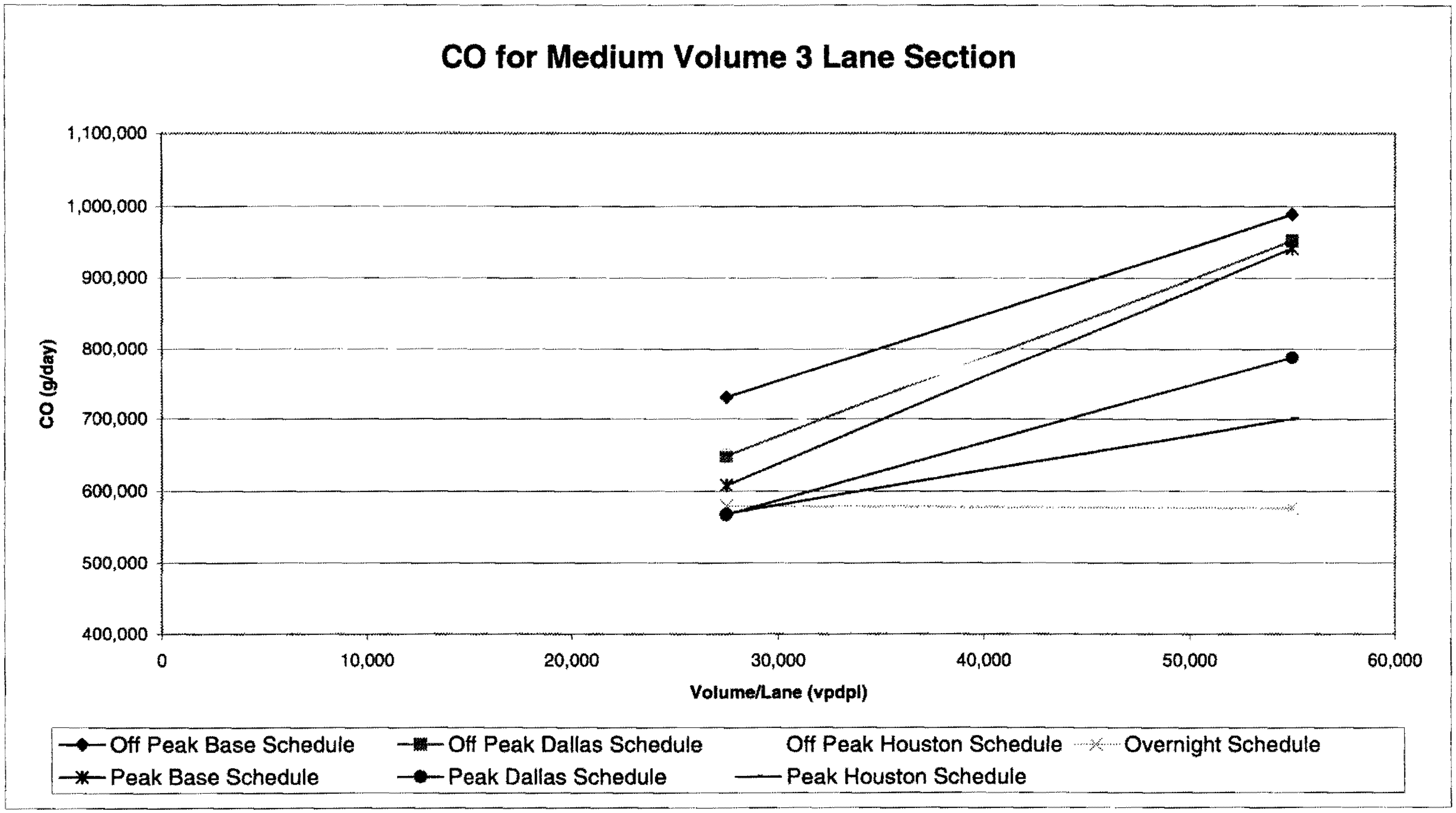
NOx for Medium Volume 5 Lane Section

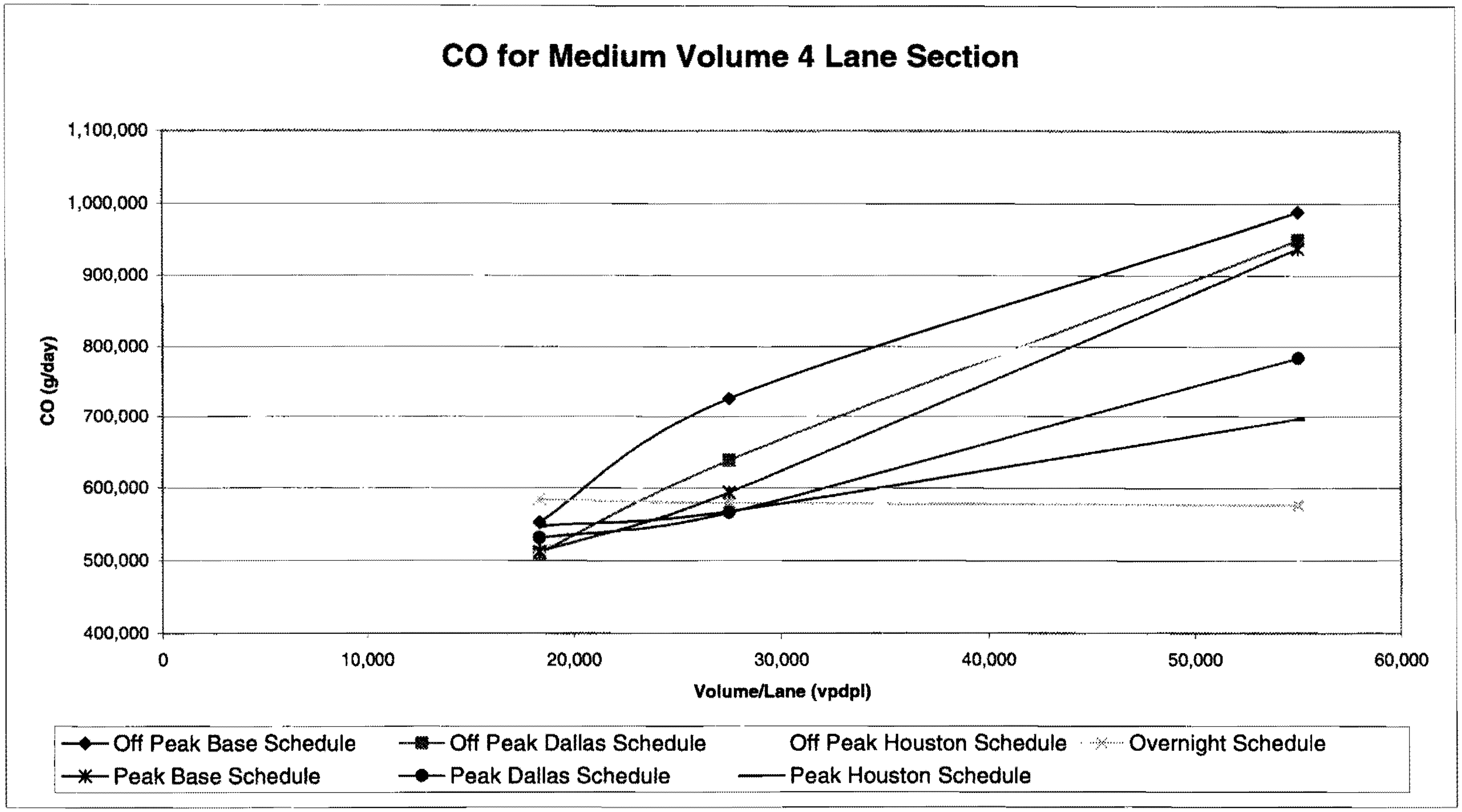

NOx for High Volume 5 Lane Section
450,000
440,000
430,000
420,000
410,000
400,000
390,000
380,000
370,000
360,000
NOx (g/day)
0
10,000
20,000
30,000
40,000
50,000
60,000
70,000
80,000
90,000
100,000
Volume/Lane (vpdpl)
Base Schedule
Dallas Schedule
Houston Schedule
Overnight Schedule
Peak Base Schedule
