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16. Abstract

When TxDOT began using an ultra-low sulfur diesel fuel, Texas Low Emission Diesel (TxLED), they commissioned a simultaneous study of the effectiveness of the use of TxLED by both the TxDOT fleet and their contractors, the Associated General Contractors (AGC). Because TxLED is similar to conventional diesel fuel, there were no health or safety issues that had to be addressed in this study. The results from the full load torque curve tests and the operator assessments, together with the properties of TxLED compared to those for 2D on-road diesel fuel, indicate that there should be no performance penalties associated with use of TxLED. It was also found that, as expected, TxLED does not separate into lighter and heavier components over time and does not pose corrosion problems. For all engines tested, TxLED provided a statistically significant benefit in NOx emissions compared to 2D on-road diesel fuel. With the exception of only one engine, the NOx emissions benefits from using TxLED were higher than the benefits claimed in Texas' State Implementation Plan. Additionally, statistically significant benefits in PM emissions were found for three of the six engines tested and small, but statistically significant, benefits in fuel consumption or fuel economy were found for three of the engines. Therefore, the cost-effectiveness of the NOx emissions reductions obtained with TxLED was the primary focus of this study. It is concluded that TxLED is a cost-effective strategy for reducing emissions from the TxDOT and AGC fleets.

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Emulsified Diesel Emission Testing, Performance Evaluation and Operational Assessment; Project Extension to Examine an Ultra-Low Sulfur Diesel Fuel: TxLED

by

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Executive Summary

1. Introduction

The Houston District of the Texas Department of Transportation (TxDOT) and two counties in TxDOT's Beaumont District began using an emulsified diesel fuel in July 2002. TxDOT commissioned a simultaneous study of the efficacy of its use of this fuel, PuriNOx. The prime contractor for this study was the University of Texas (UT). Three research teams at UT took part in this study: the Center for Transportation Research (CTR), the Engines Research Program, and the Materials Research Program. Two subcontractors were used for this project: Southwest Research Institute (SwRI) in San Antonio and Eastern Research Group (ERG) in Austin. From virtually any perspective, this was an ideal research team to pursue this project. Among the findings of this study was the conclusion that the unique operating conditions of highway construction fleets made them unsuitable for use of this fuel. However, a promising alternative was identified. Specifically, an ultra-low sulfur diesel fuel called Texas Low Emissions Diesel (TxLED), which is made by Valero Energy in San Antonio, appeared to be able to provide a larger annual NOx reduction for TxDOT's Houston operations than the emulsified diesel fuel.

TxDOT discontinued use of PuriNOx in July 2003 and subsequently began using TxLED. As was done when they adopted use of PuriNOx, TxDOT commissioned a simultaneous study of the effectiveness of the use of TxLED by both the TxDOT fleet and their contractors, the Associated General Contractors (AGC). Again, the University of Texas, teaming with SwRI and ERG, was awarded the funding for this study, as a contract extension to the emulsified diesel fuel project.

Because TxLED is similar to conventional diesel fuel, there were no obvious health or safety issues that had to be addressed in this extension of the study. Because PuriNOx contained 20% water, it produced a significant torque loss that impacted the performance of the diesel equipment. This was not a concern with TxLED, which in fact produces a torque benefit. Therefore, the cost-effectiveness of the NOx emissions reductions obtained with TxLED was the dominant issue, and the primary focus of this study.

2. Cost-Effectiveness

The major focus in the present project was the cost-effectiveness analysis. This required that we quantify the emissions and fuel consumption of TxLED relative to conventional diesel fuel for the equipment in TxDOT's fleet and for test cycles that reflect the way that TxDOT uses its equipment.

For ease of comparison of the present results for TxLED to our prior study of PuriNOx, equipment that was previously tested on PuriNOx was tested again with TxLED over the same test cycles. However, fewer engines and vehicles were tested for the present study due to limits imposed by the present funding. The test cycles used for the present study were:

- The TxDOT Telescoping Boom Excavator Cycle
- The TxDOT Single-Axle Dump Truck Cycle
- The TxDOT Tandem-Axle Dump Truck Cycle

These test cycles and the methods used by Eastern Research Group to generate them have been discussed previously (Baker et al., 2003; DeFries et al., 2004).

SwRI measured the emissions and fuel economy of an engine from a telescoping boom excavator (on an engine dynamometer using the TxDOT Telescoping Boom Excavator Cycle), two different single-axle dump trucks, and two different tandem-axle dump trucks. The dump trucks were tested on a chassis dynamometer. TxLED and 2D on-road diesel fuel (which TxDOT uses in all of its equipment and has approximately 500 ppm sulfur) were compared for all of these tests.

TxDOT uses small utility engines for riding mowers, herbicide sprayers, and traffic alerting signals (e.g., arrow boards). One of these engines was tested using both TxLED and 2D on-road diesel fuel by the engines research team at UT.

The TxDOT cost-effectiveness calculations—a point estimate for the costs incurred by TxDOT in 2003 using TxLED—revealed that it costs between $92,000/ton and $99,000/ton for the Houston District to reduce NOx emissions by using TxLED, depending on whether the fuel economy benefit is considered. Depending on the type of equipment, the annual cost-effectiveness of using TxLED to reduce NOx varied from $22,719/ton for the excavators to $149,069/ton in the case of the traffic alerting signals (arrow boards) if the fuel economy benefit is considered. Excluding the fuel economy benefit, the costs of reducing NOx emissions using TxLED ranged from $20,408/ton (for the telescoping boom excavators) to $133,907/ton (for the traffic alerting signals).

For AGC's highway construction efforts, the cost-effectiveness analysis for use of TxLED revealed that up to 43 tons per year of NOx reductions were possible, assuming 100% of the AGC fleet adopted TxLED in the 8-county ozone non-attainment area. Total implementation costs can vary, depending upon fuel purchase prices, delivery options, and fuel economy assumptions. Considering these factors, this analysis estimated a cost-effectiveness range of between $10,654 and $14,080 per ton of NOx reduced for the AGC fleet.

3. Conclusions and Recommendations

For all engines tested, TxLED provided a statistically significant benefit in NOx emissions compared to 2D on-road diesel fuel. With the exception of only one engine, the NOx emissions benefits from using TxLED were greater than the benefits claimed in Texas' State Implementation Plan. Additionally, statistically significant benefits in PM emissions were found for three of the six engines tested, and small but statistically significant benefits in fuel consumption or fuel economy were found for three of the engines.

The results from the full load torque curve tests and the operator assessments, together with the properties of TxLED compared to those for 2D on-road diesel fuel, indicate that there should be no performance penalties associated with use of TxLED.

To conclude, TxLED use in the TxDOT fleet proved to be more cost-effective compared to PuriNOx. Yet, at approximately $100,000/ton it remains relatively more expensive than the use of TxLED in the AGC fleets. Having said that, while TxLED use in the AGC fleets is relatively cost-effective compared to TxDOT applications, its use will still incur a net cost to contractors. Since TxLED will be required area-wide starting in the fall of 2005, these costs will not be recoverable through TERP grants. Accordingly, TxDOT should be aware of the potential cost impacts on AGC when developing potential TxLED use requirements or incentives.

1. Introduction

TxDOT discontinued use of an emulsified diesel fuel, PuriNOx, in July 2003 and subsequently began using an ultra-low sulfur diesel fuel made by Valero Energy of San Antonio. This fuel is called Texas Low Emissions Diesel, TxLED. As was done when they adopted use of PuriNOx, TxDOT commissioned a simultaneous study of the effectiveness of the use of TxLED by both the TxDOT fleet and their contractors, the Associated General Contractors (AGC).

The problem statement for the TxLED extension of Project 0-4576 is provided in Section 1.A. The goals and tasks for this project are presented in Section 1.B. The research team is introduced in Section 1.C. This subsection also overviews the general duties and responsibilities of each of the team members. The methodology used to assess the use of TxLED by TxDOT and its contractors is discussed in Section 1.D.

Section 2 is a summary of our findings regarding emissions and fuel consumption. Details regarding the emissions and fuel economy tests are provided in Appendix A. Our analyses of the effects of TxLED on performance are summarized in Section 3. The results of the cost-effectiveness analyses are provided in Section 4. The conclusions and recommendations from this study are presented in Section 5. Details regarding the effects of TxLED on maintenance are provided in Appendix B. Because separation and corrosion were found to be issues for PuriNOx, TxLED was subjected to similar tests, as discussed in Appendix C. The properties of TxLED are compared to those for 2D on-road diesel fuel in Appendix D.

1.A. Problem Statement

The objective of this project was to assess the use of TxLED for TxDOT operations, including the effects on: 1) emissions and fuel consumption relative to conventional 2D on-road diesel fuel, 2) corrosion, 3) productivity, 4) maintenance, and 5) cost-effectiveness. The recommendations resulting from this study are based on all test data, analyses, findings, assessments, and economics generated directly from this extension of Project 0-4576.

1.B. Project Goals and Tasks

The goal of this project was to assess the use of TxLED in TxDOT operations. The primary issues were emissions, fuel consumption, performance, and cost-effectiveness. Because a cost-effectiveness analysis was performed for use of PuriNOx in AGC highway construction operations in the Houston area, a similar analysis was performed for TxLED.

The first task was an examination of the effects of TxLED on emissions and fuel consumption. A subcontract was awarded to Southwest Research Institute to perform standardized tests on two single-axle dump trucks, two tandem-axle dump trucks, and the engine from a telescoping boom excavator. Researchers at UT performed similar tests on a small utility diesel engine. Thermochemical properties of TxLED and of 2D on-road diesel fuel were measured by SwRI.

The second task was to assess the corrosion of TxLED and of 2D on-road diesel fuel.

The third task was to examine the effects of TxLED on productivity using user surveys and by comparing full load torque curves for the two engines that were subjected to engine dyno testing.

The fourth task was to quantify the effects of the use of TxLED on maintenance. This was accomplished via interviews with maintenance personnel, comparisons of maintenance records for the year before TxDOT switched to TxLED and the year immediately after the switch. Additionally, the lubricity of TxLED was measured (as part of Subtask 1.4) for comparison to that of conventional 2D on-road diesel fuel.

The final task was the economic analyses. To allow direct comparison with the results obtained for the emulsified diesel fuel, a cost-effectiveness analysis was performed for the TxDOT Houston District and a similar analysis was performed for AGC's highway construction operations in the Houston area.

1.C. Research Team

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

CTR is the largest purely academic transportation research center in the southwest. The primary CTR personnel on this project were Professor Randy Machemehl (director of CTR) and Jolanda Prozzi (research associate). CTR was responsible for the driver and maintenance personnel surveys, the examination and analyses of TxDOT maintenance records, and the cost-effectiveness analysis for TxDOT's operations in the Houston District.

The UT Engines and Combustion Research Program is one of the top five engines research programs among U.S. universities. The principal investigators on this project were Professor Ron Matthews (Head of the Engines Research Program and Project Supervisor for the present project) and Professor Matt Hall (Associate Head of the Engines Research Program). In addition to directing the overall project, the Engines Research Program was responsible for the selection of equipment for emissions and fuel consumption testing; testing one of the engines; analysis of all emissions and fuel consumption data, including developing a methodology for its use in the cost-effectiveness analysis; and the comparative torque analysis.

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

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

ERG has extensive experience in developing standardized test cycles, developing emissions factors, and generating emissions inventories. The ERG personnel on this project were Sandeep Kishan (Vice President), Dr. Tim DeFries, and Rick Baker. ERG developed the TxDOT-specific and AGC-specific operating cycles that were used for the prior study of emulsified diesel fuel and for the present study of TxLED. They also performed the cost-effectiveness analysis for AGC highway construction operations in the Houston area.

1.D. Methodology

To allow the results from the TxLED study to be most easily compared to those from the PuriNOx project, equipment that was previously tested on PuriNOx was tested again with TxLED over the same test cycles. However, fewer engines and vehicles were tested for the present study due to limits imposed by the present funding. The test cycles used for the present study were:

- The TxDOT Telescoping Boom Excavator Cycle
- The TxDOT Single-Axle Dump Truck Cycle
- The TxDOT Tandem-Axle Dump Truck Cycle

These test cycles and the methods used by Eastern Research Group to generate them are discussed in detail elsewhere (Baker et al., 2003; DeFries et al., 2004). The specific pieces of equipment that were tested by SwRI are listed in Table 1.1. All of these pieces of equipment, with one exception, were previously tested on PuriNOx. The exception is the 1999 Volvo tandem-axle dump truck. For the PuriNOx study, TxDOT Equipment No. 15-5186G was tested. However, this dump truck developed shifting problems and had to be replaced for the TxLED tests. It was replaced by TxDOT Equipment Number 15-5184G, a nominally identical 1999 Volvo tandem-axle dump truck.

Table 1.1. Equipment Tested by SwRI

TxDOT Eqpt. No.	Model Year	Equipment	Engine
Non-road engines			
20-9826G	2001	Gradall XL3100	Cummins ISB 190
Single-Axle Dump Trucks			
15-4772G	1999	GMC C7500	Cat 3126B
5-3946G	1997	International	Int. T444E-HT
Tandem-Axle Dump Trucks			
15-3512H	2000	Volvo	Cummins ISM305V
15-5184G	1999	International	Cat C10

As for the PuriNOx study, a small utility diesel was tested at UT. A 2002 Yanmar 10 hp diesel engine was used to represent the various small utility engines used by TxDOT. TxDOT uses these engines for herbicide sprayers, traffic-alerting signals (e.g., arrowboards), and riding mowers. Two operating conditions were used for the comparisons between fuels. These two operating conditions were used, as in the PuriNOx study, to develop composite cycles for the three applications of these small utility diesel engines, as discussed previously (Baker et al., 2003).

The emissions and fuel economy measurements were used in the cost-effectiveness analyses. As was done for the PuriNOx study, cost-effectiveness was assessed for the Houston District of TxDOT and for AGC highway construction operations in the Houston area.

2. Emissions and Fuel Consumption

In the present tests, discussed in detail in Appendix A, it was found that TxLED always provides benefits in the emissions of the oxides of nitrogen (NOx). Additionally, TxLED always yields a significant benefit in the emissions of hydrocarbons (HCs). For some cases, TxLED yields a small but statistically significant benefit in fuel consumption and/or the emissions of particulate matter (PM). The effects of TxLED on emissions and fuel consumption are summarized in this section of the report.

The brake-specific emissions of NOx, PM, HCs, and CO, found in the present study of telescoping boom excavators and small utility engines, are summarized in Table 2.1. The brake-specific fuel consumption is also shown in this table. For the telescoping boom excavators and small utility engines, the test results for emissions and fuel consumption were measured in g/hp-hr (rate of emissions or fuel consumption per unit power output from the engine). For the telescoping boom excavator, these measurements were made for the typical use patterns for this type of equipment, as discussed in detail by DeFries and coworkers (2004). A 2002 Yanmar 10 hp herbicide sprayer engine was used to represent the various small utility engines used by TxDOT. TxDOT uses these engines for herbicide sprayers, traffic-alerting signals (e.g., arrowboards), and riding mowers. The typical operating conditions for these engines have been discussed previously (Baker et al., 2003).

For the telescoping boom excavator engine, TxLED provided statistically significant benefits in the emissions of NOx (6.4%), PM (17.8%), HCs, and CO. Because diesels have inherently low emissions of HCs and CO, the benefits provided by TxLED in the emissions of these species may not be important. The small benefit of TxLED for fuel consumption was not statistically significant at the 95% confidence level. For the small utility diesel engine, TxLED provided benefits in NOx, CO, and fuel consumption for all three applications of this engine. The benefits were more pronounced for this engine than for any other that was tested. This engine was designed to be manufactured as inexpensively as possible. Therefore, it should not be expected that it would respond to changes in fuel composition similarly to engines that are designed to meet stringent emissions standards.

For the single-axle dump trucks and the tandem-axle dump trucks, the emissions were measured in g/mi and the fuel economy was measured in mpg. Again, these measurements were performed for operating conditions that reflect typical use, as discussed by DeFries and coworkers (2004). Unlike the tests of the emulsified diesel fuel, only hot-start tests were performed for the analysis of TxLED. This was done because the cold-start tests are not weighted strongly and because the budget for the present tests was limited. The results for the dump trucks are summarized in Table 2.2.

The results of the dump truck tests showed that, compared to 2D on-road diesel fuel, TxLED provides a statistically significant benefit in NOx emissions for all cases examined. Additionally, there was a statistically significant benefit in the emissions of hydrocarbons for all cases, and for two of the four dump trucks, statistically significant benefits in both PM emissions and fuel economy were observed.

Table 2.1. Brake Specific Emissions and Fuel Consumption of the Telescoping Boom Excavator and Small Utility Engines

Engine	Fuel	bsNOx (g/hp-hr)	bsPM (mg/hp-hr)	bsHCs (g/hp-hr)	bsCO (g/hp-hr)	bsfc (g/hp-hr)
TxDOT Telescoping Boom Excavator Cycle						
Cummins ISB 190	2D on-road	4.13	84.3	0.10	0.97	175.51
	TxLED	3.86	69.3	0.06	0.85	173.09
% change (TxLED-2D)/2D		-6.4	-17.8	-37.7	-11.9	NSD*
Small Utility Engines (Yanmar)						
sprayer	2D on-road	7.31	611.4	0.14	7.18	271.37
	TxLED	5.45	513.5	0.11	3.00	259.21
% change (TxLED-2D)/2D		-25.5	NSD*	NSD*	-58.2	-4.5
arrow board	2D on-road	7.13	590.8	0.03	2.20	211.86
	TxLED	3.41	456.0	0.01	0.40	188.14
% change (TxLED-2D)/2D		-52.2	NSD*	NSD*	-81.8	-11.2
mower	2D on-road	7.17	595.0	0.05	3.20	223.76
	TxLED	3.82	467.5	0.03	0.92	202.36
% change (TxLED-2D)/2D		-46.8	NSD*	NSD*	-71.2	-9.6

* NSD means not significantly different at the 95% confidence level

Table 2.2. Emissions and Fuel Economy of the Dump Trucks

			NOx	**PM**	**HC**	**CO**	**Fuel Economy**
Year	**Vehicle**	**Engine**	g/mi	g/mi	g/mi	g/mi	mpg
Single-Axle Dump Trucks							
1999	GMC C7500	Cat 3126B					
		2D on-road	19.82	0.161	0.28	2.16	7.11
		TxLED	18.58	0.136	0.21	2.10	7.23
		% change (TxLED-2D)/2D	-6.25	-15.56	-25.87	NSD*	1.69
1997	International	Int. T444E-HT					
		2D on-road	8.64	0.198	0.36	2.55	7.58
		TxLED	8.07	0.197	0.27	3.06	7.66
		% change (TxLED-2D)/2D	-6.64	NSD*	-25.58	***19.87***	NSD*
Tandem-Axle Dump Trucks							
2000	Volvo	Cummins ISM305V					
		2D on-road	13.17	0.230	0.99	1.68	5.43
		TxLED	12.36	0.200	0.87	1.74	5.60
		% change (TxLED-2D)/2D	-6.09	-13.02	-12.77	NSD*	3.07
1999	International	Cat C10					
		2D on-road	11.08	0.227	0.50	3.27	5.34
		TxLED	10.85	0.218	0.38	3.42	5.39
		% change (TxLED-2D)/2D	-2.04	NSD*	-23.59	NSD*	NSD*

* NSD means not significantly different at the 95% confidence level
Percent change in bold italics = undesirable effect of TxLED.

3. Performance

In the initial portion of this study, it was necessary to quantify the effects of the water in the emulsion on performance since the water in PuriNOx does not contain any chemical energy. A similar analysis was done to determine if there is a performance penalty associated with the use of TxLED.