Peak Dallas Schedule
Peak Houston Schedule

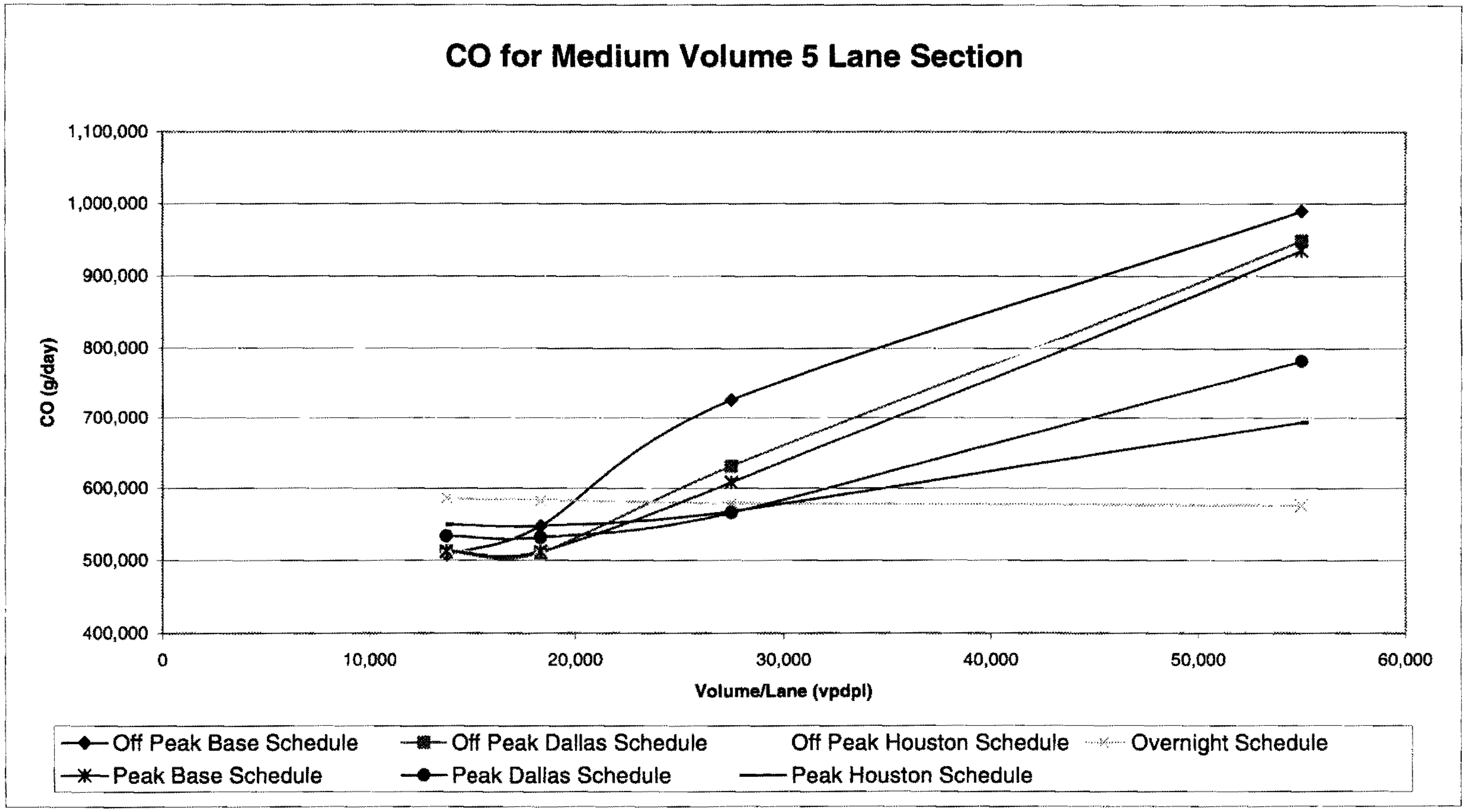

CO for Low Volume 3 Lane Section
400,000
380,000
360,000
340,000
320,000
300,000
280,000
260,000
240,000
220,000
200,000
CO (g/day)
0
5,000
10,000
15,000
20,000
25,000
30,000
Volume/Lane (vpdpl)
Off Peak Base Schedule
Off Peak Dallas Schedule
Off Peak Houston Schedule
Overnight Schedule
Peak Base Schedule
Peak Dallas Schedule
Peak Houston Schedule

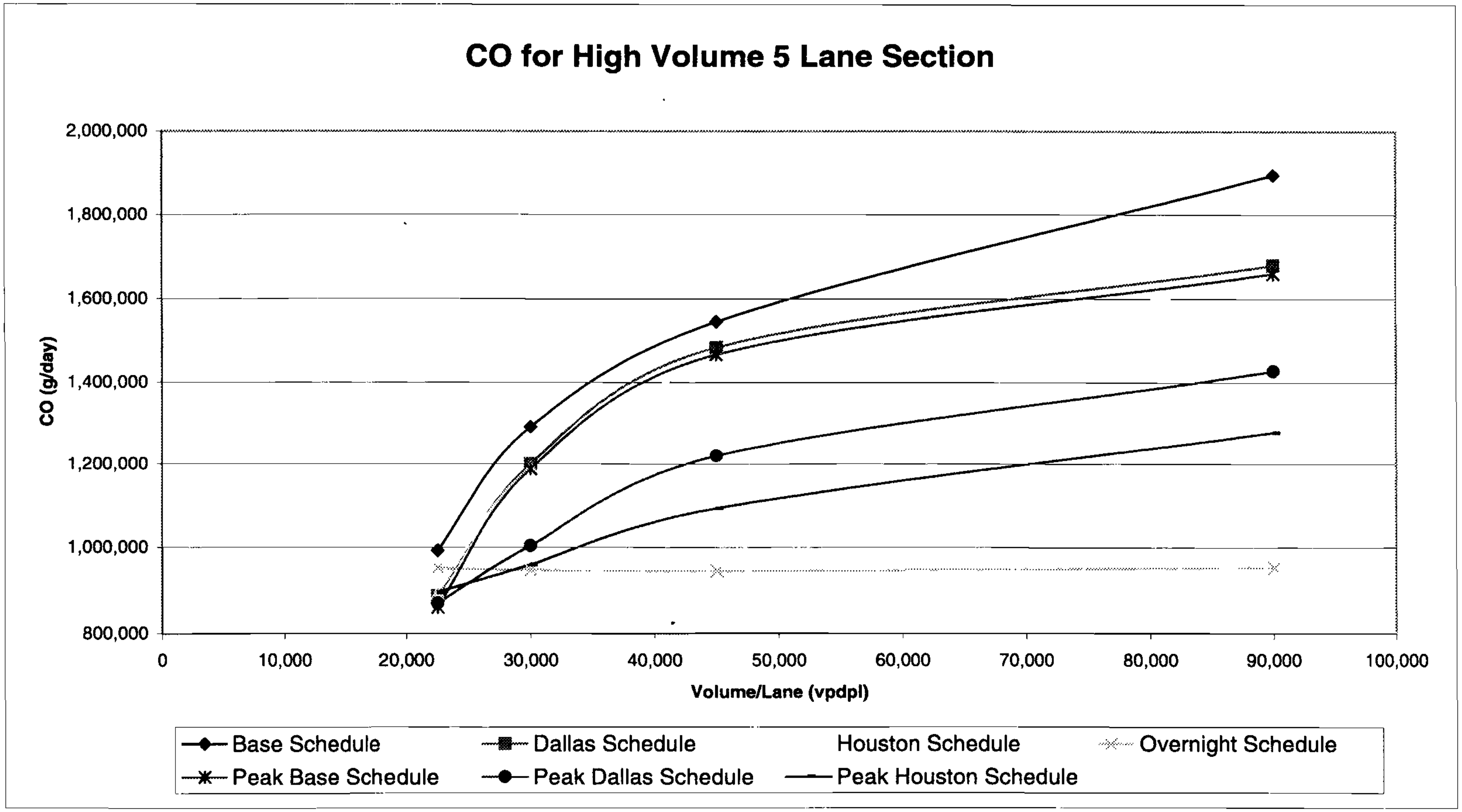

CO for Low Volume 4 Lane Section
400,000
380,000
360,000
340,000
320,000
300,000
280,000
260,000
240,000
220,000
200,000
CO (g/day)
0
5,000
10,000
15,000
20,000
25,000
30,000
Volume/Lane (vpdpl)
Off Peak Base Schedule
Off Peak Dallas Schedule
Off Peak Houston Schedule
Overnight Schedule
Peak Base Schedule
Peak Dallas Schedule
Peak Houston Schedule