3.A. Torque and Power

The full load torque curves from the Gradall engine tested at SwRI and the utility diesel tested at UT are provided in Figures 3.1 and 3.2. The results are summarized in Table 3.1.

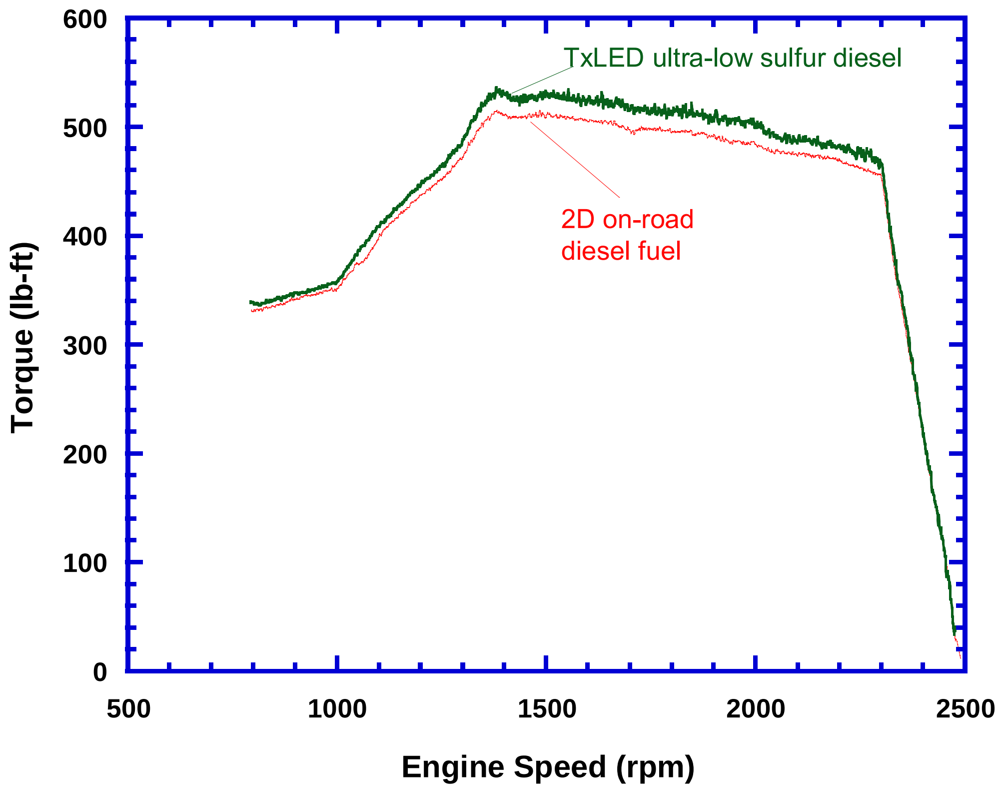

Figure 3.1. Full load torque curves for the Cummins ISB190 engine from theGradall operating on TxLED and on 2D on-road diesel fuel.

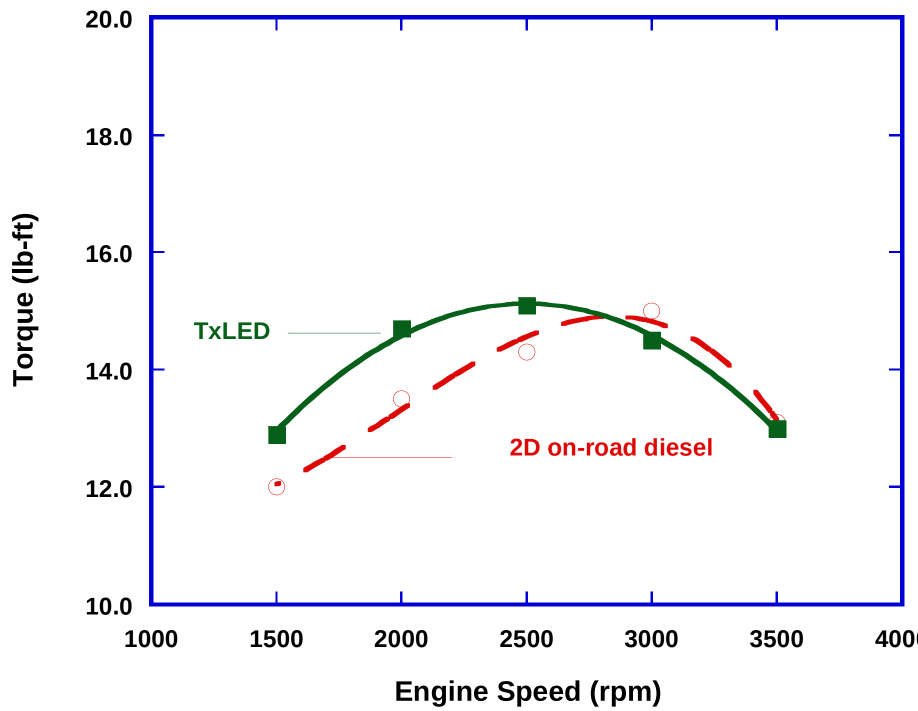

Figure 3.2. Full load torque curves for the single cylinder Yanmar diesel engine operating on TxLED and on 2D on-road diesel fuel

Table 3.1. Full Load Torque Comparison for TxLED Compared to 2D On-Road Diesel Fuel for the Two Engines Tested

	Percent Torque Gain at		Max Torque Gain	
Engine	Peak Torque Speed	Rated Speed	Percent	at RPM
Yanmar	10.2	0.1	10.2	1800
ISB190	4.0	3.2	5.9	1850

As illustrated in Figures 3.1 and 3.2 and quantified in Table 3.1, TxLED provides a small increase in torque for the two engines tested. A benefit is expected because TxLED has a larger Heating Value and density and a lower kinematic viscosity, as detailed in Appendix D.

3.B. Operator Assessments

The objective of this section is to summarize the results of the TxDOT San Antonio district user surveys. TxLED is a low-sulfur diesel fuel and has the potential to impact both the performance and the maintenance frequency of the TxDOT vehicles using TxLED. Sulfur acts as a lubricant in the diesel fuel and removal of a portion of this sulfur reduces the lubricity of the fuel, which has the potential to impact many components of the engine. TxLED users in San Antonio were surveyed to identify any performance issues associated with the use of TxLED-fueled vehicles and in what kinds of vehicle/equipment, if any, the use of TxLED was deemed problematic.

Survey Instrument and Approach

A survey instrument, containing 18 statements about specific performance impacts, was used to test the perceived effects of TxLED in the operation of San Antonio vehicles/equipment. On a scale of 1 to 5, with 1 corresponding to disagreement and 5 corresponding to agreement with the statement/question, the respondents were asked to circle the option that best described how they felt. Respondents were also given the opportunity to voice additional concerns in a "comments" section.

The survey was conducted at four area shops within the San Antonio district: Bexar 410, Northeast San Antonio, Seguin, and New Braunfels. Surveys were conducted between March 11 and March 26, 2004. Center for Transportation Research (CTR) personnel, with extensive experience in heavy equipment operations, administered the surveys.

Detailed information on the survey process and the interview results are provided in Appendix B. This section of the document highlights the salient findings of the San Antonio TxDOT operator surveys.

San Antonio Operator Survey Responses

A total of 54 operators were surveyed in March 2004. The responses were largely neutral, indicative of no perceived performance changes due to the use of TxLED. A few respondents, however, listed specific concerns regarding the use of TxLED in the comments section of the questionnaire. These were:

- increased failure of fuel pumps,
- increased failure of injector pumps,
- increased incidence of fuel leaks,
- may need lubrication additive.

Statistical Analysis

The number of responses to each of the questions in the survey was greater than 30, which allows a normal distribution to be assumed. Hypothesis testing was performed on each of the questions in a two-stage process. A two-sided test was performed initially to test the null hypothesis that the "true" mean of the responses was 3. Restated, the null hypothesis of the two-tailed test was that the operators were neutral towards each of the statements. This would suggest that there was no perceived difference between the performance attributes of the vehicles/equipment with TxLED and conventional diesel fuel. The alternative hypothesis to the two-sided test was simply that the mean was not equal to 3. If the two-sided test revealed that the null hypothesis had to be rejected for any statement, indicating that the operators were not neutral, a second (one-sided) test was performed to determine whether the operators agreed or disagreed with the statement.

The null hypothesis for the one-sided test was again that the "true" mean of the responses was 3. In other words, the operators' responses were neutral. The one-sided test's alternative hypothesis, however, was that the "true" mean was less than 3, meaning that the operators disagreed with the statement/question.

These tests allowed for the calculation of a confidence interval for the population mean for each of the statements. All tests were performed at a 1% significance level, allowing for less than 1% of the variance in the responses to be due to chance alone. For further details regarding the analysis, see Appendix B.

Two-Sided Test Results

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

Table 3.2 Two-Sided Test Results

Statement	Reject Null?	Confidence Interval	
		Lower limit	Upper limit
I noticed a substantial improvement in the performance of my vehicle/equipment.	Yes	2.20	2.91
I had more tasks since switching to TxLED.*	No	2.26	3.05
Even at full throttle, it took me longer than normal to perform the same task when using hydraulics.	No	2.43	3.19
My vehicle/equipment used more fuel than before.	Yes	2.19	2.87
I asked a mechanic to check my vehicle/equipment during the past few weeks	No	2.12	2.99
I was able to do all my usual tasks faster than before.	Yes	2.16	2.90
The engine of the vehicle/equipment was noticeably noisier than before.	No	2.27	3.16
I suffered from more backaches, sore muscles, and headaches than usual.	Yes	1.54	2.21
I changed my driving/operating behavior since switching to TxLED.*	Yes	1.77	2.53
I moved heavier loads since switching to TxLED.*	Yes	1.73	2.53
I experienced some of these symptoms: runny nose, nausea, hair loss, skin rash.	Yes	1.48	2.10
I noticed that my vehicle had less power than before.	No	2.23	3.08
I had a problem starting my vehicle/equipment early in the morning.	Yes	2.71	1.85
My vehicle/equipment was accelerating faster than before.	Yes	1.87	2.69
My vehicle/equipment smelled better than before.	No	2.21	3.05
I noticed more smoke coming from my vehicle/equipment	Yes	1.92	2.68
I had to shift gears more often when doing my work.	Yes	1.96	2.70
My vehicle/equipment was vibrating more than before.	Yes	1.75	2.42

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

As shown in Table 3.2, the null hypothesis was not rejected for six of the 18 statements:

(1) I had more tasks since switching to TxLED;
(2) Even at full throttle, it took me longer than normal to perform the same task when using hydraulics;
(3) I asked a mechanic to check my vehicle/equipment during the past few weeks;
(4) The engine of the vehicle/equipment was noticeably noisier than before;
(5) I noticed that my vehicle had less power than before;
(6) My vehicle/equipment smelled better than before.

For these six statements/attributes, the San Antonio TxLED users did not perceive any difference between TxLED and standard diesel fuel.

The null hypothesis was rejected for the remaining 18 statements, which can be interpreted as the TxLED users perceiving a difference in performance between standard diesel fuel and TxLED. It is also apparent from Table 3.2 that the confidence intervals for the rejected null hypotheses are less than three, which implies disagreement with the respective statements. A one-sided test was performed on the remaining 12 statements for which the null hypothesis was rejected to determine if indeed the San Antonio operators disagreed with the respective statements and to ascertain whether this disagreement was positive or negative with regards to TxLED.

One-Sided Test Results

The remaining 10 statements (excluding the working conditions statements) were divided into two groups, “negative statements” and “positive statements.” Tables 3.3 and 3.4 summarize the results of the one-sided test, reporting whether the null hypothesis (mean = 3) was rejected, and the confidence interval for the population mean at a 1% significance level.

Table 3.3 One-Sided Test Results: Negative TxLED Statements

Statement	Reject Null?	Confidence Interval
My vehicle/equipment used more fuel than before.	Yes	≤ 2.83
I suffered from more backaches, sore muscles, and headaches than usual.	Yes	≤ 2.18
I experienced some of these symptoms: runny nose, nausea, hair loss, skin rash.	Yes	≤ 2.07
I had a problem starting my vehicle/equipment early in the morning.	Yes	≤ 2.67
I noticed more smoke coming from my vehicle/equipment	Yes	≤ 2.64
I had to shift gears more often when doing my work.	Yes	≤ 2.67
My vehicle/equipment was vibrating more than before.	Yes	≤ 2.39

Note: If the null hypothesis is rejected, then the “true” mean response is less than 3, indicating the respondent disagreed with the statement.

From Table 3.3, it is evident that there are no significant concerns regarding the use of TxLED. For each negative statement, the null hypothesis (mean = 3) was rejected, therefore indicating that the “true” mean is less than three. This means that the respondents disagreed with these negative statements. The results do not necessarily indicate a very strong positive experience associated with the use of TxLED, as the 99% confidence levels are relatively close to the neutral value of three, with the exception of the health statements.

Table 3.4 summarizes the results of the one-sided test for the positive TxLED statements. In all three of these statements, the null hypothesis (mean = 3) was rejected, indicating the respondents disagreed with the statement. The 99% confidence levels are, however, close to the neutral value of three, indicating that while overall the operators disagreed with these positive statements regarding the use of TxLED, in general, their responses are relatively neutral.

Table 3.4 One-Sided Test Results: Positive TxLED Statements

Statement	Reject Null?	Confidence Interval
I noticed a substantial improvement in the performance of my vehicle/equipment.	Yes	2.87
I was able to do all my usual tasks faster than before.	Yes	2.86
My vehicle/equipment was accelerating faster than before.	Yes	2.65

Note: If the null hypothesis is rejected, then the “true” mean response is less than 3, indicating that the respondent disagreed with the statement.

3.C. Conclusions Regarding Performance

From the operator survey, it is evident that the operators did not perceive any gains in performance since switching to TxLED, nor did they perceive any detriments to performance. Several maintenance concerns were expressed in the comments section of the questionnaire, including: increased fuel pump failure; increased fuel injector pump failure, increased fuel leaks, and low lubricity. These maintenance issues are explored in detail in Appendix C. The results from the full load torque curve tests and the operator assessments, together with the properties of TxLED, compared to those for 2D on-road diesel fuel thus indicate that there should be no performance penalties associated with the use of TxLED.

4. Cost-Effectiveness Analyses

The study quantified the costs of reducing emissions attributable to the adoption of TxLED by the TxDOT Houston District and by AGC members. For the TxDOT case the analysis was undertaken for the District and for the following specific pieces of equipment: telescoping boom excavators, single-axle dump trucks, herbicide sprayers, and arrowboards. It was assumed that, on average, the Houston non-road equipment has the same emissions reductions and incurred costs as the average of those tested, and a similar assumption was made for the on-road vehicles. This is a simplistic assumption, which introduces some margin of error into the cost-effectiveness calculation. In practice, the quantity of emissions, for a given pollutant, from a vehicle/equipment depends on (1) the type of fuel consumed, (2) age and condition of the equipment, (3) model year, (4) weight, (5) emissions control technologies, and (6) any tampering with emissions control technologies.

For the TxDOT case, all benefits and costs associated with the use of TxLED were estimated relative to federal 2D on-road diesel. The study draws extensively on operational (for fiscal year 2001) and cost information (for fiscal year 2003) captured by TxDOT for the six counties in the TxDOT Houston District. The calculated cost-effectiveness of using TxLED in the TxDOT fleet provides a point estimate for the costs of the achieved emissions reductions.

In addition, all benefits and costs associated with the use of TxLED by AGC members were estimated. As TxDOT contractors, AGC members operate a large number of engines in a variety of applications. Similarly to the TxDOT case, the costs and emissions reductions were estimated for the 2001 AGC fleet. The TxDOT and AGC analyses are discussed separately in this chapter of the report.

4.A. Texas Department of Transportation

This section summarizes the costs associated with the use of TxLED, incurred by TxDOT, used in the cost-effectiveness analysis, including:

- the higher cost of TxLED, and
- increased maintenance.

In addition, since some equipment showed a fuel economy benefit, a sensitivity analysis was undertaken to demonstrate the cost-effectiveness under two scenarios: no fuel economy benefit and a 2% fuel economy benefit.

Fuel Cost Penalty

The increase in direct fuel costs due to the use of TxLED, which resulted in a higher fuel price, was estimated. The average prices for federal 2D on-road diesel (2003) and TxLED were estimated based on information from TxDOT's fuel records. The price differential between TxLED and 2D on-road diesel used in this analysis amounted to approximately $0.44/gallon for on-road vehicles and off-road equipment. TxDOT uses on-road diesel in all of its equipment, but does not pay the state taxes when used in off-road equipment. This increase in the fuel price was applied to the diesel fuel consumption for 2001. This resulted in additional costs to TxDOT of $111,296/year, as shown in Table 3.5.

Table 4.1 Fuel Cost Penalty

Fuel Economy Benefit	Houston Equipment (Total)	Excavator	Single-Axle Dump Truck	Tandem-Axle Dump Truck	Herbicide Sprayer	Arrow Board	Mower
On-road diesel (gallons)—2001	213,377		29,314	40,504	12,601		
Off-road diesel (gallons)—2001	37,685	19,478				359	601
#2 diesel price/gallon (2003)	1.16	1.16	1.16	1.16	1.16	1.16	1.16
#2 off-road diesel price/gallon, including tax rebate (2003)	0.96	0.96	0.96	0.96	0.96	0.96	0.96
TxLED price/gallon (2003/2004)	1.60	1.60	1.60	1.60	1.60	1.60	1.60
Off-road TxLED price/gallon, including tax rebate	1.40	1.40	1.40	1.40	1.40	1.40	1.40
Total ($)	111,296	8,635	12,995	17,955	5,586	159	266

Note: "Arrow board" refers to traffic alerting signals

Maintenance Penalty

TxDOT maintenance personnel did not notice significant increases in maintenance expenditures since switching to TxLED relative to federal 2D on-road diesel. When interviewed, maintenance personnel were also reluctant to attribute the slight increase in fuel leaks to the use of TxLED. An analysis of the TxDOT maintenance records in the Dallas, Fort Worth, San Antonio, and Corpus Christi districts, however, revealed a statistically significant increase in the number of fuel leaks that were experienced in the year in which TxLED was used compared to the previous baseline year in which conventional diesel was used (see Appendix C). Although significant, the practical importance is debatable since fuel leaks, as a percentage of the fleet, only rose from about 1% of the fleet to 3% of the fleet.

In addition, maintenance costs increased due to the need to replace fuel injectors, transfer pumps, and injector pumps. It was therefore conservatively estimated that the maintenance penalty associated with the use of TxLED in the Houston fleet will result in the following annual maintenance expenditures:

- the repair of 3 injector pumps,
- the replacement of 3 transfer pumps, and
- the replacement of 1 injector.

Table 4.2 summarizes the estimated maintenance penalty associated with the use of TxLED.

Table 4.2 Maintenance Cost Penalty

Maintenance	Houston Equipment (Total)
Number of fuel injectors	1
Number of injector pumps	3
Number of transfer pumps	3
Average cost/injector (2003)	472
Average cost/injector pump (2003)	42
Average cost/transfer pump (2003)	184.50
Labor cost: injector replacement (2003)	496
Labor cost: injector pump (2003)	240
Labor cost: transfer pump (2003)	185
Total	2,921

As stated earlier, a sensitivity analysis was undertaken to demonstrate the cost-effectiveness under two scenarios: no fuel economy benefit and a 2% fuel economy benefit. The 2% fuel economy benefit applied to the diesel gallons consumed in 2001, amounted to a cost savings to TxDOT of $7,900/ year (see Table 4.3).

Table 4.3 Fuel Economy Benefit (2%)

Fuel Economy Benefit	Houston Equipment (Total)	Excavator	Single-Axle Dump Truck	Tandem-Axle Dump Truck	Herbicide Sprayer	Arrow Board	Mower
Fewer on-road TxLED gallons	4,268		586	810	252		
Fewer off-road TxLED gallons	754	390				7	12
TxLED price/gallon (2003)	1.60	1.60	1.60	1.60	1.60	1.60	1.60
Off-road TxLED price/gallon, including tax rebate (2003)	1.40	1.40	1.40	1.40	1.40	1.40	1.40
Total ($)	7,900	547	940	1,299	404	10	17

Note: “Arrow board” refers to traffic alerting signals

Table 4.4 summarizes the estimated increase in the costs associated with the use of TxLED, relative to conventional diesel in the Houston District. As can be seen, the estimated annual costs incurred by TxDOT, associated with the use of TxLED, are $106,317 or $114,217, depending on whether the fuel economy benefit is considered.

Table 4.4 Annual TxLED Cost Penalty

Cost Category	Houston Equipment (Total)
Fuel price penalty	111,296
Maintenance penalty	2,921
Fuel economy benefit	7,900
Total, excluding fuel economy benefit ($)	114,217
Total, including fuel economy benefit ($)	106,317

State and local agencies use cost-effectiveness as one criterion when deciding whether to implement a particular emissions control program. Table 4.5 summarizes the calculated cost-effectiveness of using TxLED in TxDOT's Houston fleet.

Table 4.5 Cost-Effectiveness of TxLED for Reducing NOx Emissions (TxDOT, Houston)

Cost Category	Houston Equipment (Total)	Excavator	Single- Axle Dump Truck	Tandem-Axle Dump Truck	Herbicide Sprayer	Arrow Board	Mower
NOx benefit (tons/year)	1.157	0.356	0.220	(0.037)	0.054	0.001	(0.001)
Total costs, including fuel economy benefit ($)	106,317	8,088	12,055	16,657	5,182	149	250
Total costs, excluding fuel economy benefit ($)	114,217	7,265	10,934	15,108	4,700	134	224
Cost-effectiveness, including fuel economy benefit ($/ton)	91,890	22,719	54,795		95,962	149,069	
Cost-effectiveness, excluding fuel economy benefit ($/ton)	98,718	20,408	49,701		87,040	133,907	

From Table 4.5, it is evident that the cost-effectiveness of reducing NOx emissions through the use of TxLED ranges between $92,000/ton and $99,000/ton for the Houston District. Depending on the type of equipment, the annual cost-effectiveness of using TxLED to reduce NOx varied from $22,719/ton for the excavators, to $149,069/ton in the case of the traffic alerting signals (arrow boards), if the fuel economy benefit is considered. Excluding the fuel economy benefit, the costs of reducing NOx emissions using TxLED ranged from $20,408/ton (for the telescoping boom excavators) to $133,907/ton (for the traffic alerting signals).

4.B. Cost-Effectiveness for AGC

This analysis also evaluated the potential emissions reductions and costs associated with the use of TxLED in engines operated by AGC members under TxDOT contracts.

Data Sources

As TxDOT contractors, AGC members operate a large number of engines in a variety of applications. In order to determine the potential benefits of TxLED use in this fleet, it was necessary to characterize the total population of diesel engines operated by AGC in their capacity as TxDOT contractors. This analysis relied heavily on a previous survey of AGC members performed for the Houston-Galveston Area Council (HGAC) in 2000.[1] The HGAC study estimated the total number of off-road diesel construction engines greater than 25 hp operating in the eight-county ozone non-attainment area.[2] The study characterized these engines by equipment type (e.g., wheeled loaders and excavators) as well as annual activity level. Estimates of diesel fuel consumption were also provided. For this analysis, only the results for the "Heavy-Highway" sector were included, corresponding to work performed under TxDOT federal and state highway letting funds.

The HGAC study found that, in 1999, AGC members in the heavy-highway sector owned and operated 988 pieces of off-road diesel construction equipment greater than 25 hp, consuming 2,038,482 gallons of off-road diesel per year.[3] The general equipment categories and their populations are summarized in Table 4.6. The current study assumed the same populations and diesel fuel consumption levels for the 2002 analysis year.

Table 4.6 Equipment Types, Population and Activity Estimates for AGC Contractors Operating in the Eight-County Area (1999)

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

[1] "Development of a Revised Emissions Inventory for Construction Equipment in the Houston-Galveston Ozone Non-Attainment Area," prepared for the Houston-Galveston Area Council, Eastern Research Group and Starcrest Consulting Group, April 20, 2000.
[2] Area includes Brazoria, Chambers, Fort Bend, Galveston, Harris, Liberty, Montgomery, and Waller counties.
[3] Although rental equipment is not included in this evaluation, AGC representatives have indicated that the fraction of rental equipment used by AGC highway contractors is quite small.

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

Estimating Baseline Emissions

The TxDOT engine representing heavy off-road applications, tested at SwRI over the excavator cycle, was certified only to on-road emission standards. Because on-road NOx standards are significantly cleaner than off-road standards for recent model year engines, and because engines certified to on-road standards are not typically used in off-road applications by AGC[4], it was not appropriate to use the SwRI test data to estimate baseline emissions from the AGC fleet. Therefore EPA's NONROAD2002 emissions model was used to estimate baseline emissions for this fleet. NONROAD's default activity and population files were modified to reflect the characteristics of the eight-county AGC fleet.

Selected load factors in the NONROAD model were also modified to reflect the wheeled loader and excavator cycles developed for this analysis. Comparing actual power output to maximum power at the same rpm levels, at each second of the cycle, the average load factor of the excavator and wheeled loader cycles were calculated at 0.35 and 0.47, respectively. However, as seen in Table 4.6 above, AGC operates a number of different equipment types, each likely to have its own typical operation cycle and load factor. Therefore, it may not be appropriate to apply the load factors for the excavator and/or wheeled loader cycles to all of the AGC equipment types.

According to NONROAD model documentation, off-road diesel equipment can be grouped into three representative "load factor assignments," corresponding to low and high transient load, and steady-state load cycles.[5] EPA's approach assigned excavators and wheeled loaders to the high load factor grouping. Therefore this analysis modified the load factors for all of the remaining high load factor equipment categories, leaving the load factors for the low transient and steady-state groupings unmodified.

The EPA has developed its own representative operation cycles for seven non-road diesel engine categories. Three of these categories are included in the high load factor assignment for diesel construction equipment—excavators, wheeled loaders, and crawler dozers. Following the EPA's methodology, we averaged the load factors for the excavator and wheeled loader cycles developed for this project, along with EPA's load factor for crawler dozers (average load factor of 0.58) to determine representative load factors for the high load factor grouping as a whole.[6,7] Averaging load factors over these three cycles results in a 0.47 value for the entire high transient

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[4] Bob Lanham, personal communication, January 23, 2003.

[5] "Median Life, Annual Activity, and Load Factor Values for Nonroad Engine Emissions Modeling," EPA Report No NR-005b, May 30, 2002, page 14.

[6] Ibid.

[7] Note that EPA's wheeled loader cycle agrees quite well with the wheeled loader cycle developed under this project in terms of average load (0.48 compared to 0.47, respectively). However, the corresponding excavator cycles did not correspond well (0.53 for EPA's cycle vs. 0.35). Given that EPA's excavator cycle exhibited anomalous readings above 100% load at several points in the cycle, the 0.53 factor was deemed suspect and the 0.35 factor was used for this analysis.

group. The 0.47 value was subsequently input in the NONROAD activity file for these categories (listed in Table 4.7).

Table 4.7 Equipment Types in High Transient Load Factor Assignment Grouping

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

Once the population and activity files were modified to reflect the AGC equipment population and use characteristics, NONROAD was run to determine baseline tons-per-year estimates for NOx in 2002 for the eight-county area. NONROAD defaults were used for temperature and diesel sulfur levels, as these factors do not influence exhaust NOx estimates for diesel engines in the model. Given this approach, **718 tons per year** of NOx are estimated for the AGC fleet using federal off-road number 2D diesel fuel.[8]

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

The second qualification is that the AGC emissions estimates do not account for on-road diesel use in dump trucks and related equipment. (Information on AGC's on-road fleet was not included in the HGAC report and was not readily available.) According to one rough estimate, on-road diesel fuel use could account for around 20% of total diesel fuel consumption among AGC highway contractors.[9] However, on-road engines typically emit 3 to 5 times less NOx than off-road engines of comparable model year and hp. For example, the 1997 and 2000 model year 190 hp engines tested at SwRI were certified to 4.0 g/mi NOx, translating to between 2 and 3 g/bhp-hr.[10] However, comparable Base and Tier 0 off-road engines are typically certified to

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[8] Note this is a 5% increase in NOx relative to the draft version of NONROAD used to estimate emissions for the previous PuriNOx analysis.

[9] Personal communication, Bob Lanham, Williams Brothers Construction, February 13, 2003.

[10] Brake-specific fuel consumption factors for on-road engines were taken from EPA document EPA420-P-98-015, for truck classes 3 to 6.

between 8 and 11 g/bhp-hr. So if total on-road fuel consumption for on-road engines were around 20% of all diesel use for AGC, the on-road contribution to total emissions would be much smaller, perhaps 5 to 10%. Therefore, the exclusion of on-road equipment from this analysis should not introduce large errors in the estimation of total emissions and reduction potentials.

Potential Emission Reductions

The HGAC study estimated 2,038,482 gallons of off-road number 2D diesel were used per year for the AGC fleet in the eight-county area. Based on test results showing no fuel economy penalty measured in the current study, we use this same value of TxLED per year, assuming the same hp-hrs of use. Emission reduction factors for TxLED were assumed to be the same for electronic and mechanical engines, at 6.0%. (Attempts to obtain emission test results on mechanically controlled engines from Valero were unsuccessful as of this writing. However, according to EPA's Unified Diesel Fuel Model, diesel engines not equipped with exhaust gas recirculation (EGR) technology should experience a 6.2% reduction when operating on TxLED, in close agreement with the observed data for electronic engines.[11]) Applying these factors leads to an estimate of **43 tons per year** in NOx reductions, assuming TxLED is used in 100% of all AGC diesel applications.

Incremental Cost Analysis

The use of TxLED in the AGC fleet will incur the same types of costs discussed above for the TXDOT fleet. However, given the much higher fuel consumption rates (about an order of magnitude), absolute cost levels will increase accordingly.

Fuel Costs

The incremental cost of TxLED for AGC was based on the 2002 TxDOT purchasing contract with Valero. In this contract incremental costs over and above base number 2D diesel were specified as a function of purchase volumes. One AGC representative estimated that approximately 70% of their total fuel purchases were full tanker truck volumes (about 7,400 gal).[12] This corresponds to the TxDOT ferry delivery volumes in Houston, with an incremental cost of 15.29 cents per gallon.

However, only the largest highway contractors operating in the Houston area would be expected to purchase fuel in such large quantities. The HGAC study found 2 large contractors were responsible for 71% of the total fuel use in the area, with the remainder attributed to numerous smaller contractors. Therefore this analysis assumed all other fuel purchases would occur in 4,000 gal bobtail volumes. From the 2002 TxDOT contract with Valero, these purchase volumes have a higher incremental cost, at 41.84 cents per gallon.

Based on these figures, total fuel cost increases for AGC would come to **$587,326 per year.** If the 2003 TxDOT contract terms were used instead—17.23 cents per gallon increment for tanker deliveries, and 44.33 cents for bobtails—total fuel cost increases would come to **$632,582 per year.** This represents the high-end fuel cost estimate for our analysis.

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[11] "Strategies and Issues in Correlating Diesel Fuel Properties with Emissions – Staff Discussion Document", EPA420-P-01-001, July 2001.
[12] Bob Lanham, September 23, 2004.

Valero representatives indicated that if the barge currently carrying TxLED from Corpus Christi to Houston once a month could be dedicated to TxLED shipments, fuel delivery costs would likely fall by 5 cents per gallon. Under the above condition with AGC using over 2 million gallons of TxLED per year, higher delivery volumes requiring dedicated transport are likely. In addition, based on the SwRI test data, off-road engines may experience up to 2% improvement in fuel economy using TxLED relative to current number 2D diesel. Therefore a sensitivity case was performed to estimate a reasonable low-end fuel cost increment for TxLED use in AGC off-road engines. Under these assumptions AGC would save $45,178 per year due to fuel economy impacts, and incur $485,402 per year due to per gallon price differentials. Total fuel cost increases for the low-end estimate come to **$440,224 per year.**

Maintenance

Since the TxDOT and AGC fleets are not readily comparable in terms of equipment type mix, it was assumed that maintenance costs could be scaled directly from fuel use estimates. Using TxDOT's maintenance records for TxLED consumption in the four analysis districts from July 2003 to July 2004, the incremental number of fuel leak repairs was calculated for the AGC fleet using total fuel consumption ratios. TxDOT records also provided an estimate of labor hours per type of repair. In this case it was assumed that all repairs were related to injector pump leaks (although some unknown fraction of repair costs were also due to lower-priced transfer pump repairs). The calculation assumes all fuel leak repairs are outsourced by AGC. Table 4.8 summarizes the major cost elements of this analysis.

Table 4.8 AGC Annual Maintenance Cost Projection

	TXDOT	**AGC**
Gallons of TxLED	1,222,438	2,038,482
# Injector Pump leaks (incremental)	31	52
Labor Hrs - / Injector Pump	4	
	$/Unit	**Total $**
Injector Pump	$42	$2,171
Outsource Labor	$72.60	$15,012
	Total	$17,183

* TxDOT Maintenance Records—TxLED consumption July 2003–July 2004

Cost-Effectiveness Evaluation

A range of cost-effectiveness estimates were developed for AGC's use of TxLED, accounting for different cost and fuel efficiency scenarios. These findings, presented in dollars per ton of NOx reduction, are summarized in Table 4.9. Note that the "Low" cost scenario assumes a 2% fuel efficiency improvement, 2002 vendor fuel contract terms, and a five cent per gallon discount resulting from dedicated barge delivery. "High" cost scenario assumes no fuel economy benefit and the current TxDOT fuel constant cost increment.

Table 4.9 Cost Effectiveness Ranges for AGC Use of TxLED

Scenario	Low	High
Current engine mix	$10,654	$14,080

Assuming no other implementation, maintenance, or performance costs are incurred, if adopted by AGC this fuel could provide approximately 43 tons per year of NOx reductions in the eight-county area, at a cost-effectiveness between $10,654 and $14,080 per ton. These figures compare to the previous comparable analysis of PuriNOx, which estimated a 108 ton-per-day NOx reduction at cost-effectiveness between $20,333 and $62,225 per ton.

4.C. Conclusions Regarding Cost-Effectiveness

The TxDOT cost-effectiveness calculations, a point estimate for the costs incurred by TxDOT in 2003 using TxLED, revealed that it costs between $92,000/ton and $99,000/ton for the Houston District to reduce NOx emissions by using TxLED, depending on whether the fuel economy benefit is considered. Also, depending on the type of equipment, the annual cost-effectiveness of using TxLED to reduce NOx varied from $22,719/ton for the excavators to $149,069/ton in the case of the traffic alerting signals (arrow boards) if the fuel economy benefit is considered. Excluding the fuel economy benefit, the costs of reducing NOx emissions using TxLED ranged from $20,408/ton (for the telescoping boom excavators) to $133,907/ton (for the traffic alerting signals).

5. Summary, Conclusions, and Recommendations

The initial part of the present study was the most extensive study of an emulsified diesel fuel (PuriNOx) to date, involving a field test of 386 diesel engines in normal service, plus emissions and fuel consumption tests of eight dump trucks, two engines used for non-road applications, and a small utility engine. When it was determined that, in spite of the significant reductions in the emissions of NOx and PM that result from use of this fuel, it was not cost-effective for highway construction operations, TxDOT began using an ultra-low sulfur diesel fuel, Texas Low Emission Diesel (TxLED). As was done when they adopted use of PuriNOx, TxDOT commissioned a simultaneous study of the effectiveness of the use of TxLED by both the TxDOT fleet and their contractors, the Associated General Contractors (AGC). Again, the University of Texas, teaming with SwRI and ERG, was awarded the funding for this study, as a contract extension to the emulsified diesel fuel project.

The study of TxLED was designed to be as similar as possible to that done for PuriNOx. However, some differences in the examinations of these two fuels were necessary due to the smaller budget available for the study of TxLED.

Because TxLED is similar to conventional diesel fuel, there were no obvious health or safety issues that had to be addressed in this extension of the study. Because PuriNOx contains 20% water, it produced a significant torque loss that impacted the performance of the diesel equipment. This was not of concern for TxLED, which in fact, produces a small torque benefit. In the initial portion of this study, it was found that the emulsified diesel fuel tended to separate over time. This could result in problems with starting the engines and with corrosion of some components of the fuel system. Similar tests were performed for TxLED. As expected, TxLED does not separate into lighter and heavier components over time. No corrosion problems were found either.

For all engines tested, TxLED provided a statistically significant benefit in NOx emissions compared to 2D on-road diesel fuel. With the exception of only one engine, the NOx emissions benefits from using TxLED were higher than the benefits claimed in Texas' State Implementation Plan. Additionally, statistically significant benefits in PM emissions were found for three of the six engines tested and small, but statistically significant, benefits in fuel consumption or fuel economy were found for three of the engines.

The results from the full load torque curve tests and the operator assessments, together with the properties of TxLED compared to those for 2D on-road diesel fuel, indicate that there should be no performance penalties associated with use of TxLED.

Therefore, the cost-effectiveness of the NOx emissions reductions obtained with TxLED was the dominant issue, and was the primary focus of this study.

The TxDOT cost-effectiveness calculations—a point estimate for the costs incurred by TxDOT in 2003 using TxLED—revealed that it costs between $92,000/ton and $99,000/ton for the Houston District to reduce NOx emissions by using TxLED, depending on whether the fuel economy benefit is considered. The AGC cost-effectiveness evaluation found that up to 43 tons per year of NOx reductions were possible, assuming 100% of the AGC fleet adopted TxLED in the eight-county ozone non-attainment area. Total implementation costs can vary, depending upon fuel purchase prices, delivery options, and fuel economy assumptions. Considering these factors this analysis estimated a cost-effectiveness range of between $10,654 and $14,080 per ton of NOx reduced for the AGC fleet.

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

- TxDOT should continue to take a leading role in decreasing emissions. Because maintenance of this leading role involves public funds, cost-effectiveness should be a primary criterion in choosing between alternatives. TxLED is a cost-effective strategy for reducing emissions from the TxDOT fleet.

- TxLED use in the AGC fleets is relatively cost-effective compared to TxDOT applications. However, its use will still incur a net cost to contractors. Since TxLED will be required area-wide starting in the fall of 2005, these costs will not be recoverable through TERP grants. Accordingly, TxDOT should be aware of the potential cost impacts on AGC when developing potential TxLED use requirements or incentives.

Appendix A. Emissions and Fuel Consumption

The emissions and fuel consumption for the engines evaluated in this project are discussed in this appendix. The results of tests over the Telescoping Boom Excavator Cycle are discussed in Section A.1, the Single-Axle Dump Truck Cycle tests are discussed in Section A.2, and the Tandem-Axle Dump Truck Cycle tests are discussed in Section A.3. The results of tests of a small utility engine are discussed in Section A.4. These sections compare emissions and fuel consumption for TxLED relative to the baseline diesel fuel (2D on-road diesel fuel).

In many of the figures presented in this appendix, comparisons are required between species that are emitted at significantly different rates. To allow all of these emissions (and, for some of the figures, the brake specific fuel consumption, BSFC) to be illustrated on the same scale, it was necessary to either multiply or divide one or more of the rates by some factor of 10. As an example of how to read these figures, in Figure A.1 for operation on 2D on-road diesel fuel, it is shown that PM*100 = 8.4 g/hp-hr. Thus, the PM emissions rate is 0.084 g/hp-hr (84 mg/hp-hr).