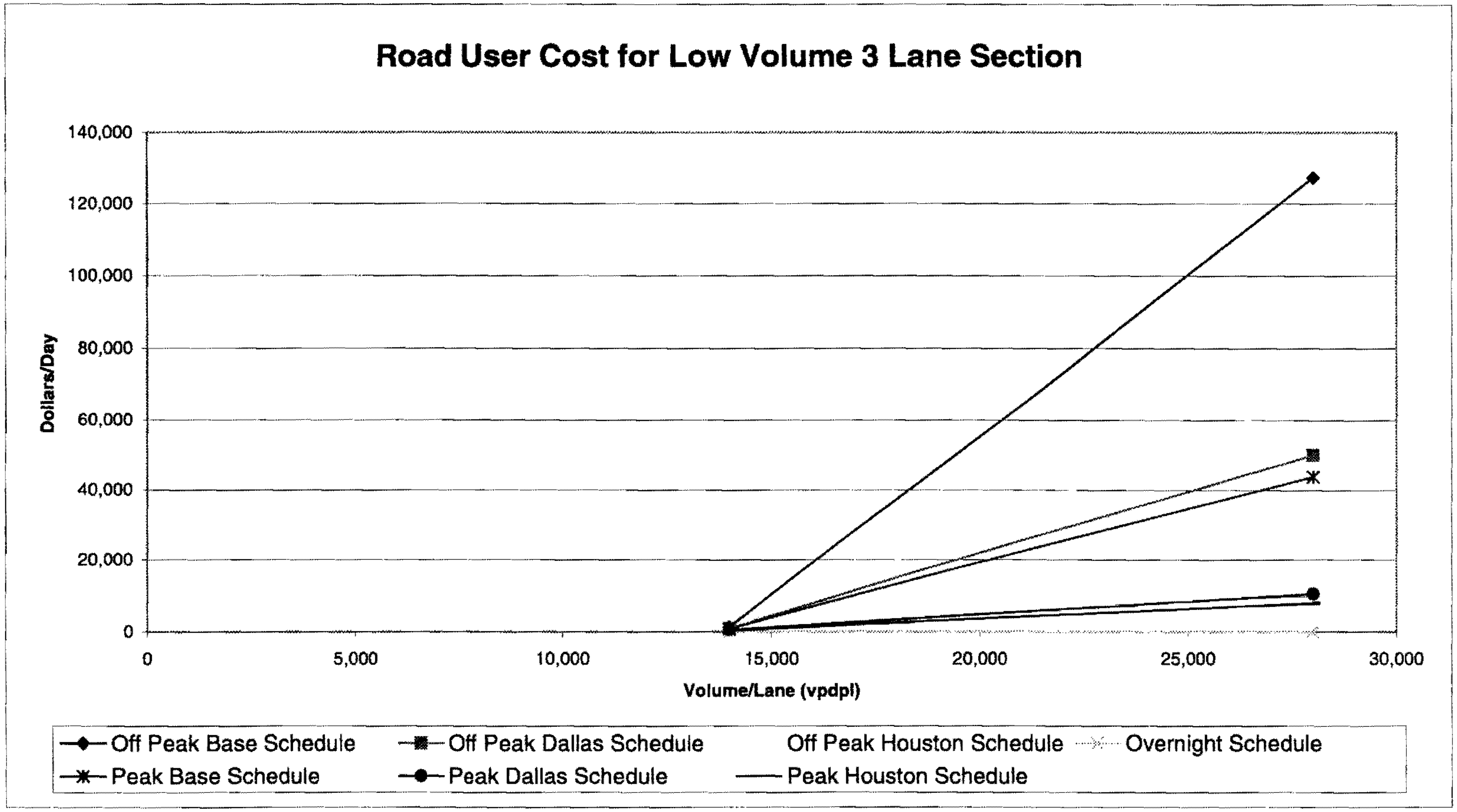

CO for Low Volume 5 Lane Section
CO (g/day)
400,000
380,000
360,000
340,000
320,000
300,000
280,000
260,000
240,000
220,000
200,000
0
5,000
10,000
15,000
20,000
25,000
30,000
Volume/Lane (vpdpl)
Off Peak Base Schedule
Off Peak Dallas Schedule
Off Peak Houston Schedule
Overnight Schedule
Peak Base Schedule
Peak Dallas Schedule
Peak Houston Schedule

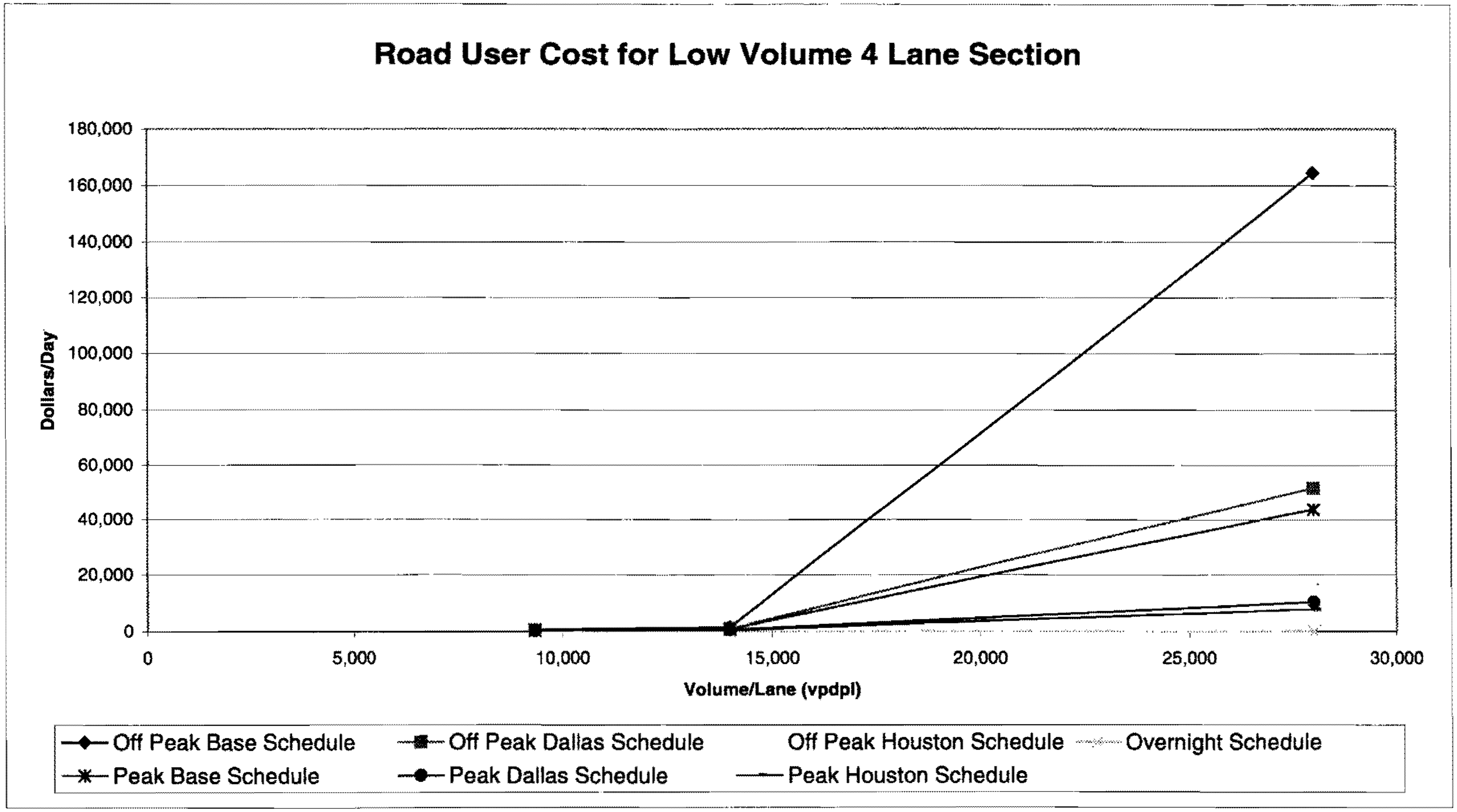

CO for Medium Volume 3 Lane Section
CO (g/day)
1,100,000
1,000,000
900,000
800,000
700,000
600,000
500,000
400,000
0
10,000
20,000
30,000
40,000
50,000
60,000
Volume/Lane (vpdpl)
Off Peak Base Schedule
Off Peak Dallas Schedule
Off Peak Houston Schedule
Overnight Schedule
Peak Base Schedule
Peak Dallas Schedule
Peak Houston Schedule