For the emulsified diesel fuel study, SwRI performed measurements for both cold start cycles and hot start cycles. The emissions were then calculated for the "composite" cycle:

$$\text{Composite emissions} = (1/7)*\text{cold start emissions} + (6/7)*\text{hot start emissions} \qquad \text{(A.1)}$$

where the weighting factors were taken from the EPA's procedure for heavy-duty engines (diesel or gasoline). Due to the more limited budget for the study of TxLED, cold start tests were not performed because of the time and expense of these tests and because the cold start cycle is weighted weakly (14%). Three hot start cycles were performed for each piece of equipment to allow statistical analysis regarding whether fuel-to-fuel differences are significant or are within the normal scatter of test-to-test reproducibility. The figures present the average for the hot starts.

Due to complaints of adverse health effects that might be related to the use of the emulsified diesel fuel, the PuriNOx study also included exhaust speciation to acquire information about the composition of the hydrocarbon emissions to identify any "Hazardous Air Pollutants" (HAPs) that might be significant. These additional tests were not done for the study of TxLED due to the added cost and the lack of any indication of adverse health effects.

A.1. Telescoping Boom Excavator Engine

An electronically-controlled 2000 Cummins ISB-190 engine was tested over the TxDOT Telescoping Boom Excavator Cycle at Southwest Research Institute. This cycle is described by Baker et al. (2003).

To allow all of these emissions and the BSFC to be illustrated on the same scale in Figure A.1, the BSFC is divided by 100, the PM is multiplied by 100, and the HC emissions are multiplied by 10. For this engine operating over this cycle, TxLED offers a 6.4% benefit in NOx and a 17.8% benefit in PM. There are also benefits in the emissions of CO and HCs. However, because the emissions of CO and HCs from diesels are inherently low, the benefits in the emissions of these species are not generally of significant interest. The difference between the two fuels in the average result for the brake specific fuel consumption was not statistically significant at the 95% confidence level. This lack of a statistically significant difference in the fuel consumption between the two fuels is also reflected in Table A.1 in which the difference between the two fuels in CO2 emissions was also not statistically significant at the 95% confidence level (the CO2 emissions scale directly with fuel consumption).

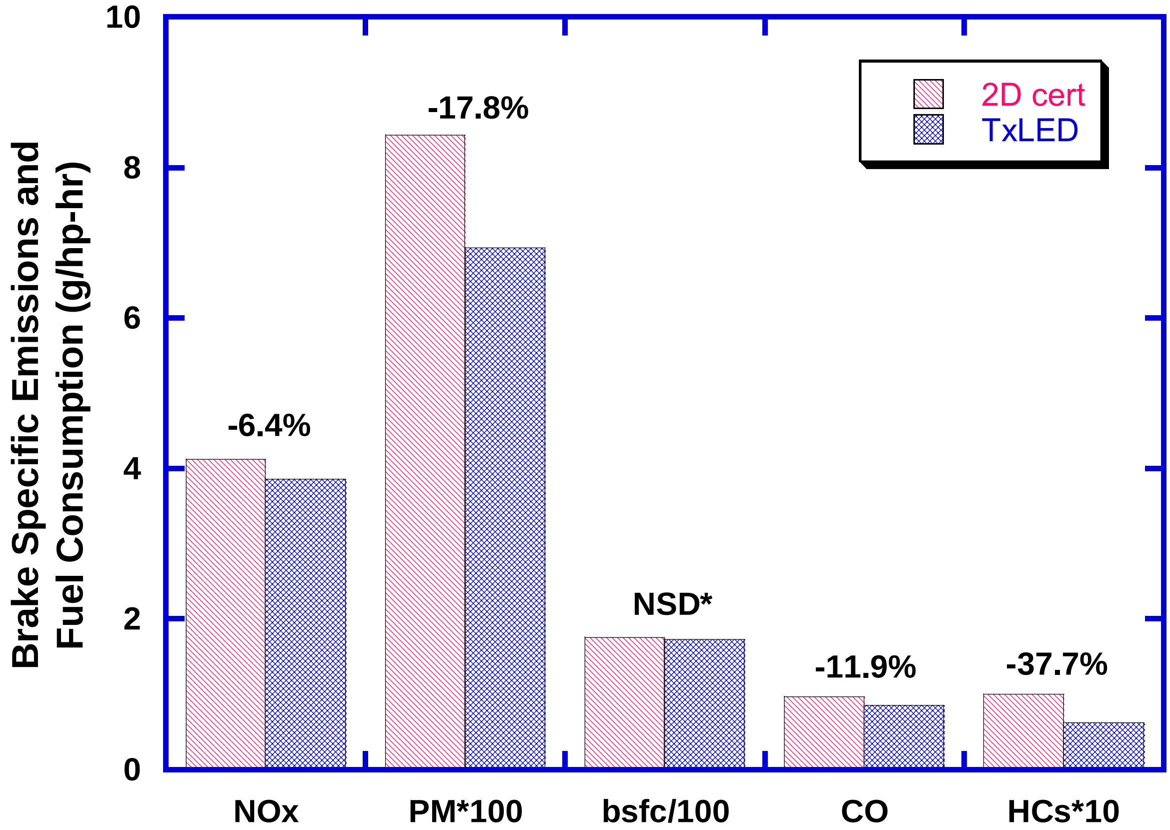

Figure A.1. Emissions and fuel consumption for the Cummins ISB-190 operating over the TxDOT Telescoping Boom Excavator Cycle

Note: *NSD means that differences between the two fuels are not statistically significant at the 95% confidence level

Table A.1. Emissions from the ISB-190 for the TxDOT Telescoping Boom Excavator Cycle For Each of the Fuels.

Fuel	HC g/hp-hr	PM g/hp-hr	NOx g/hp-hr	CO2 g/hp-hr	CO g/hp-hr	BSFC g/hp-hr	Reference Work hp-hr	Actual Work hp-hr	Actual vs. Ref. (%)
Low Sulfur	0.10	0.084	4.12	557	0.96	175.51	25.57	25.66	0.4
Low Sulfur	0.10	0.085	4.09	557	0.97	175.51	25.57	25.65	0.3
Low Sulfur	0.10	0.084	4.17	557	0.96	175.51	25.57	25.66	0.4
Average:	**0.10**	**0.084**	**4.13**	**557**	**0.97**	**175.51**	**25.57**	**25.657**	**0.3**
TxLED	0.06	0.069	3.80	552	0.83	173.70	25.57	25.85	1.1
TxLED	0.06	0.069	3.90	542	0.86	170.52	25.57	25.94	1.4
TxLED	0.07	0.070	3.90	556	0.86	175.06	25.57	25.90	1.3
Average:	**0.06**	**0.069**	**3.86**	**550**	**0.85**	**173.09**	**25.57**	**25.897**	**1.3**
95% conf?	**Y**	**Y**	**Y**	**N**	**Y**	***N***		***Y***	

As also shown in Table A.1, the engine did slightly more work over the cycle when using TxLED in spite of an attempt to run the tests in a manner that would assure the same work for both fuels. More work should produce increased NOx and PM emissions and more fuel consumption for TxLED. However, in spite of this TxLED showed benefits in NOx and PM emissions with no effect on brake specific fuel consumption (at the 95% confidence level).

A.2. Single-Axle Dump Trucks

SwRI measured the emissions and fuel economy of two single-axle dump trucks operating over the TxDOT Single-Axle Dump Truck Cycle. This cycle is described in detail by Baker et al. (2003). The chassis dyno was set to simulate a loaded vehicle weight of 28,480 lb (these trucks have a GVW Rating of about 33,000 lb and weigh about 15,000 lb when empty, depending upon the specific truck). The two single axle dump trucks were:

- 1999 GMC C7500 with an electronically-controlled Cat 3126B (6.6 L, 210 hp, 2600 rpm, serial no. FS6306A, engine family WCPXH0442HSK, TxDOT Eqpt. No. 15-4772-G; certification standards: 4.0 gNOx/hp-hr, 0.10 gPM/hp-hr; certification levels: 3.85 gNOx/hp-hr, 0.094 gPM/hp-hr). An identical truck (TxDOT Eqpt. No. 15-4771-G) was used for the study of emulsified diesel fuel but developed a problem and was replaced for these tests.

- 1997 International with an electronically-controlled Navistar Power Stroke T444E-HT (7.27 L, 228 hp, 2500 rpm, engine family VN444C8DASW, TxDOT Eqpt. No. 5-3946-G; certification standards: 5.0 gNOx/hp-hr, 0.10 gPM/hp-hr).

One problem with conventional comparisons of emulsified and conventional diesel fuel is that the torque loss associated with the water in emulsion affects the ability to stay on the prescribed cycle when using the emulsion. This results in a different amount of work over the cycle, and thereby affects emissions. To overcome this problem, a new technique—the "route" test—was developed for the initial portion of this project. The route test was described previously (Baker et al., 2003; DeFries et al., 2004) and was retained for the study of TxLED.

A.2.A. Cat 3126B—The results for the GMC with the Caterpillar 3126B engine are illustrated in Figure A.2 for the TxDOT Single-Axle Dump Truck Cycle. Detailed results are provided in Table A.2.

Figure A.2 shows that the NOx emissions benefit of TxLED is 6.2% and the PM emissions benefit is 15.6% for this dump truck. Also, there is a fuel economy benefit of 1.7%, which is small but statistically significant with 95% confidence. TxLED also provides a 25.9% benefit in HC emissions but no statistically significant effect on CO emissions.

As shown in Table A.2, it can be stated with 95% confidence that there is no statistically significant difference in the distance traveled between the two fuels. However, the average speed was 0.1 mph (0.5%) faster for the tests with TxLED. The higher average speed for the TxLED tests should produce higher NOx and PM emissions and lower fuel economy. In spite of this, TxLED showed benefits in NOx and PM emissions and in fuel economy compared to 2D on-road diesel fuel.

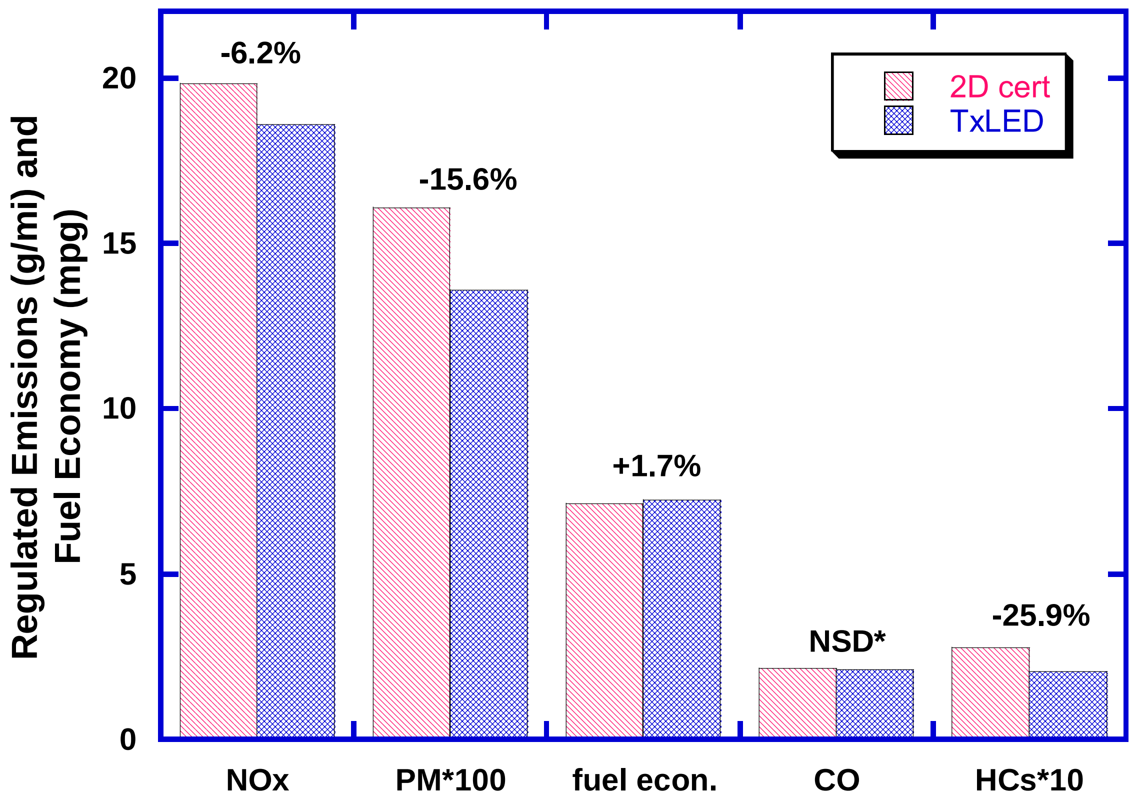

Figure A.2. Emissions and fuel economy for the GMC single-axle dump truck with the Caterpillar 3126B engine.

Note: *NSD means that differences between the two fuels are not statistically significant at the 95% confidence level

Table A.2. Results for the Electronically-Controlled Caterpillar 3126B Engine in the 1999 GMC Single-Axle Dump Truck.

	g/mile						miles			mph
Fuel	HC	PM	NOx	CO2	CO	MPG	Reference distance	Actual distance	Actual vs. Ref. (%)	Average speed
Low Sulfur	0.29	0.162	19.82	1384	2.17	7.11	8.78	8.79	0.1	23.9
Low Sulfur	0.29	0.160	19.88	1385	2.17	7.11	8.78	8.8	0.2	23.9
Low Sulfur	0.26	0.160	19.78	1383	2.12	7.12	8.78	8.79	0.1	23.9
Avg:	**0.28**	**0.161**	**19.82**	**1384**	**2.16**	**7.11**	**8.78**	**8.79**	**0.2**	**23.9**
TxLED	0.19	0.137	18.41	1368	2.12	7.20	8.78	8.79	0.1	24.1
TxLED	0.21	0.135	18.66	1355	2.08	7.27	8.78	8.79	0.1	24.0
TxLED	0.22	0.135	18.68	1363	2.11	7.23	8.78	8.8	0.2	24.0
Avg:	**0.21**	**0.136**	**18.58**	**1362**	**2.10**	**7.23**	**8.78**	**8.79**	**0.2**	**24.0**
95% conf?	Y	Y	Y	Y	N	Y		N		Y

<u>**A.2.B. Navistar T444E**</u>—The results for the 1997 International with the electronically-controlled T444E engine are illustrated in Figure A.3 for the TxDOT Single-Axle Dump Truck Cycle. Detailed results are provided in Table A.3.

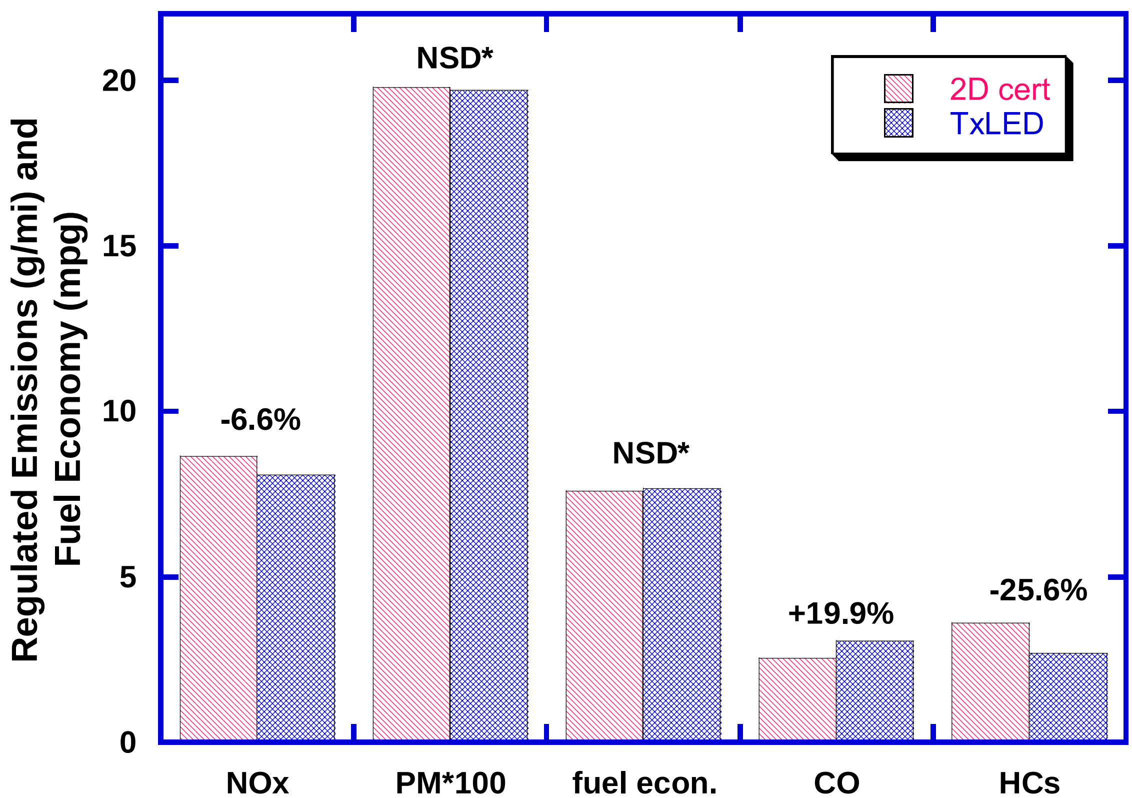

Figure A.3. Emissions and fuel economy for the International single-axle dump truck with the Navistar Power Stroke T444E engine

Note: *NSD means that differences between the two fuels are not statistically significant at the 95% confidence level

TxLED provides a 6.6% benefit in NOx emissions without a statistically significant effect on PM emissions or fuel economy. There is also a 25.6% benefit in HC emissions. Surprisingly, the CO emissions are 20% higher when using TxLED.

Table A.3. Results for the Electronically-Controlled Navistar Power Stroke T444E engine in the 1997 International Single-Axle Dump Truck

	g/mile						miles			mph
Fuel	HC	PM	NOx	CO2	CO	MPG	Reference distance	Actual distance	Actual vs. Ref. (%)	Average speed
Low Sulfur	0.37	0.198	8.66	1331	2.42	7.39	8.78	8.8	0.2	23.9
Low Sulfur	0.40	0.203	8.65	1270	2.65	7.74	8.78	8.8	0.2	23.9
Low Sulfur	0.31	0.192	8.62	1294	2.59	7.61	8.78	8.8	0.2	23.9
Avg:	**0.36**	**0.198**	**8.64**	**1298**	**2.55**	**7.58**	**8.78**	**8.80**	**0.2**	**23.9**
TxLED	0.28	0.193	8.09	1303	2.95	7.55	8.78	8.8	0.2	24.1
TxLED	0.26	0.192	8.16	1273	3.00	7.72	8.78	8.8	0.2	24.0
TxLED	0.27	0.206	7.96	1272	3.22	7.72	8.78	8.8	0.2	24.0
Avg:	**0.27**	**0.197**	**8.07**	**1283**	**3.06**	**7.66**	**8.78**	**8.80**	**0.2**	**24.0**
95% conf?	Y	N	Y	N	Y	N		N		Y

As was also true for the other single-axle dump truck, for these tests the differences in distance traveled over the cycle are not statistically different, but the average speeds are. Again, the average speed was 0.1 mph (0.5%) faster for the tests with TxLED. The higher average speed for the TxLED tests should produce higher NOx and PM emissions and lower fuel economy. In spite of this, TxLED showed a benefit in NOx emissions but no effects on PM emissions or fuel economy compared to 2D on-road diesel fuel.

A.3. Tandem-Axle Dump Trucks

SwRI measured the emissions and fuel economy of two tandem-axle dump trucks operating over the TxDOT Tandem-Axle Dump Truck Cycle. This cycle was described in detail previously (Baker et al., 2003). The chassis dyno was set to simulate a loaded vehicle weight of 47,000 lb (these trucks have a GVW Rating of about 54,000 lb and weigh about 24,000 lb when empty, depending upon the specific truck). The two tandem-axle dump trucks were:

- 2000 Volvo WG64F with an electronically-controlled Cummins ISM 305V (11.0 L, 305 hp, 2100 rpm, engine serial no. 35010090, Engine Family YCEXH0661MAI, TxDOT Eqpt no. 15-3512-H; certification standards: 4.0 gNOx/hp-hr, 0.10 gPM/hp-hr)

- 2000 International 2574 with an electronically-controlled Caterpillar C10 (10.3 L, 305 hp, 1700 rpm, engine serial no. 3CS0382, Engine Family XCPXH0629ERK, TxDOT Eqpt no. 15-5184-G; certification standards: 4.0 gNOx/hp-hr, 0.10 gPM/hp-hr). An identical truck (TxDOT Eqpt. No. 15-5186-G) was used for the study of emulsified diesel fuel but developed a shifting problem and was replaced for these tests.

As discussed in Section A.2 for the single-axle dump trucks, “route” tests were performed for the tandem-axle dump trucks as well. The emissions and fuel economy for each of the two tandem-axle dump trucks are discussed in this subsection.

<u>A.3.A. Cummins ISM 305V</u>—The results for the Volvo with the Cummins ISM 305V engine are illustrated in Figure A.4 for the TxDOT Tandem-Axle Dump Truck Cycle. Detailed results are provided in Table A.4.

As shown in Figure A.4, compared to the diesel fuel normally used by TxDOT (2D on-road diesel), TxLED provides statistically significant benefits in NOx (6.1%), PM (13.0%), and HC (12.8%) emissions with a 3.1% benefit in fuel economy. As shown in Table A.4, it can be said with 95% confidence that there were no statistically significant differences between the tests of the two fuels in the distance traveled or average speed over the tandem-axle dump truck route (cycle).

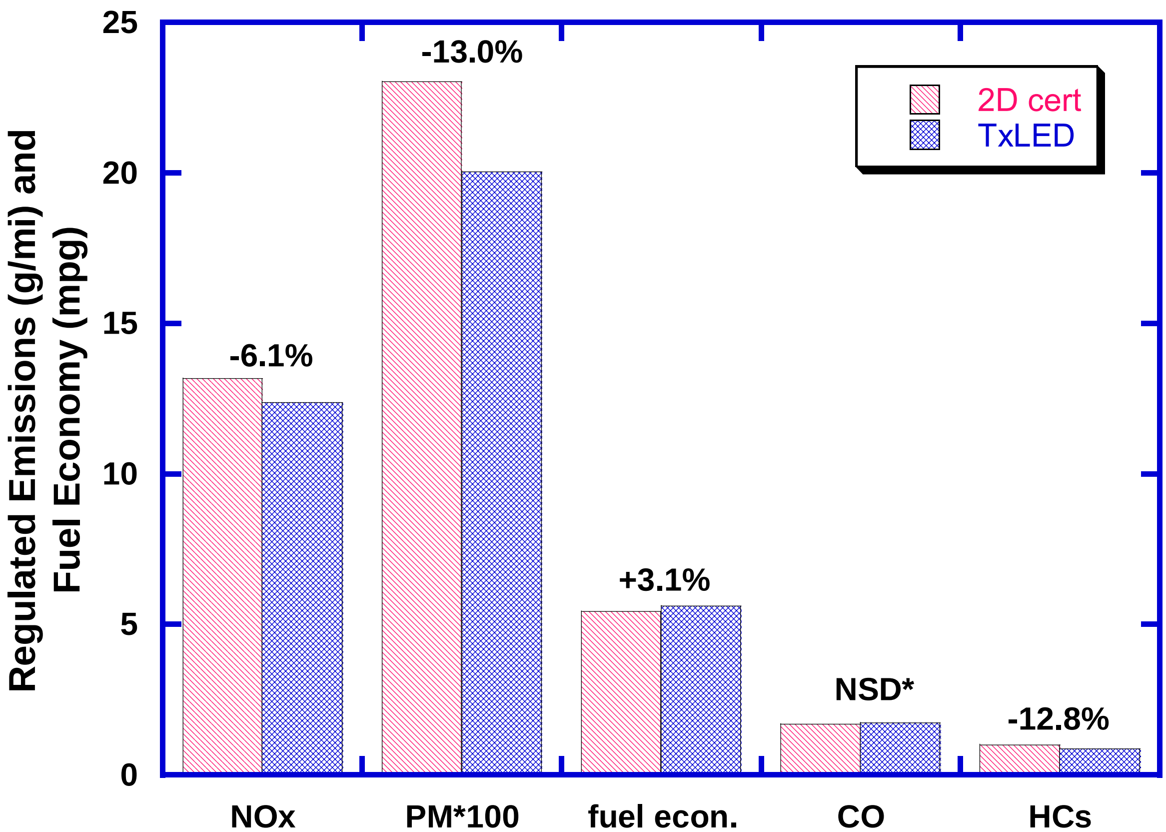

Figure A.4. Emissions and fuel economy for the Volvo tandem-axle dump truck with the Cummins ISM 305V engine.

Note: *NSD means that differences between the two fuels are not statistically significant at the 95% confidence level

Table A.4. Results for the Electronically-Controlled Cummins ISM 305V engine in the 2000 Volvo Tandem-Axle Dump Truck

	g/mile						miles			mph
Fuel	**HC**	**PM**	**NOx**	**CO2**	**CO**	**MPG**	Reference distance	**Actual distance**	**Actual vs. Ref. (%)**	**Average speed**
Low Sulfur	1.03	0.235	13.47	1815	1.72	5.42	10.58	10.61	0.3	24.9
Low Sulfur	0.97	0.226	12.93	1805	1.62	5.46	10.58	10.61	0.3	25.0
Low Sulfur	0.99	0.230	13.10	1816	1.71	5.42	10.58	10.61	0.3	24.9
Avg:	**0.99**	**0.230**	**13.17**	**1812**	**1.68**	**5.43**	**10.58**	**10.61**	**0.3**	**24.9**
TxLED	0.87	0.199	12.20	1779	1.68	5.54	10.58	10.61	0.3	25.1
TxLED	0.86	0.200	12.45	1774	1.71	5.55	10.58	10.61	0.3	24.9
TxLED	0.88	0.202	12.44	1725	1.82	5.71	10.58	10.61	0.3	24.5
Avg:	**0.87**	**0.200**	**12.36**	**1759**	**1.74**	**5.60**	**10.58**	**10.61**	**0.3**	**24.8**
95% conf?	Y	Y	Y	Y	N	Y		N		N

A.3.B. Cat C10 - The results for the Volvo with the Caterpillar C10 engine are illustrated in Figure A.5 for the TxDOT Tandem-Axle Dump Truck Cycle. Detailed results are provided in Table A.5.

As shown in Figure A.5, TxLED provides a much smaller NOx benefit for this engine, at only 2%, than for any other engine tested. Additionally, the effects of TxLED on the emissions of PM and CO were not statistically significant at the 95% confidence level, and the same was true for the effect on fuel economy. However, as shown in Table A.5, it can be said with 95% confidence that there were no statistically significant differences between the tests of the two fuels in the distance traveled or average speed over the tandem-axle dump truck route (cycle).

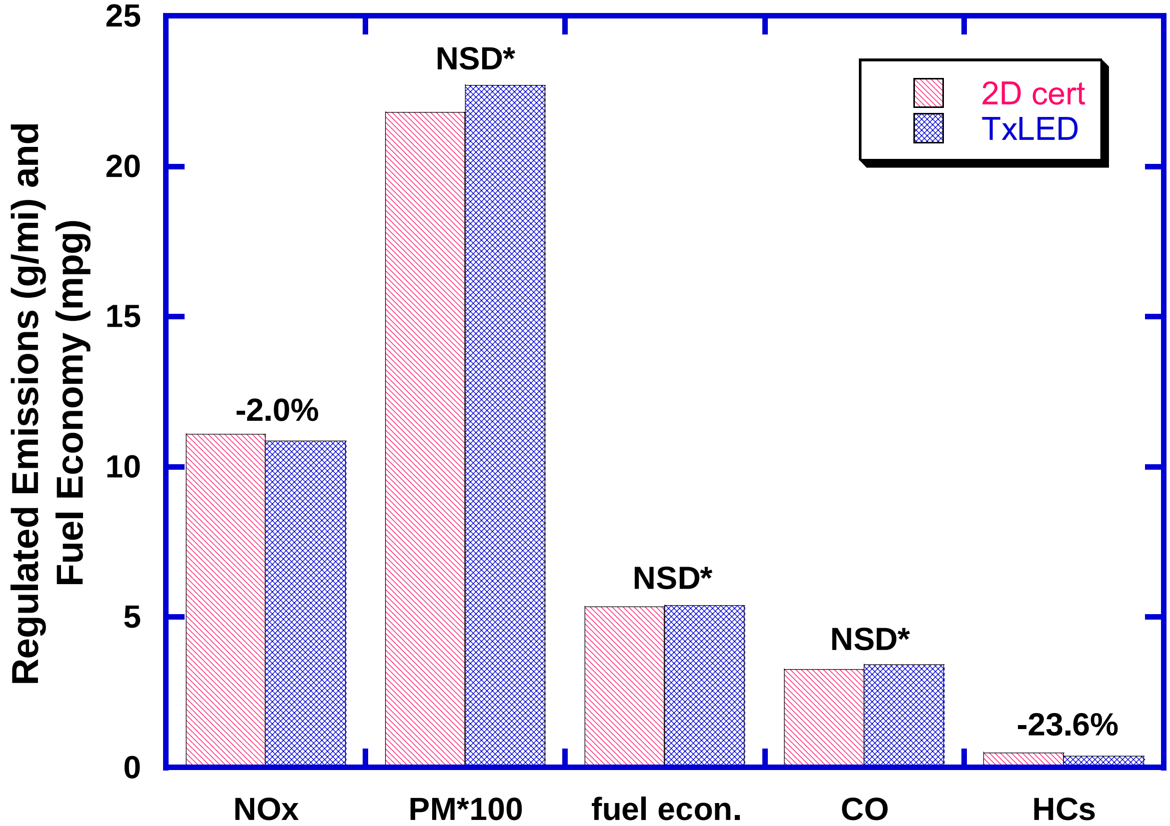

Figure A.5. Emissions and fuel economy for the International tandem-axle dump truck with the Cat C10 engine

Note: *NSD means that differences between the two fuels are not statistically significant at the 95% confidence level

Table A.5. Results for the Electronically-Controlled Caterpillar C10 engine in the 1999 International Tandem-Axle Dump Truck

	g/mile						miles			mph
Fuel	**HC**	**PM**	**NOx**	**CO2**	**CO**	**MPG**	Reference distance	**Actual distance**	**Actual vs. Ref. (%)**	**Average speed**
Low Sulfur	0.49	0.221	11.10	1819	3.26	5.41	10.58	10.64	0.6	25.20
Low Sulfur	0.48	0.232	11.06	1866	3.36	5.27	10.58	10.63	0.5	25.17
Low Sulfur	0.52	0.227	11.09	1847	3.21	5.33	10.58	10.63	0.5	25.15
Avg:	**0.50**	**0.227**	**11.08**	**1844**	**3.27**	**5.34**	**10.58**	**10.63**	**0.5**	**25.17**
TxLED	0.39	0.213	10.85	1858	3.48	5.30	10.58	10.63	0.5	25.21
TxLED	0.38	0.221	10.69	1828	3.59	5.38	10.58	10.63	0.5	25.22
TxLED	0.37	0.219	10.80	1808	3.31	5.44	10.58	10.60	0.2	25.14
TxLED	0.37	0.219	11.08	1808	3.31	5.44	10.58	10.60	0.2	25.14
Avg:	**0.38**	**0.218**	**10.85**	**1826**	**3.42**	**5.39**	**10.58**	**10.62**	**0.3**	**25.18**
95% conf?	Y	N	Y	N	N	N		N		N

A.4. Small Utility Engines

A 2002 Yanmar 10 hp herbicide sprayer engine was used to represent the various small utility diesel engines used by TxDOT. TxDOT uses these engines for herbicide sprayers, traffic-alerting signals (e.g., arrowboards), and riding mowers.

This engine was tested to estimate the typical emissions and fuel consumption for these engines. TxDOT estimated that the single cylinder engines used for traffic alerting signals are used at maximum speed, full load 100% of the time; that the single cylinder herbicide sprayer engines are used at maximum speed, full load 50% of the time and half speed, slight load the remaining 50%; and that the two cylinder diesels in riding lawn mowers operate at maximum speed, full load 90% of the time and half speed, slight load the remaining 10% (Nicholes, 2003). This represents only two operating conditions, which we took to be 3550 rpm, full load, and 1500 rpm, 2.5 lb-ft of torque.

The engine was installed in an engine test cell, coupled to an engine dynamometer, and instrumented to measure speed, torque output, fuel consumption, and emissions. NOx was measured using a chemiluminescence analyzer and PM was measured gravimetrically. Steady-state emissions and fuel consumption were evaluated using TxLED and compared with operation on 2D on-road diesel fuel. The results of these tests are discussed in this subsection.

As noted above, typical TxDOT operation of small utility engines includes only two modes, which we have taken to be 3550 rpm, full load, and 1500 rpm, 2.5 lb-ft of torque. To calculate composite emissions and fuel consumption for these two modes, the weighting factors for the high speed and load point are 0.9 for mowers, 1.0 for traffic alerting signals, and 0.5 for sprayers. The results are provided in Table A.6.

As shown in Table A.6, TxLED provides statistically significant benefits in fuel consumption and the emissions of NOx and CO for all three of the engine applications. The benefits for the Yanmar are much more pronounced than for the other engines because this diesel engine was designed to be manufactured at the lowest possible cost. Thus, it cannot be expected to behave similarly to more expensive engines that are designed to meet stringent emissions standards.

Table A.6. Composite Emissions and Fuel Consumption for Small Utility Engine

	bsNOx	bsfc	bsPM	bsHCs	bsCO	EINOx	EIPM
	g/hp-hr					g/kg	
2D on-road diesel fuel							
high speed and load	7.13	211.9	0.591	0.026	2.20	33.28	2.80
mid-speed, low load	7.31	330.9	0.632	0.253	12.16	21.51	2.08
composite-mowers	7.17	223.8	0.595	0.049	3.20	32.10	2.55
composite-signals	7.13	211.9	0.591	0.026	2.20	33.28	2.60
composite-sprayers	7.31	271.4	0.611	0.139	7.18	27.39	2.34
TxLED							
high speed and load	3.41	188.1	0.456	0.014	0.40	18.10	2.41
mid-speed, low load	7.67	329.7	0.571	0.212	5.60	23.17	1.67
composite-mowers	3.82	202.4	0.468	0.034	0.92	18.61	2.51
composite-signals	3.41	188.1	0.456	0.014	0.40	18.10	2.60
composite-sprayers	5.45	259.2	0.514	0.113	3.00	20.63	2.14
% change (TxLED-2D)/2D							
mowers	-46.8	-9.6	NSD*	NSD*	-71.2	-42.0	-1.6
signals	-52.2	-11.2	NSD*	NSD*	-81.8	-45.6	NSD*
sprayers	-25.5	-4.5	NSD*	NSD*	-58.2	-24.7	-8.7

Note: *NSD means that differences between the two fuels are not statistically significant at the 95% confidence level.

Appendix B. Effects on Operations

The detailed results regarding the perceived effects of TxLED on operations of TxDOT equipment in the San Antonio district are presented in this appendix. The objective of surveying TxLED users in San Antonio was to determine the performance effects or issues associated with the use of TxLED-fueled vehicles/equipment, and in what kind of vehicles/equipment, if any, the use of TxLED was deemed problematic.

B.1 Survey Instrument and Pilot

A survey instrument was developed consisting of 18 statements regarding the perceived effect of using TxLED on the operation of vehicles/equipment. More than one question was included to evaluate the perceived performance in terms of particular attributes. In other words, questions were asked in different ways to test the consistency among responses. The respondents were asked to circle the option that best described how they feel on a scale of 1 to 5, where 1 meant disagreement and 5 meant agreement with the statement/question. The respondents were also given the opportunity to voice any other concerns in the “any other comments” section.

The survey instrument was very similar to the one used in the evaluation of PuriNOx in 2002 and 2003. The questionnaire that was designed during the PuriNOx study was modified to capture the driver and operator responses regarding the operational performance of TxLED.

Center for
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Phone: (512) 232-3100 • *Fax:* (512) 232-3153 • *Website:* www.utexas.edu/research/ctr

Dear Sir:

The Texas Department of Transportation (TxDOT) has started to use Texas Low Emission Diesel (TxLED) in an effort to reduce emissions from its operations. TxDOT contracted with the University of Texas at Austin to conduct extensive experiments to determine the benefits, detriments, and real-world operational characteristics of this fuel when applied to TxDOT's on-road and off-road equipment.

You are part of a sample of carefully selected operators that have used TxLED. The objective of the attached questionnaire is to gain your perceptions on the effect of this particular fuel on the operation of the vehicle/equipment compared to diesel fuel. For each of the statements, please ***circle*** the option that best describes how you feel. Your honest response is essential to the success of the study, but please remember that there is no "right" or "wrong" answer.

Your participation is completely voluntary. Please be assured that your responses will be treated as confidential and will be used solely for the study purpose. **It will not be provided to anyone outside the study team and will never be reported in a manner that could identify you.**

Thank you in advance for completing the survey. If you have any questions, please do not hesitate to ask the surveyor or contact Ms. Jolanda Prozzi at (512) 232 3079.

Questionnaire

Operator Assessment

Date: ____________________
Surveyor: ____________________
Name: ____________________
Location: ____________________
Vehicle/ Equipment used: ____________________
Type of Engine: ____________________
Tasks Performed: ____________________

____
____
____

1. I noticed a substantial improvement in the performance of my vehicle/equipment since switching to TxLED.

1 .... 2 .... 3 .... 4 .... 5 ☐6
Strongly Disagree Strongly Agree Not Applicable

2. I had more tasks since switching to TxLED.

1 .... 2 .... 3 .... 4 .... 5 ☐6
Strongly Disagree Strongly Agree Not Applicable

3. Even at full throttle, it takes me longer to perform the same task when using the hydraulics since switching to TxLED.