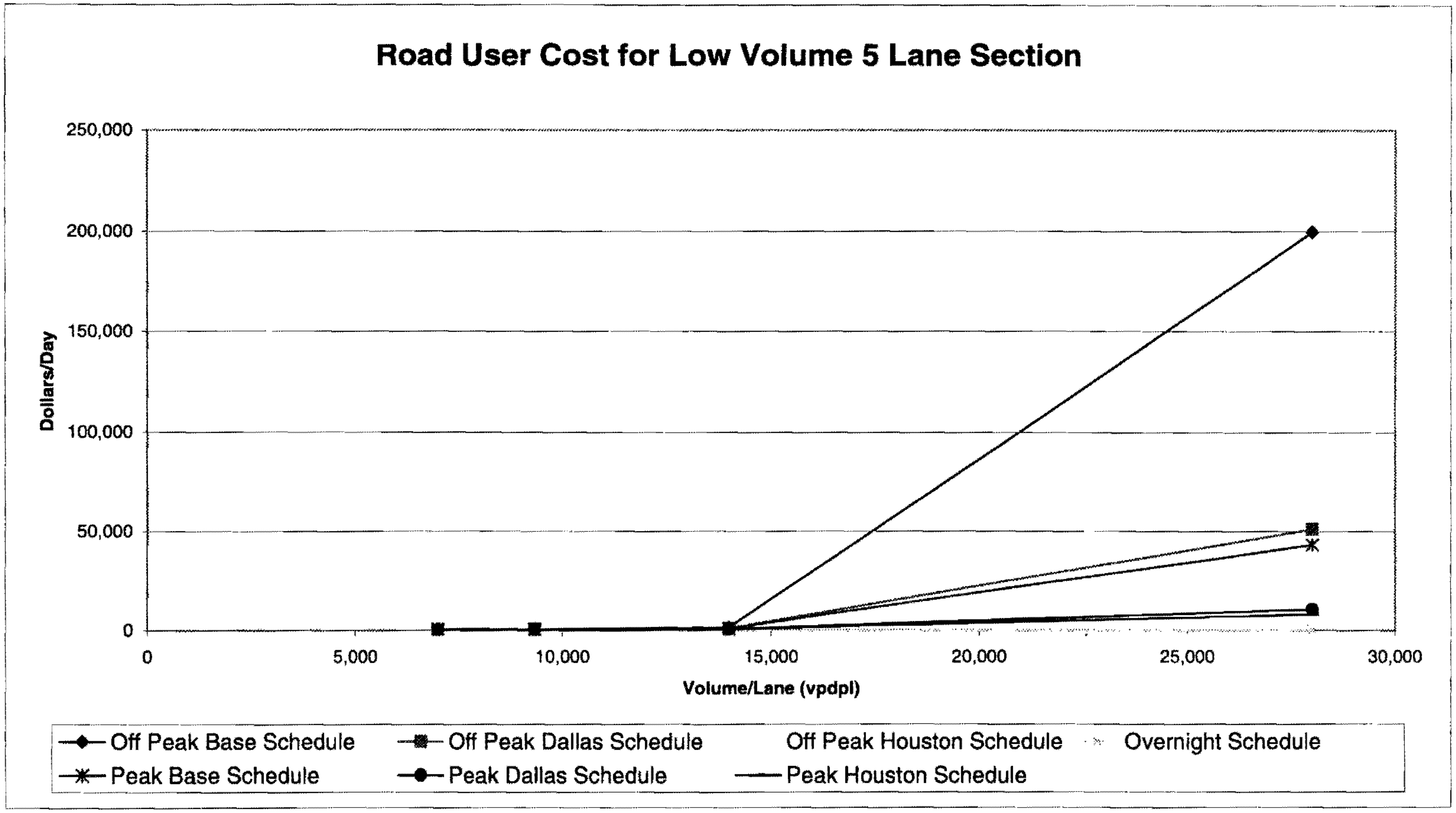

CO for Medium Volume 4 Lane Section
CO (g/day)
1,100,000
1,000,000
900,000
800,000
700,000
600,000
500,000
400,000
0
10,000
20,000
30,000
40,000
50,000
60,000
Volume/Lane (vpdpl)
Off Peak Base Schedule
Off Peak Dallas Schedule
Off Peak Houston Schedule
Overnight Schedule
Peak Base Schedule
Peak Dallas Schedule
Peak Houston Schedule