1 .... 2 .... 3 .... 4 .... 5 ☐6
Strongly Disagree Strongly Agree Not Applicable

4. My vehicle/equipment is using more fuel since switching to TxLED.

1 .... 2 .... 3 .... 4 .... 5 ☐6
Strongly Disagree Strongly Agree Not Applicable

5. I have asked a mechanic to check my vehicle/equipment more often since switching to TxLED.

1 .... 2 .... 3 .... 4 .... 5 ☐6
Strongly Disagree Strongly Agree Not Applicable

6. I am able to do all my usual tasks faster since switching to TxLED.

1 .... 2 .... 3 .... 4 .... 5 ☐6
Strongly Disagree Strongly Agree Not Applicable

7. The engine of the vehicle/equipment is noticeably noisier since switching to TxLED.

1 .... 2 .... 3 .... 4 .... 5 ☐6
Strongly Disagree Strongly Agree Not Applicable

8. I suffer from more backaches, sore muscles, and headaches since switching to TxLED.

1 .... 2 .... 3 .... 4 .... 5 ☐6
Strongly Disagree Strongly Agree Not Applicable

9. I changed my driving/operating behavior since switching to TxLED.

1 .... 2 .... 3 .... 4 .... 5 ☐6
Strongly Disagree Strongly Agree Not Applicable

10. I am moving heavier loads since switching to TxLED.

1 .... 2 .... 3 .... 4 .... 5 ☐6
Strongly Disagree Strongly Agree Not Applicable

11. I experienced some of the following symptoms since switching to TxLED: runny nose, nausea, hair loss, or skin rash.

1 .... 2 .... 3 .... 4 .... 5 ☐6
Strongly Disagree Strongly Agree Not Applicable

12. I noticed that my vehicle/equipment had less power since switching to TxLED.

1 .... 2 .... 3 .... 4 .... 5 ☐6
Strongly Disagree Strongly Agree Not Applicable

13. I have problems starting my vehicle/equipment early in the morning since switching to TxLED.

1 .... 2 .... 3 .... 4 .... 5 ☐6
Strongly Disagree Strongly Agree Not Applicable

14. My vehicle is accelerating faster since switching to TxLED.

1 .... 2 .... 3 .... 4 .... 5 ☐6

Strongly Disagree | Strongly Agree | Not Applicable

15. My vehicle/equipment smells better since switching to TxLED.

1 .... 2 .... 3 .... 4 .... 5 ☐6

Strongly Disagree | Strongly Agree | Not Applicable

16. I notice more smoke coming from my vehicle/equipment since switching to TxLED.

1 .... 2 .... 3 .... 4 .... 5 ☐6

Strongly Disagree | Strongly Agree | Not Applicable

17. I have to shift gears more often when doing my work since switching to TxLED.

1 .... 2 .... 3 .... 4 .... 5 ☐6

Strongly Disagree | Strongly Agree | Not Applicable

18. My vehicle/equipment is vibrating more since switching to TxLED.

1 .... 2 .... 3 .... 4 .... 5 ☐6

Strongly Disagree | Strongly Agree | Not Applicable

19. Any other comments:

B.2 San Antonio Driver/Operator Surveys

A total of 54 drivers/operators were surveyed in March 2004. The responses were largely neutral, indicating no perceived performance changes due to the use of TxLED. At the same time, relatively few users used the “comment section” to highlight a specific concern/ issue about the use of TxLED. Specific concerns raised in the comments section of the questionnaire were:

- increased failure of fuel pumps;
- increased failure of injector pumps;
- increased fuel leaks;
- lubrication additive was needed.

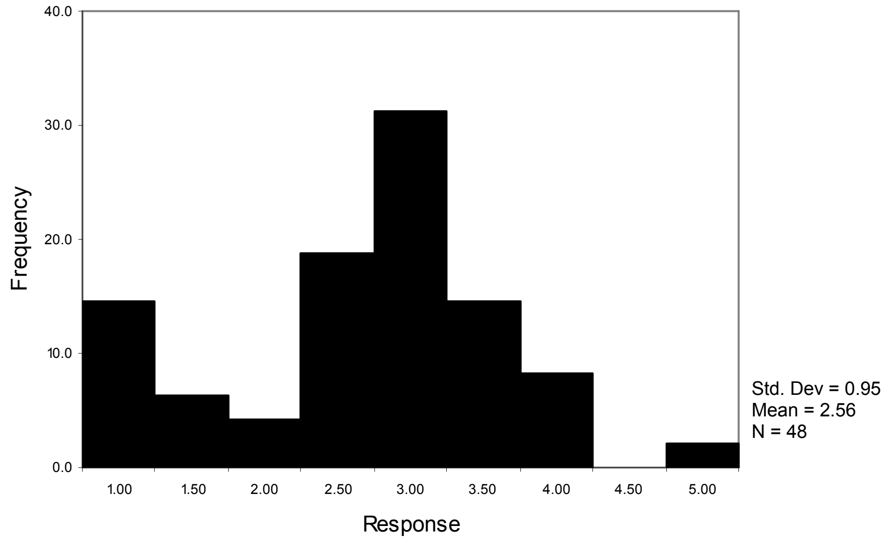
Table B.1 Number of Survey Responses (March 2004

	Total Responses	Valid Driver/Operator Responses
Bexar 410	14	14
Northeast San Antonio	15	14
Seguin	14	13
New Braunfels	14	13
Total	57	54

B.3 Frequency Distribution of San Antonio Responses: March 2004\

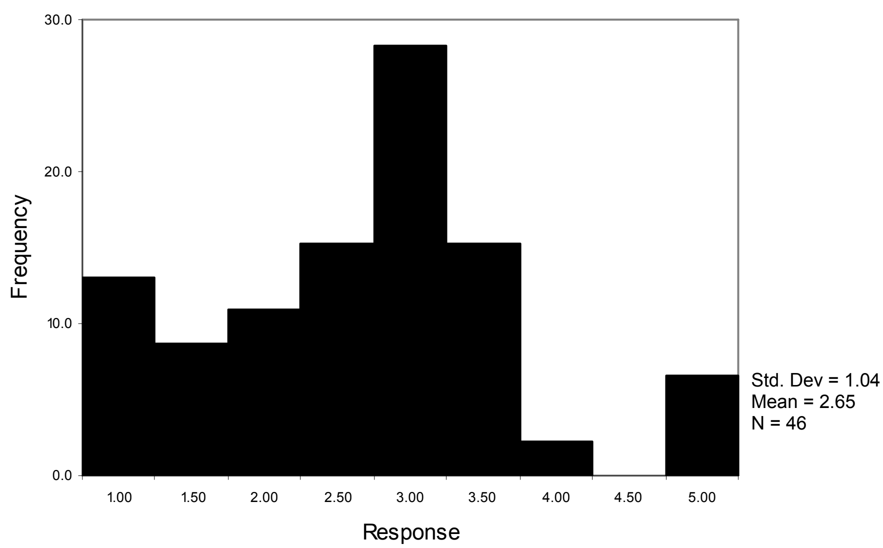
This section of the appendix shows the frequency distribution, mean, standard deviation, and the number of responses to each question. The number of responses to each question is often less than the total number of valid responses, because a “not applicable” option was included for each question. The vast majority of the responses were neutral and did not require further discussion. Also, no question garnered a response at the high or low end of the rating spectrum.

I noticed a substantial improvement in the performance of my vehicle/equipment.



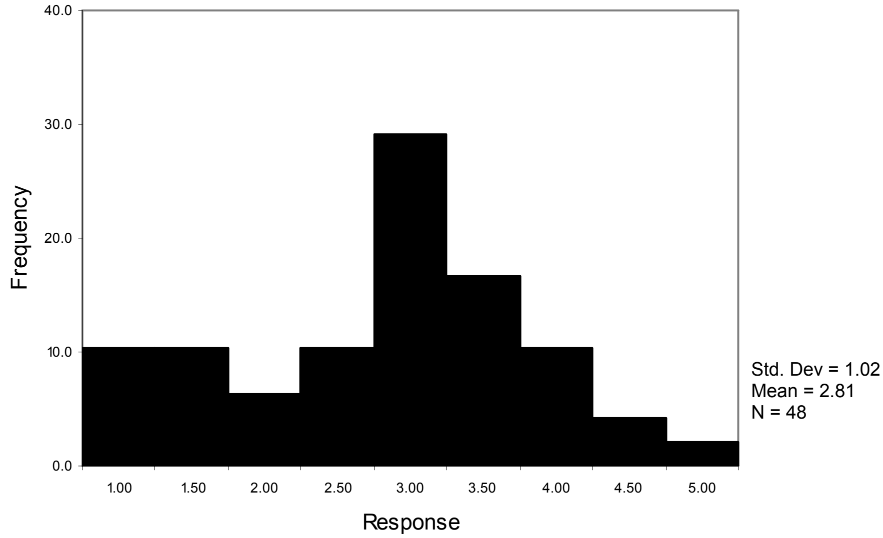
Of the 48 responses to this first question, 77.1% of the responses were between 2 and 4. Of that 77.1%, 15 responded neutrally (circled 3) to the question. The overall response to this question was “neutral,” leaning towards disagreement. This implies an overall neutral opinion of the effects of TxLED on performance.

I had more tasks since switching to TxLED



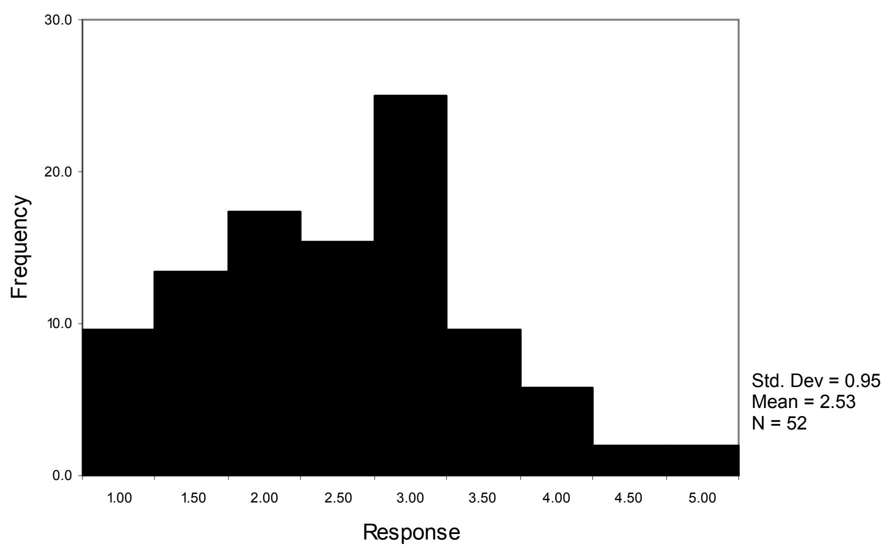
The two-sided z-test for this question was unable to reject the null hypothesis that the mean equaled 3 or, restated, that the response to this question was neutral. The frequency diagram displays the large number of neutral responses, which corresponds to being unable to reject the null hypothesis.

Even at full throttle, it takes me longer to perform the same task when using the hydraulics since switching to TxLED



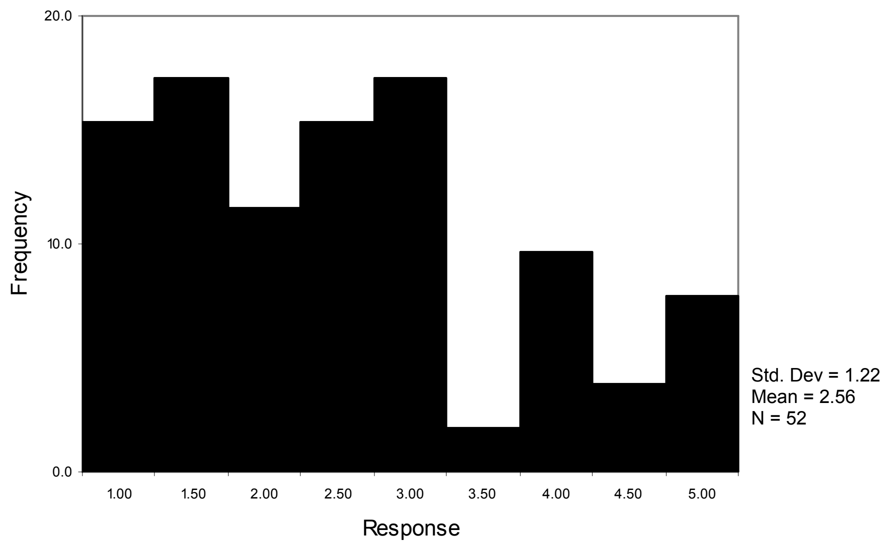
The above frequency diagram also displays a large number of neutral responses, though comparatively less than for previous questions. In this case, the one-sided z-test concluded that the mean is less than 3, indicating disagreement with the question. This implies that the operators did not perceive an impact in terms of the amount of time it took for operators to perform their usual tasks.

My vehicle/equipment is using more fuel since switching to TxLED



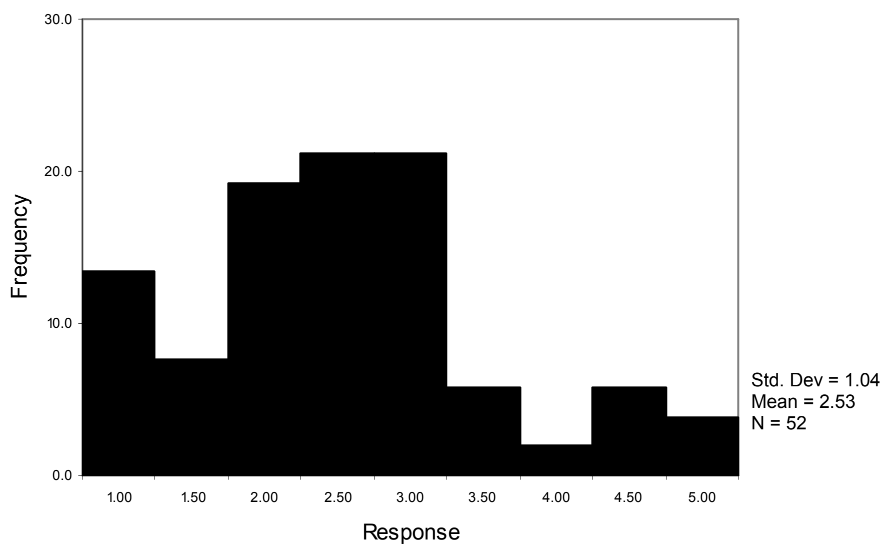
This is another situation in which the one-sided z-test concluded that the operators disagreed with the statement/question. It thus implies that the operators do not think that their vehicles were consuming more fuel since switching to TxLED.

I have asked a mechanic to check my vehicle/equipment more often since switching to TxLED



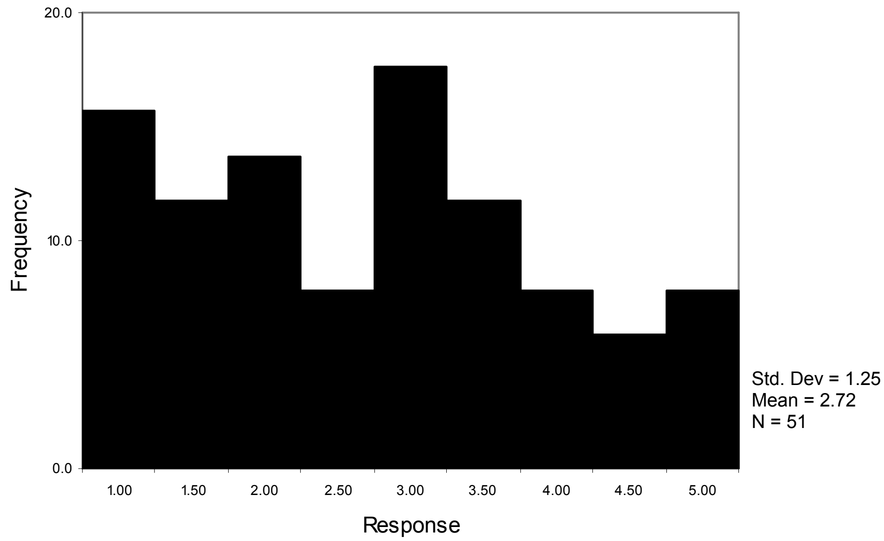
As can be seen in the frequency diagram above, most respondents disagreed with this statement. This finding asserts that the drivers/operators did not ask a mechanic to check their vehicles/equipment more often since beginning the use of TxLED.

I am able to do all of my usual tasks faster since switching to TxLED



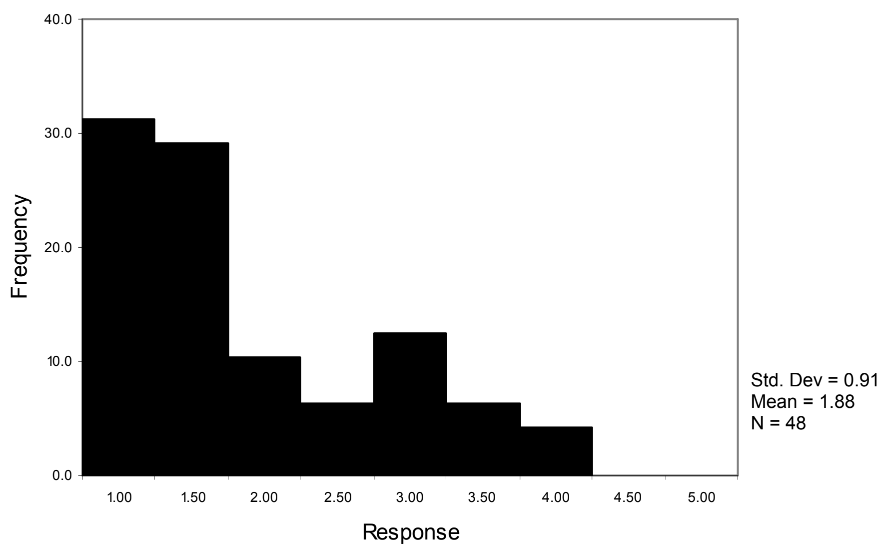
Most respondents also disagreed with this statement, which means that the drivers/operators did not notice an improvement in the speed with which they can perform their tasks.

The engine of the vehicle/equipment is noticeably noisier since switching to TxLED



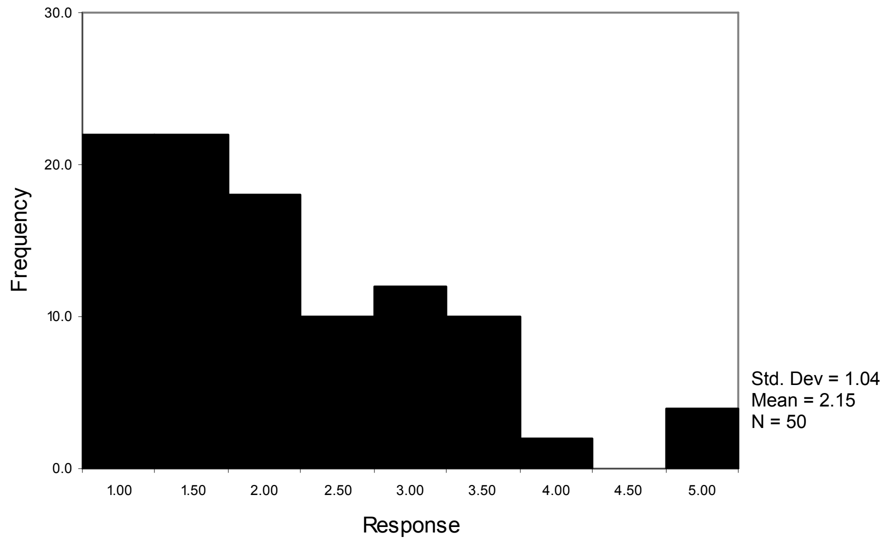
The statistical results to this question, while more difficult to discern in the frequency diagram, conclude that the operators had a neutral response to this question. Of the 51 responses, 30 were between 2 (somewhat disagree) and 4 (somewhat agree).

I suffer from more backaches, sore muscles, and headaches since switching to TxLED



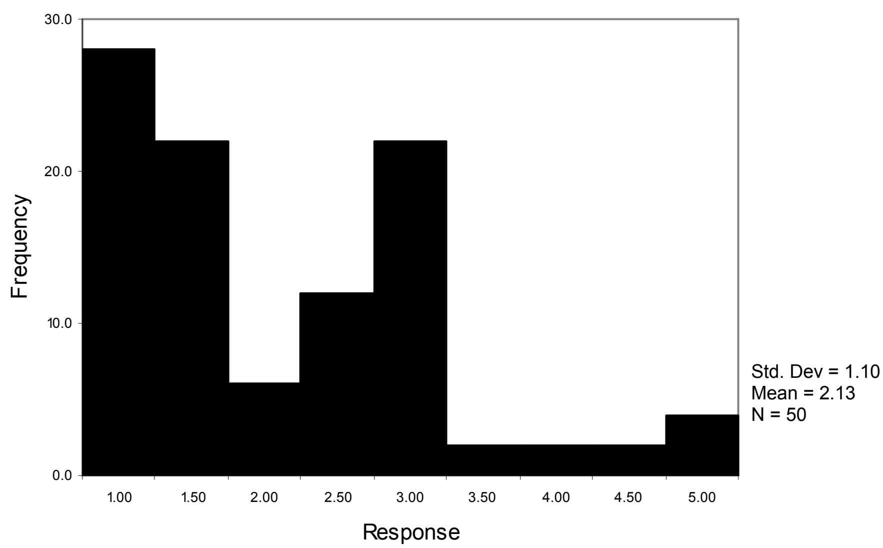
Most drivers/operators disagreed with this statement/question and thereby indicated that they do not suffer from any additional backaches, sore muscles, or headaches since switching to TxLED.

I changed my driving/operating behavior since switching to TxLED



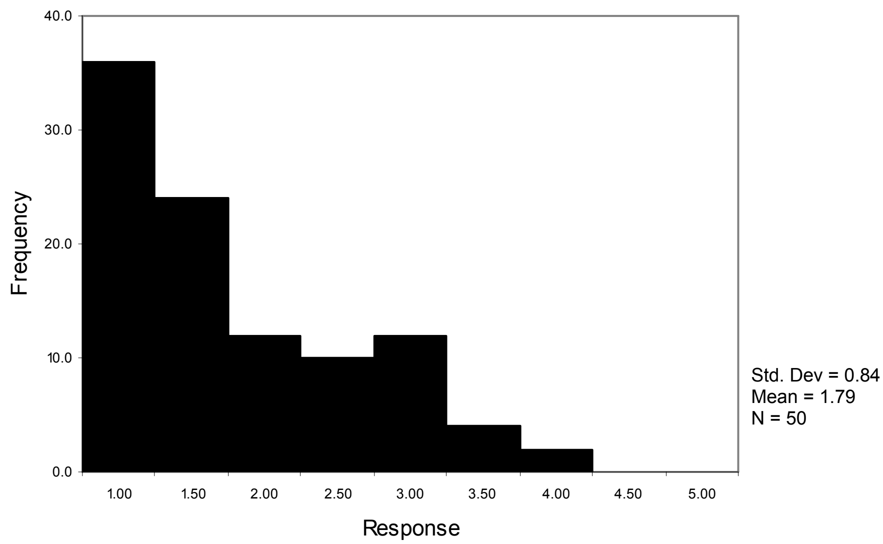
The responses to this question display a definite trend toward disagreement in the frequency diagram above. This is statistically shown as well, with the one-sided z-test concluding that the mean is less than 3. The drivers/operators surveyed, therefore, did not believe they have changed their driving behavior since switching to TxLED.

I am moving heavier loads since switching to TxLED



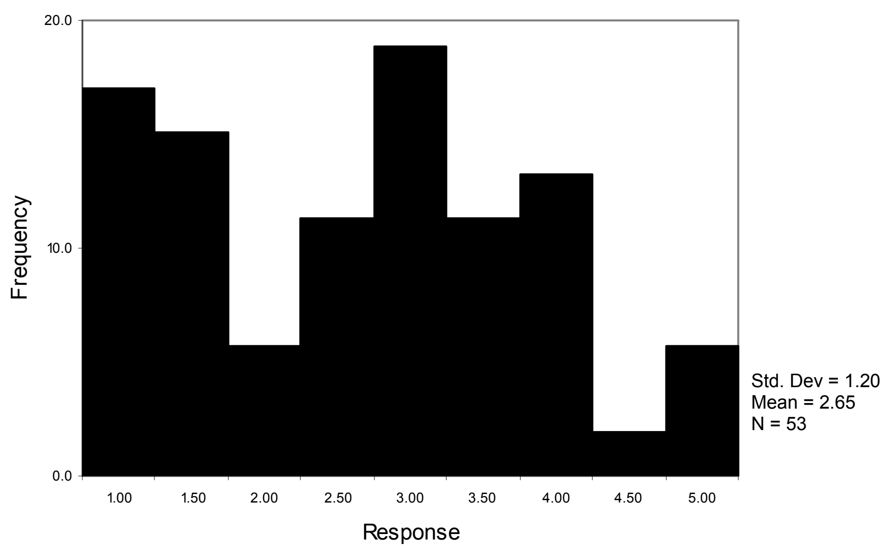
The responses to this question establish that the drivers/operators did not think that they have been moving heavier loads since switching to TxLED. This trend in the frequency diagram above is supported by the statistical analysis, which concludes that the mean is less than 3.

I experienced some of the following symptoms since switching to TxLED: runny nose, nausea, hair loss, or skin rash.



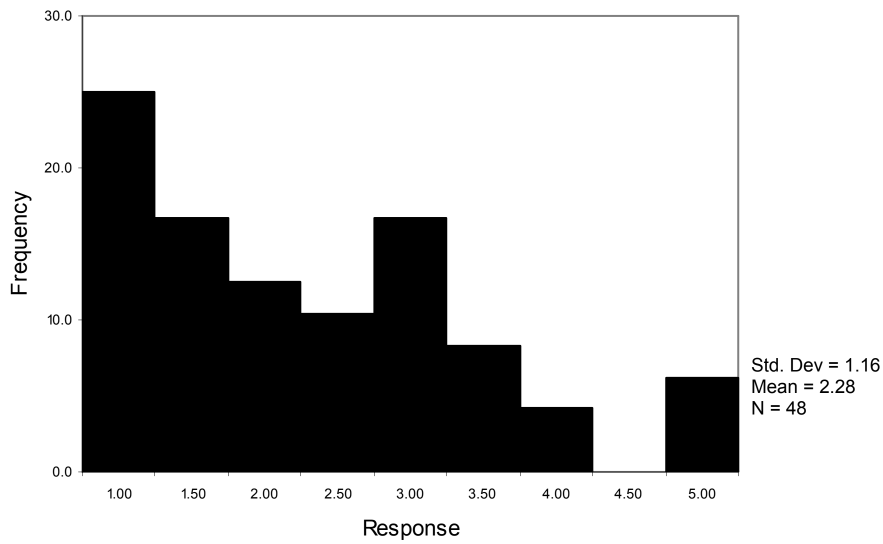
Again, strong disagreement from the drivers/operators in response to the question/statement regarding health issues arising since TxLED use began. The disagreement with this statement/question is statistically supported, with the z-test concluding that the mean is less than 3.

I noticed that my vehicle/equipment had less power since switching to TxLED



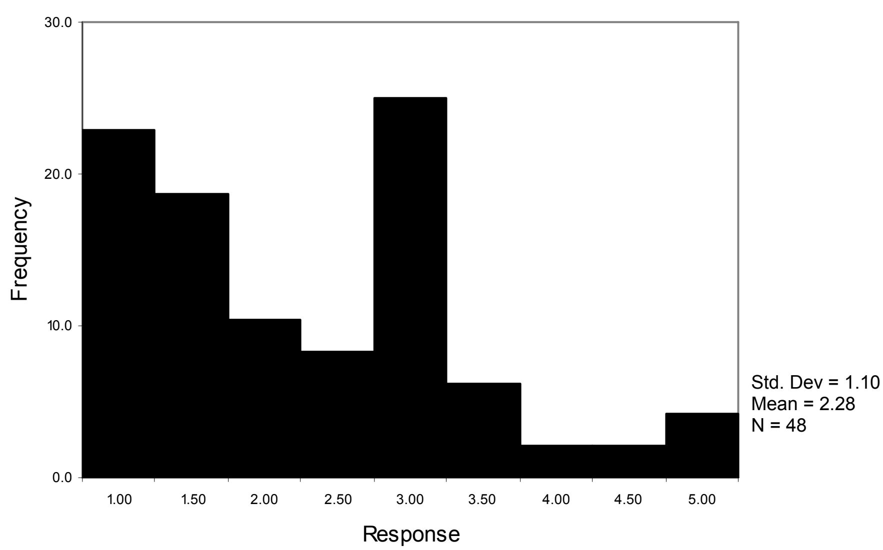
The two-tailed z-test for this question revealed that the operators had an overall neutral response regarding a power loss in their vehicle/equipment since switching to TxLED. In all, 36 of the 53 responses were in the range of 1 (disagree) to 3 (neutral).

I have problems starting my vehicle/equipment early in the morning since switching to TxLED



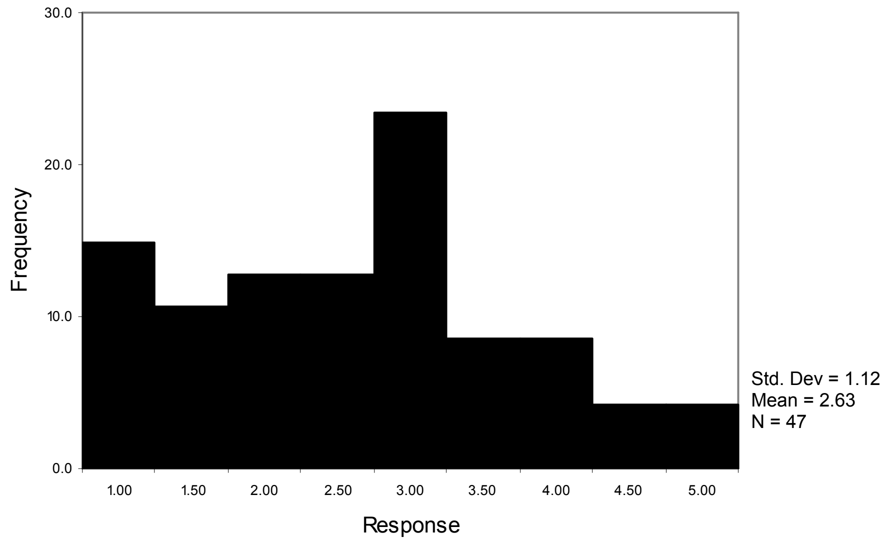
Again from the frequency diagram, it is evident that most drivers/operators disagreed with the statement that they experienced problems starting their vehicle/equipment early in the morning since switching to TxLED.

My vehicle is accelerating faster since switching to TxLED



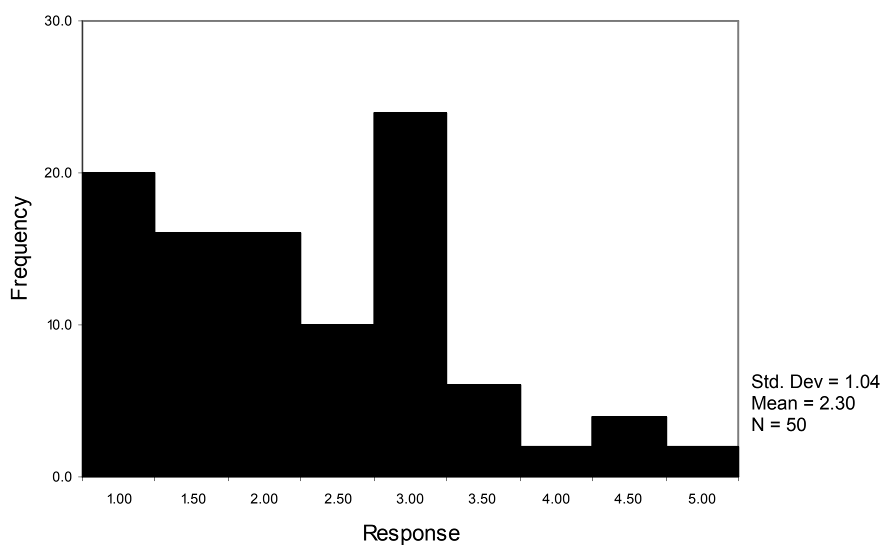
Drivers/operators disagreed that TxLED use improved the acceleration of their vehicles/equipment as is evident from both the frequency diagram and the z-test for this statement.

My vehicle/equipment smells better since switching to TxLED



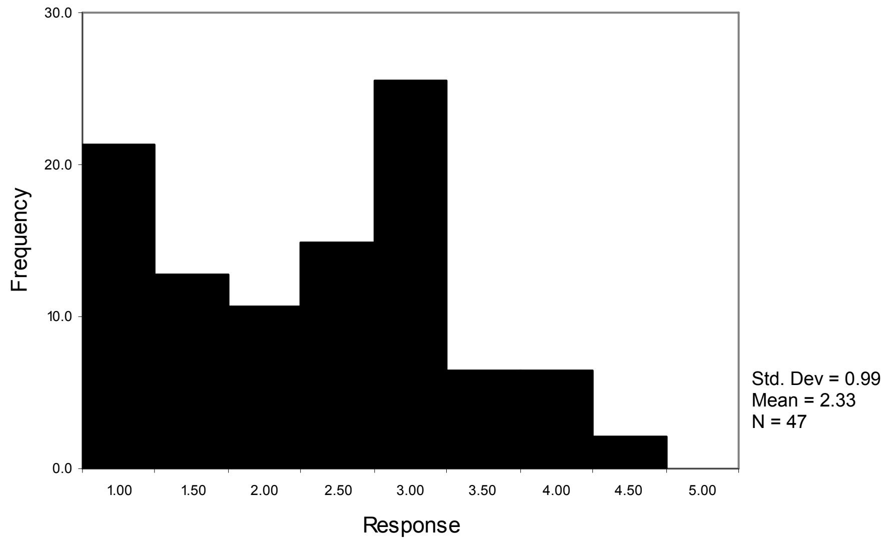
Most drivers/operators indicated a neutral response to this question. This implies that the drivers/operators did not notice a change in the smell of their vehicles/equipment since switching to TxLED.

I notice more smoke coming from my vehicle/equipment since switching to TxLED



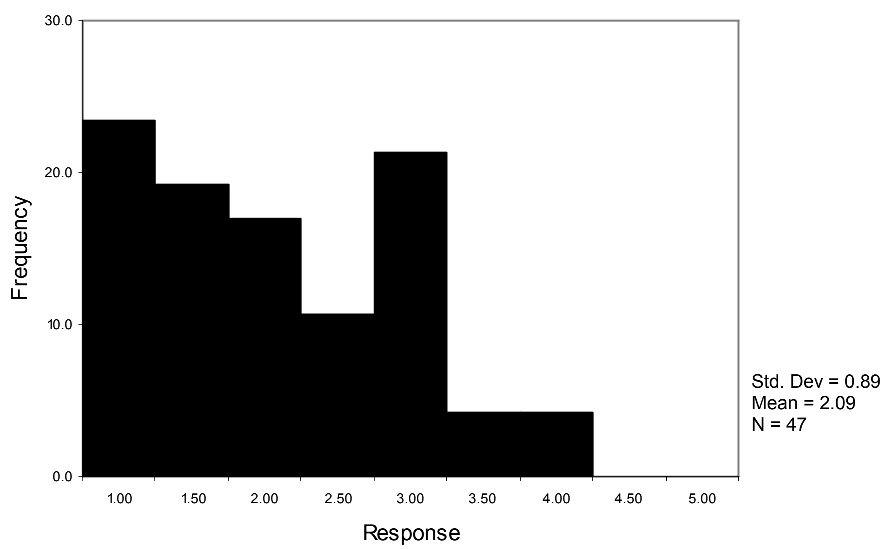
Again, drivers/operators tended to disagree with this statement/question, with 43 of the 50 responses being 3 or less.

I have to shift gears more often when doing my work since switching to TxLED



As illustrated in the frequency diagram above, 40 of the 47 operators responding to this statement were neutral or disagreed with the statement. Of the 47 responses, 21.3% strongly disagreed with this statement.

My vehicle/equipment is vibrating more since switching to TxLED



On this final question, 59.6% of the responses were 2 or less, indicating disagreement with the statement that vehicles/equipment vibrated more with TxLED relative to standard diesel.

Appendix C. Effects on Maintenance

The purpose of this appendix is to provide insight into the potential maintenance impacts of switching from the use of standard diesel fuel to TxLED. This section of the report begins with a description of the maintenance data collection procedure followed by a description of the data, a detailed analysis of the baseline year data, a detailed look at the TxLED year data, a discussion of the limitations of the data, a statistical analysis of the data, and finally a summary of the findings and recommendations.

C.1. TxDOT Maintenance Records

Maintenance records are kept in all TxDOT districts as part of their Equipment Operations System (EOS) database. This system maintains a history of all vehicle maintenance activities undertaken at the district and area maintenance shops. The EOS database requires all maintenance records to specify a "reason" code to aid in distinguishing different types of repairs. In this study, the fuel used was changed in the Dallas, Fort Worth, San Antonio, and Corpus Christi districts from standard diesel to TxLED. It was hypothesized that any maintenance impacts observed from switching to TxLED from standard diesel would surface in repairs involving the fuel system. Performing maintenance within TxDOT initiates the Repair Order (RO) process. The RO documents the problems a vehicle is experiencing, what maintenance was performed to correct the problem, and the amount of time invested in the repair. All ROs must state a "reason code" for proper input into the overall EOS database. The EOS reason code for fuel system maintenance is 027.

Fuel System ROs

The EOS database was queried for all fuel system ROs using reason code 027 in the four districts that switched to TxLED. It was assumed that the mechanics and operators that completed the RO forms provided an accurate reason code. A baseline year was established on a county-by-county basis as the year prior to the first delivery of TxLED in each county. Fuel system maintenance data was gathered for this baseline year to serve as a basis of comparison for TxLED-fueled maintenance needs in the TxLED year. The TxLED year was established on a county-by-county basis depending upon the distribution date of TxLED to each of the counties' maintenance shops. Table C.1 displays the TxLED distribution date for each of the counties within the four districts.

Table C.1 TxLED Distribution Date by District and County

Fort Worth		San Antonio	
Erath	7/14/2003	Bexar	3/20/2003
Johnson	7/14/2003	Atascosa	7/16/2003
Palo Pinto	8/7/2003	Bandera	7/14/2003
Parker	8/7/2003	Comal	7/9/2003
Somervell	9/10/2003	Frio	8/21/2003
Tarrant	7/15/2003	Guadalupe	7/9/2003
		Kerr	7/10/2003
Corpus Christi		Medina	7/10/2003
Alice	5/19/2003	Uvalde	7/18/2003
Beeville	5/19/2003	McMullen	6/18/2003
Goliad	5/29/2003		
Jim Wells	4/15/2003		
Karnes City	5/29/2003	Dallas	
Kleberg	4/15/2003	Kaufman	8/25/2003
Live Oak	4/15/2003		
Nueces	4/15/2003		
Sinton	7/11/2003		

Fuel System RO Categories

Once the fuel system ROs (EOS database reason code 027) were obtained, they were organized into categories based on the type of repair and/or problem stated on the RO form. Not all ROs, however, included this information and not all categorical information was complete. Nonetheless, the ROs were organized into the following four categories:

- Fuel Filters: This category includes the routine replacement of fuel filters. In many cases it appears that changing fuel filters is a preliminary step in diagnosing a fuel system problem. Changing fuel filters also often appears as a secondary task, i.e., when performing a more involved fuel system maintenance procedure a mechanic will change fuel filters as a preventative measure. This category of maintenance is preventative in nature, is a very common occurrence, and often accompanies other fuel system maintenance procedures. Because of the nature of fuel filter replacements, no in-depth analysis is undertaken.

- Fuel Leaks: This category is of primary importance to this study. The California Diesel Fuel Task Force Final Report (Diesel Fuel Task Force, 1996) reported that the concentration of aromatic carbon atoms in low-sulfur diesel fuel may cause an increase in fuel leaks due to a change in the swelling characteristics of O-rings and seals caused by the concentration of these atoms. Thefore, this category of fuel system maintenance is directly related to changing the type of fuel, and will require in-depth analysis.

- Other Maintenance (Defined): This category includes other fuel system problems that are less common yet are well defined in the ROs, such as issues with fuel pumps, fuel injectors, fuel injector pumps, fuel kill solenoids, fuel/water separators, and primer pumps. Because these repairs had to be aggregated to obtain a large enough sample size for analysis, specific component data was not analyzed; however, a general analysis on this category of repair was undertaken.