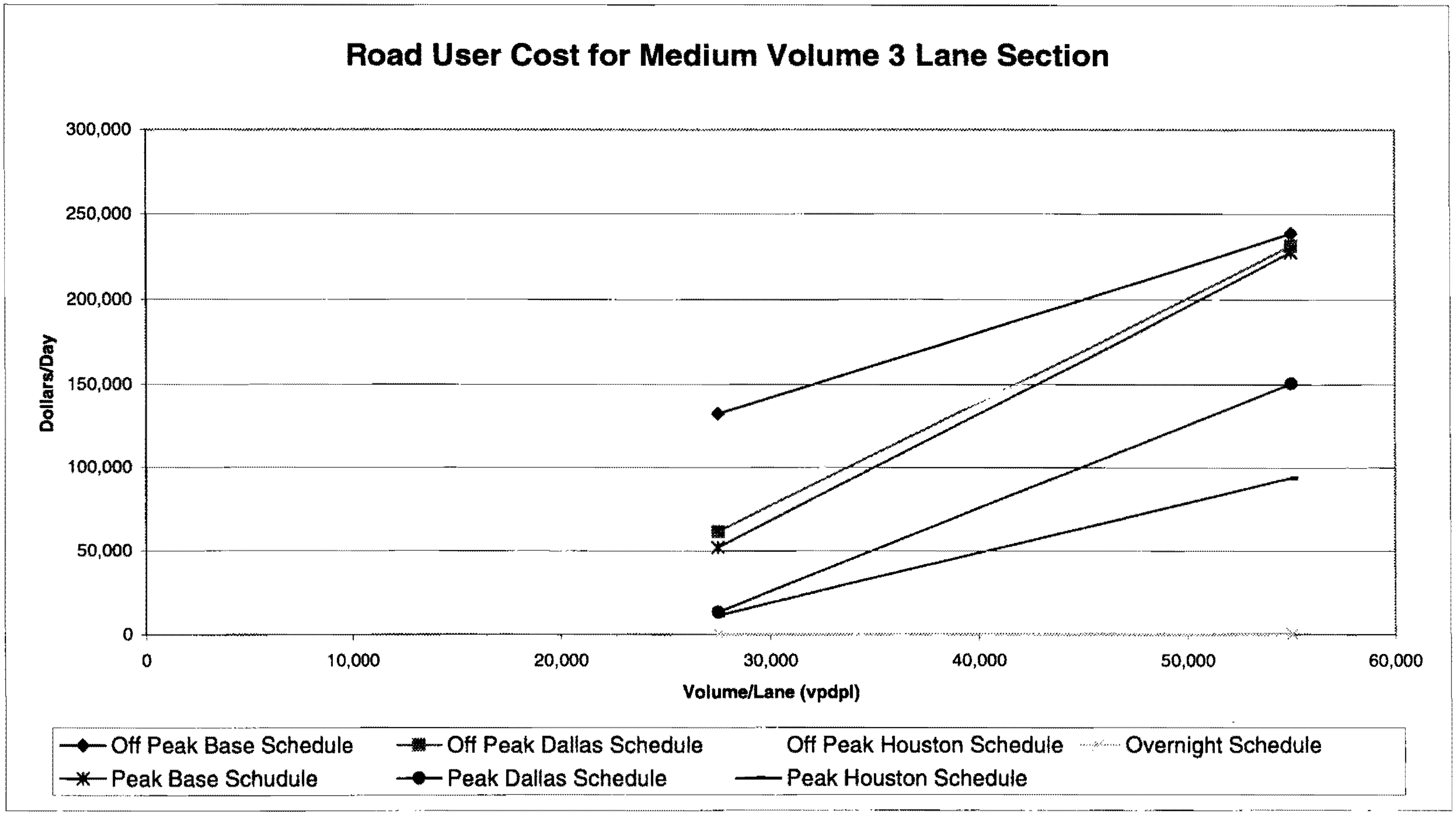

CO for Medium Volume 5 Lane Section
CO (g/day)
1,100,000
1,000,000
900,000
800,000
700,000
600,000
500,000
400,000
0
10,000
20,000
30,000
40,000
50,000
60,000
Volume/Lane (vpdpl)
Off Peak Base Schedule
Off Peak Dallas Schedule
Off Peak Houston Schedule
Overnight Schedule
Peak Base Schedule
Peak Dallas Schedule
Peak Houston Schedule

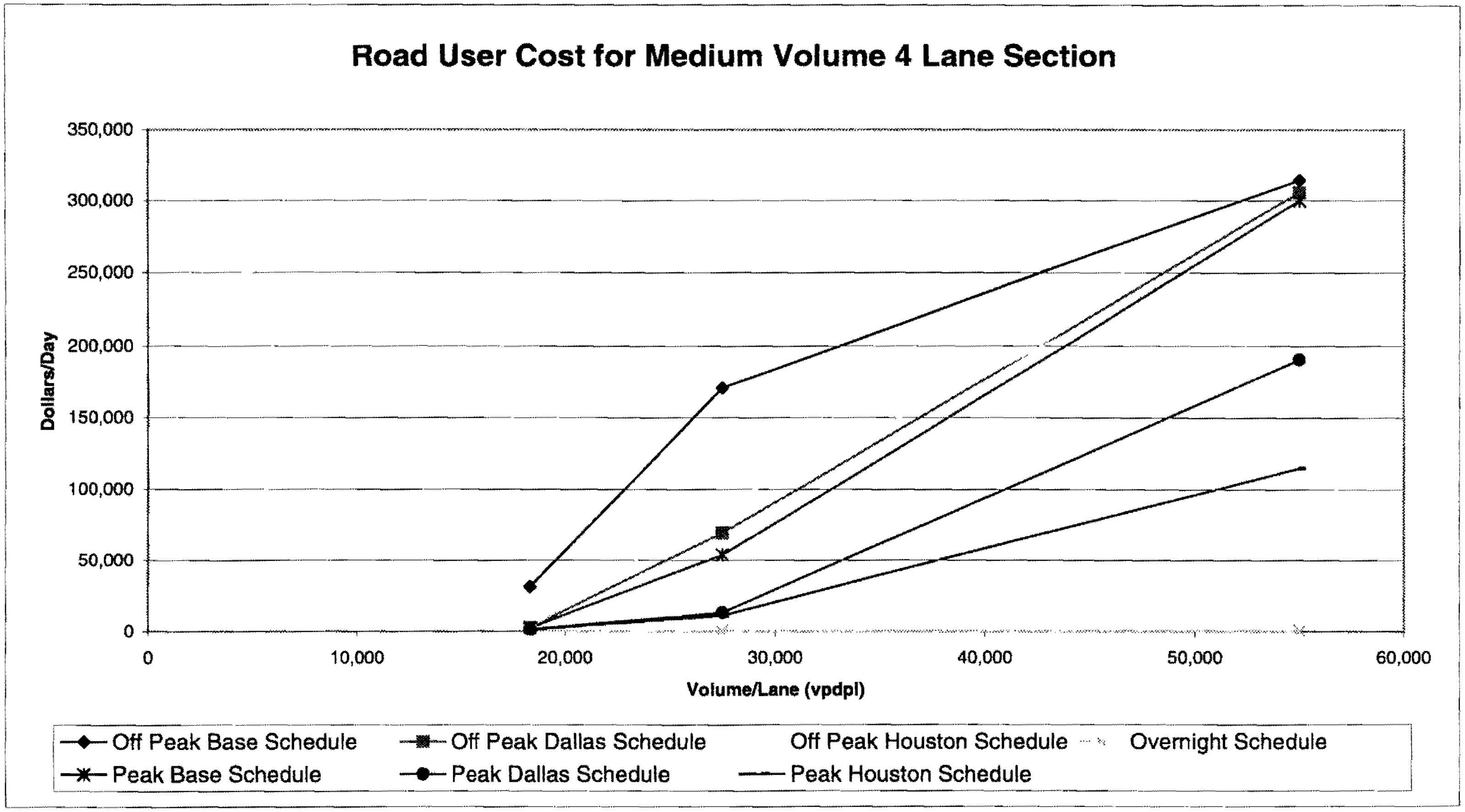

CO for High Volume 5 Lane Section
CO (g/day)
2,000,000
1,800,000
1,600,000
1,400,000
1,200,000
1,000,000
800,000
0
10,000
20,000
30,000
40,000
50,000
60,000
70,000
80,000
90,000
100,000
Volume/Lane (vpdpl)
Base Schedule
Dallas Schedule
Houston Schedule
Overnight Schedule
Peak Base Schedule
Peak Dallas Schedule
Peak Houston Schedule

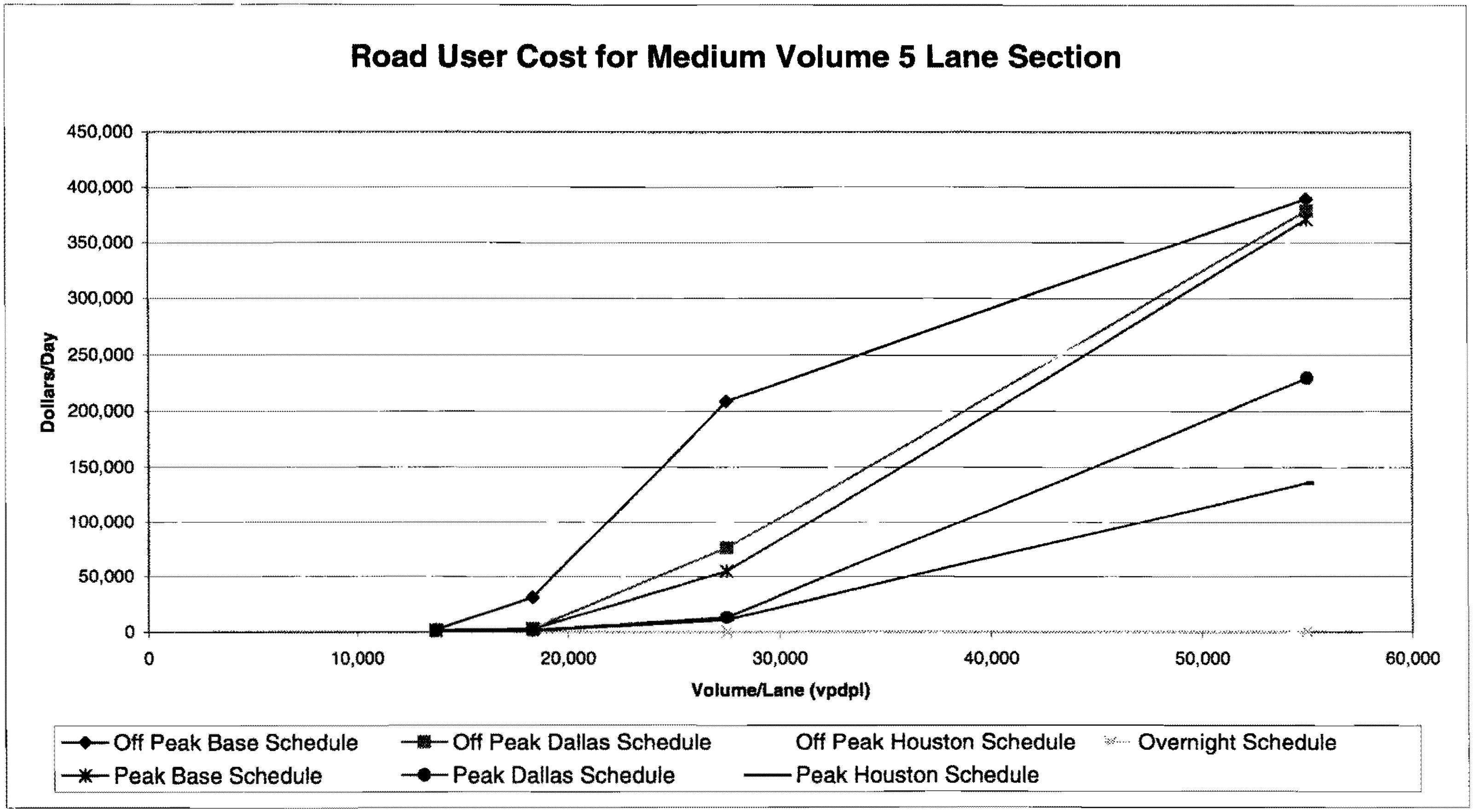

Road User Cost for Low Volume 3 Lane Section
Dollars/Day
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
0
5,000
10,000
15,000
20,000
25,000
30,000
Volume/Lane (vpdpl)
Off Peak Base Schedule
Off Peak Dallas Schedule
Off Peak Houston Schedule
Overnight Schedule
Peak Base Schedule
Peak Dallas Schedule
Peak Houston Schedule

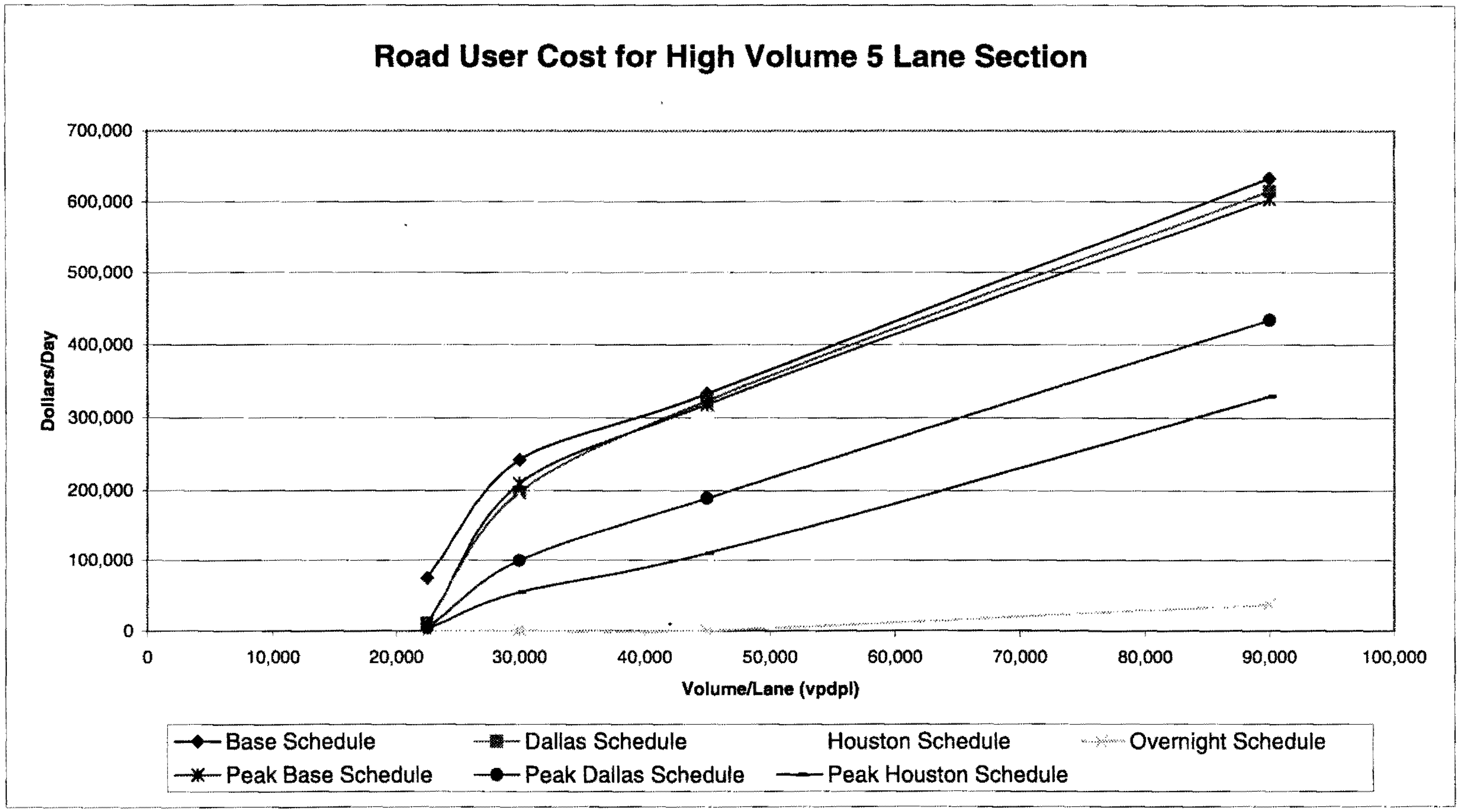

Road User Cost for Low Volume 4 Lane Section
Dollars/Day
180,000
160,000
140,000
120,000
100,000
80,000
60,000
40,000
20,000
0
0
5,000
10,000
15,000
20,000
25,000
30,000
Volume/Lane (vpdpl)
Off Peak Base Schedule
Off Peak Dallas Schedule
Off Peak Houston Schedule
Overnight Schedule
Peak Base Schedule
Peak Dallas Schedule
Peak Houston Schedule


Road User Cost for Low Volume 5 Lane Section
Dollars/Day
250,000
200,000
150,000
100,000
50,000
0
0
5,000
10,000
15,000
20,000
25,000
30,000
Volume/Lane (vpdpl)
Off Peak Base Schedule
Off Peak Dallas Schedule
Off Peak Houston Schedule
Overnight Schedule
Peak Base Schedule
Peak Dallas Schedule
Peak Houston Schedule


Road User Cost for Medium Volume 3 Lane Section
Dollars/Day
300,000
250,000
200,000
150,000
100,000
50,000
0
0
10,000
20,000
30,000
40,000
50,000
60,000
Volume/Lane (vpdpl)
Off Peak Base Schedule
Off Peak Dallas Schedule
Off Peak Houston Schedule
Overnight Schedule
Peak Base Schudule
Peak Dallas Schedule
Peak Houston Schedule


Road User Cost for Medium Volume 4 Lane Section
Dollars/Day
350,000
300,000
250,000
200,000
150,000
100,000
50,000
0
0
10,000
20,000
30,000
40,000
50,000
60,000
Volume/Lane (vpdpl)
Off Peak Base Schedule
Off Peak Dallas Schedule
Off Peak Houston Schedule
Overnight Schedule
Peak Base Schedule
Peak Dallas Schedule
Peak Houston Schedule


Road User Cost for Medium Volume 5 Lane Section
Dollars/Day
450,000
400,000
350,000
300,000
250,000
200,000
150,000
100,000
50,000
0
0
10,000
20,000
30,000
40,000
50,000
60,000
Volume/Lane (vpdpl)
Off Peak Base Schedule
Off Peak Dallas Schedule
Off Peak Houston Schedule
Overnight Schedule
Peak Base Schedule
Peak Dallas Schedule
Peak Houston Schedule


Road User Cost for High Volume 5 Lane Section
Dollars/Day
700,000
600,000
500,000
400,000
300,000
200,000
100,000
0
0
10,000
20,000
30,000
40,000
50,000
60,000
70,000
80,000
90,000
100,000
Volume/Lane (vpdpl)
Base Schedule
Dallas Schedule
Houston Schedule
Overnight Schedule
Peak Base Schedule
Peak Dallas Schedule
Peak Houston Schedule