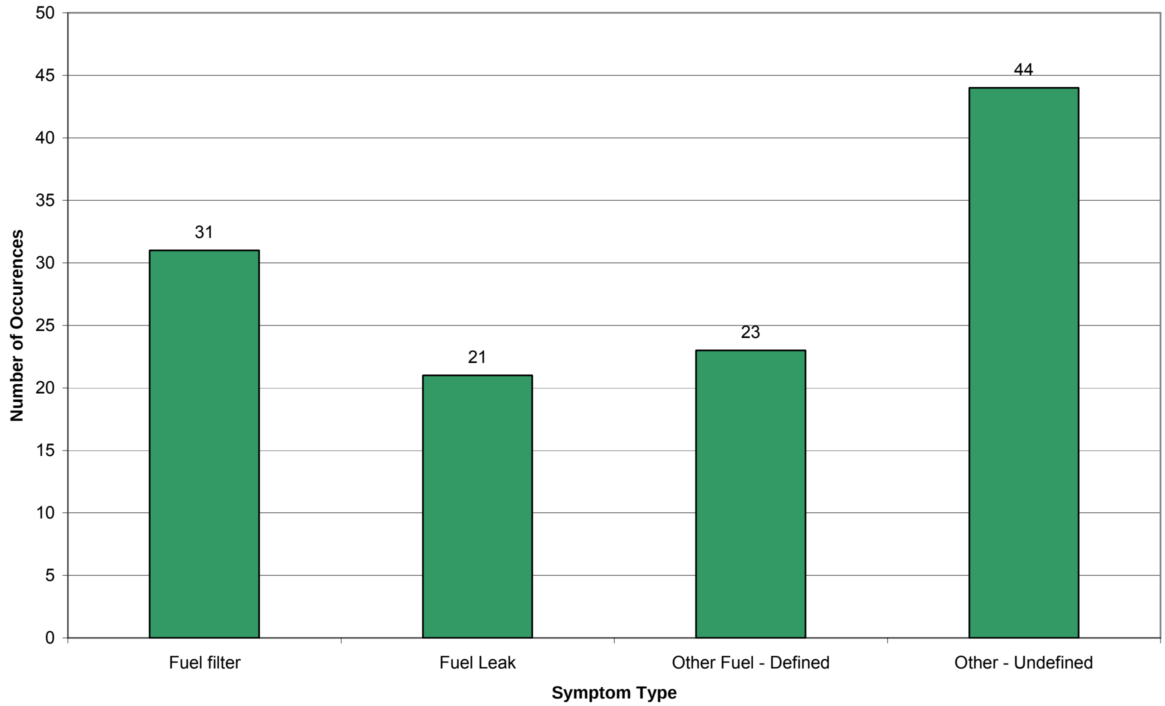
- Other Maintenance (Undefined): ROs falling into this category either do not have the specific fuel system problem stated or the problem stated is not regarded as a traditional fuel system maintenance activity (e.g., tire rotation, headlight replacement, and throttle cable replacement). These records provide either no information or ambiguous information and give little insight into the impact of TxLED usage on fuel system maintenance; therefore, this data was excluded from any further analysis.

Baseline Year Data

The fuel distribution dates listed in Table C.1 are used to determine the baseline (standard diesel) year for the four TxDOT districts. The baseline year was defined as the year prior to the date listed in Table C.1. It was assumed that the baseline year represents a typical maintenance year for the TxDOT fleet. This assumption implies that there were no large-scale changes to the fleet, maintenance procedures, or to the equipment used in maintaining the fleet. Extending this assumption to the subsequent TxLED year, it was assumed that the only significant change to the TxDOT fleet in these four districts was the switch to TxLED after the stated distribution date.

Figure C.1 displays a frequency diagram of the four categories of fuel system repairs. Out of the 119 total 027-coded ROs in the baseline year, the following percentages of fuel system repairs by category were observed:

- Fuel Filter–26%
- Fuel Leak–18%
- Other (Defined)–19%
- Other (Undefined)–37%



Note: Total of 119 ROs

Figure C.1. Number of Fuel System Repairs by Category in Base Year

Fuel leaks were of primary concern in this study with the result that the fuel leak data was scrutinized to a greater degree than the data for the other fuel system repair categories. It is useful to know not only that a certain number of fuel leaks occurred, but also the age of the vehicle experiencing the fuel leak, and the location/type of fuel leak experienced. Table C.2 summarizes the fuel leak data for the baseline year. As evident in Table C.2, many of the fuel leak ROs do not specify the location and/or type of fuel leak experienced. From the ROs that do specify the type of fuel leak, it appears that the most common location for fuel leaks is in the fuel lines.

Table C.2 Baseline Fuel Leak RO Details

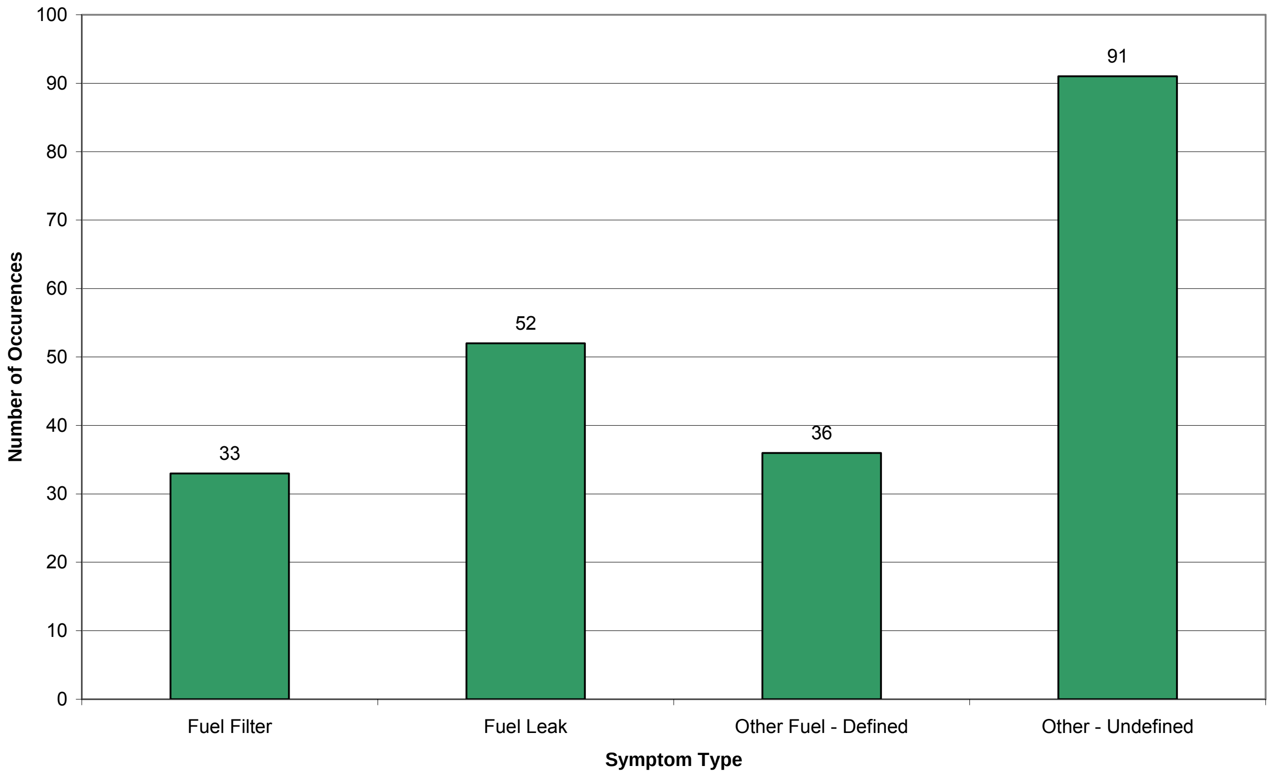
District	Equipment Number	Model Year	Repair Order Number	County	Initiation Date	Fuel Leak Type/Location
15	7600	1982	771235	Bexar	6/20/2002	Fuel Line
16	05071E	1991	826049	Kleberg	1/8/2003	Fuel Line
16	01697A	1997	842999	Karnes	3/19/2003	Fuel Line
16	05874G	1999	742612	Nueces	8/5/2002	Fuel Line and Fuel tank
16	05606D	1989	860732	Karnes	4/15/2003	Fuel Line, Seals & O-rings
2	2550	1987	961637	Tarrant	4/30/2003	Fuel Tank
2	05660D	1989	961785	Tarrant	4/8/2003	Injector Pump
15	03372G	1997	894056	Wilson	4/9/2003	Injector Pump
2	02159G	2000	802166	Tarrant	2/5/2003	N/A
15	2501	1986	992106	Uvalde	6/2/2003	N/A
15	1307	1989	958517	Uvalde	1/31/2003	N/A
15	05703E	1993	879314	Wilson	11/5/2002	N/A
15	05703E	1993	894535	Wilson	12/2/2002	N/A
15	03600G	1997	885097	Bexar	2/22/2003	N/A
15	01123A	1999	958508	Medina	1/7/2003	N/A
15	01123A	1999	958530	Medina	2/5/2003	N/A
16	6526	1985	842988	Bee	3/12/2003	N/A
16	02051C	1986	981430	Nueces	3/6/2003	N/A
16	1331	1990	770798	Karnes	11/25/2002	N/A
16	03352G	1997	882347	Refugio	12/6/2002	N/A
16	04435H	2001	895566	Nueces	2/19/2003	N/A

TxLED Year Data

Table C.2 depicts the TxLED county-specific distribution dates within the four districts using TxLED. As with the baseline dates, the different distribution dates resulted in different TxLED use time frames by the counties. This variable TxLED start date is adhered to on a county-by-county basis because of the anticipated impacts upon fuel system maintenance from TxLED use. The California Diesel Fuel Task Force (1996) reported that an increase in fuel leaks may be experienced with the implementation of a low-sulfur diesel fuel. It is hypothesized that fuel leaks will develop shortly after TxLED use begins and it is necessary to collect fuel system maintenance data as close to the TxLED distribution date as possible to identify any early fuel leaks.

Figure C.2 displays a frequency diagram of the four fuel system problems for the TxLED year. The following percentages of the 212 total fuel system ROs were observed for the four fuel system repair categories:

- Fuel Filter–16%
- Fuel Leak–25%
- Other (Defined)–16%
- Other (Undefined)–43%



Total of 212 ROs

Figure C.2. Number of Fuel System Repairs by Category in TxLED Year

In addition to an increase in fuel leaks, a noticeable increase in the total number of fuel system ROs is also apparent in Figure C.2, when compared to the baseline situation in Figure C.1. It should be noted, however, that the increase in the number of total fuel system ROs is accounted for by the Other (Undefined) category and the Fuel Leak category. The Other (Undefined) category's lack of specific information excludes the 91 ROs in that category from analysis. The remaining increase in total ROs is accounted for by the Fuel Leak category, which will be analyzed in more detail.

Table C.3 depicts more detail of the 52 fuel leak ROs during the TxLED year.

Table C.3 TxLED Fuel Leak RO Details

District	Equipment Number	Equipment Year	Repair Order Number	County	Fuel Leak Type/Location
15	09909D	1992	55178	Bexar	Compressor Engine
16	05426D	1989	135406	Live Oak	Fuel Filter
2	1650A	1995	5128	Johnson	Fuel Line
15	2529	1986	985949	Bexar	Fuel Line
15	01004G	2000	972939	Bexar	Fuel Line
15	2518	1986	140517	Comal	Fuel Line
2	6012A	1996	17806	Tarrant	Fuel Pump
2	6141G	2001	6197	Tarrant	Fuel Pump
2	6180G	2002	16516	Tarrant	Fuel Pump
15	03836G	1997	993496	Comal	Fuel Pump
15	02012D	1990	974773	Guadalupe	Fuel Pump
16	6849	1989	50104	Beeville	Fuel Pump
16	1402	1992	975608	Beeville	Fuel Pump
18	6716A	1994	37013	Kaufman	Fuel Pump
2	8367E	1987	528196	Tarrant	Injector
16	6910	1990	973266	Kleberg	Injector
2	8367E	1987	528183	Tarrant	Injector Drain Line
2	4147E	1990	16544	Johnson	Injector Pump
15	04747E	1990	993453	Bexar	Injector Pump
15	05706E	1993	974735	Bexar	Injector Pump
15	2518	1986	68781	Comal	Injector Pump
15	05634D	1989	994533	Frio	Injector Pump
15	04427H	2001	994852	Guadalupe	Injector Pump
16	2794D	1980	48304	Goliad	Injector Pump
16	2794D	1980	70937	Goliad	Injector Pump
16	2039D	1990	50103	Beeville	Injector Pump
16	6909	1990	970554	Live Oak	Injector Pump
15	1309	1989	989183	Bexar	Injector Pump and Lift Pump
2	1390	1992	6077	Somervell	Transfer Pump
2	9830G	2002	924195	Tarrant	Transfer Pump
16	1404	1992	977012	Jim Wells	Transfer Pump
16	1476	1994	77963	Kleberg	Transfer Pump
2	6137	1984	6105	Tarrant	N/A
2	2363	1984	929786	Tarrant	N/A
2	5447D	1989	6248	Tarrant	N/A
2	1991	1991	925046	Tarrant	N/A
2	6102B	1993	6150	Tarrant	N/A
2	6846A	1998	34191	Tarrant	N/A

Table C.3 TxLED Fuel Leak RO Details *(continued)*

District	Equipment Number	Equipment Year	Repair Order Number	County	Fuel Leak Type/Location
15	2501	1986	992139	Uvalde	N/A
15	04304F	1995	994864	Bexar	N/A
15	03601G	1997	974989	Bexar	N/A
15	05531G	1999	985893	Bexar	N/A
15	04382H	2001	994869	Bexar	N/A
15	04426H	2001	994893	Bexar	N/A
16	2116C	1986	133865	Nueces	N/A
16	1332	1990	977114	Goliad	N/A
16	09804E	1992	20439	Kleberg	N/A
16	2945	1992	69302	Nueces	N/A
16	09804E	1992	971326	Kleberg	N/A
16	05924G	2000	49250	Nueces	N/A
16	05924G	2000	133829	Nueces	N/A
16	5926G	2000	971444	Alice	N/A

Table C.3 displays an important aspect of the fuel leak locations of TxLED-fueled vehicles. Fourteen of the 52 (27%) total fuel leaks involved the injectors in some manner while 11 of the 52 (21%) involved the injector pump specifically. When the fuel leaks with no type or location information are excluded, 14 of the 32 ROs (44%) involve the injectors and 34% involve the injector pump specifically. When compared to the baseline condition in which 2 of 21 total ROs (10%) or when non-specific ROs are excluded, 2 of 8 (25%) ROs involve injector pumps. The TxLED-fueled vehicles seem to experience a higher rate of fuel leaks in the injector and injector pump components specifically.

<u>Statistical Analysis of Fuel Leaks</u>

Limitations of Fuel Leak Data

There are inherent limitations to the data collected for this study. Because data was collected for only one baseline year and one TxLED use year, there is no variance or standard deviation associated with the fuel leak RO counts. Without a measure of variance, no distribution of the number of fuel leaks on a yearly basis is known. A single count of yearly fuel leaks does not provide enough information to confidently state whether the increase in observed fuel leaks during the TxLED year is statistically significant. There is no way of knowing whether the baseline and TxLED count would fall near the mean of the yearly fuel leak distribution or at one of the tails of the distribution. Restated, from the available data it is not possible to determine or estimate the number of fuel leaks that would occur in subsequent years with either TxLED or conventional diesel fuel using conventional analysis of variance (ANOVA) computations.

Fuel Leak Distribution Relative to Fleet

It is possible to determine whether the number of fuel leaks relative to the total number of vehicles in the fleet changes significantly with the introduction of TxLED by the four study districts. Table C.4 displays the fuel leak distribution in a 2x2 matrix for conventional diesel and TxLED relative to the total four district fleet.

Table C.4 Fuel Leak Distribution Relative to Fleet Size

	Conventional Diesel	TxLED	Total
Leaks	21	52	73
No Leaks	1926	1895	3821
Total	1947	1947	3894

Intuitively, more than doubling of the number of fuel leaks would seem a significant change regardless of the relative percentage of the vehicle fleet experiencing fuel leaks. The Chi-Square analysis supports this intuition, as the resulting Chi-Square value is 13.42. This value is much greater than the 3.84 needed to reject the null hypothesis at a 95% confidence level with one degree of freedom. The null hypothesis, in this instance, is that the conventional Diesel and TxLED fuel leak distributions are from the same population distribution. A significant Chi-Square value allows us to reject the null hypothesis and state that the two fuel's fuel leak distributions are significantly different. In this case, the difference implies that TxLED-fueled vehicles tend to experience more fuel leaks than conventional diesel-fueled vehicles relative to the fleet.

This finding is statistically significant; however, the practical importance of such a finding is debatable. Fuel leaks, as a percentage of the fleet, only rose from about 1% of the fleet to 3% of the fleet. This is a marginal increase not likely to have a large financial or temporal impact on the TxDOT maintenance shops. The contingency coefficient calculation, which is a measure of the relationship of the occurrence of leaks and the type of fuel used in the vehicle, speaks to the practical importance of the result. The contingency coefficient, C, for this analysis is 0.05. This number is computed using the Chi-Square value calculated above, so the coefficient is significantly different than zero, but in terms of magnitude the relationship between the two variables is not large.

Time Frame Reduction for ANOVA

The baseline and TxLED year data can be broken into smaller time frames in an effort to fabricate a measure of variance to perform ANOVA to determine if the change in the number of fuel leaks is significant on a leaks/quarter basis. Table C.5 shows the fuel leak count for both types of fuel broken into quarters. There is an obvious difference in the amount of fuel leaks per quarter between the two fuel types; TxLED averages around 10 leaks per quarter while conventional diesel averages about 5. With only four quarters and a small amount of fuel leaks per quarter, the variance is high and it is unlikely that the two distributions will be significantly different at the $\alpha = 0.05$ level. Table C.6 displays the results of running one-way ANOVA on the data set, using the computer program SPSS. However, the high variance of the quarterly fuel leaks prohibits the change in quarterly fuel leaks from being significant at the 95% confidence level, though the difference is significant for an $\alpha = 0.07$, or 93% confidence level.

Table C.5 Fuel Leak Counts by Quarter for Each Fuel Type

Quarter	Baseline	TxLED	Total
1	0	7	7
2	7	21	28
3	5	13	18
4	9	11	20
Total	21	52	73

Table C.6 ANOVA Results of Quarterly Fuel Leaks

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	120.125	1	120.125	4.845	.070
Within Groups	148.750	6	24.792		
Total	268.875	7			

Age Analysis

The Diesel Fuel Task Force Final Report (1996) states that older vehicles (i.e., measured in years, miles, or hours) tend to experience more fuel leaks than newer vehicles. This increase may be due to the swelling properties of older O-rings and seals, commonly made of nitrile rubber, when exposed to low-sulfur diesel fuel. It is then hypothesized that the percentage of older vehicles will be higher in the sample of fuel leak vehicles than the percentage of older vehicles found in the TxDOT fleet in the San Antonio, Dallas, Corpus Christi, and Fort Worth Districts.

According to the EOS database, there are 1,947 diesel fueled vehicles in the four TxLED districts. Their age distribution is shown in Figure C.3. The age distribution of the TxLED fuel leak vehicles is shown in Figure C.4. While differences exist in the particular age categories, 67% of TxLED fuel leak vehicles are 3–15 years old; 67% of the TxDOT fleet is in the same age range. This striking similarity implies that it may be unlikely that any significant difference will be found statistically.

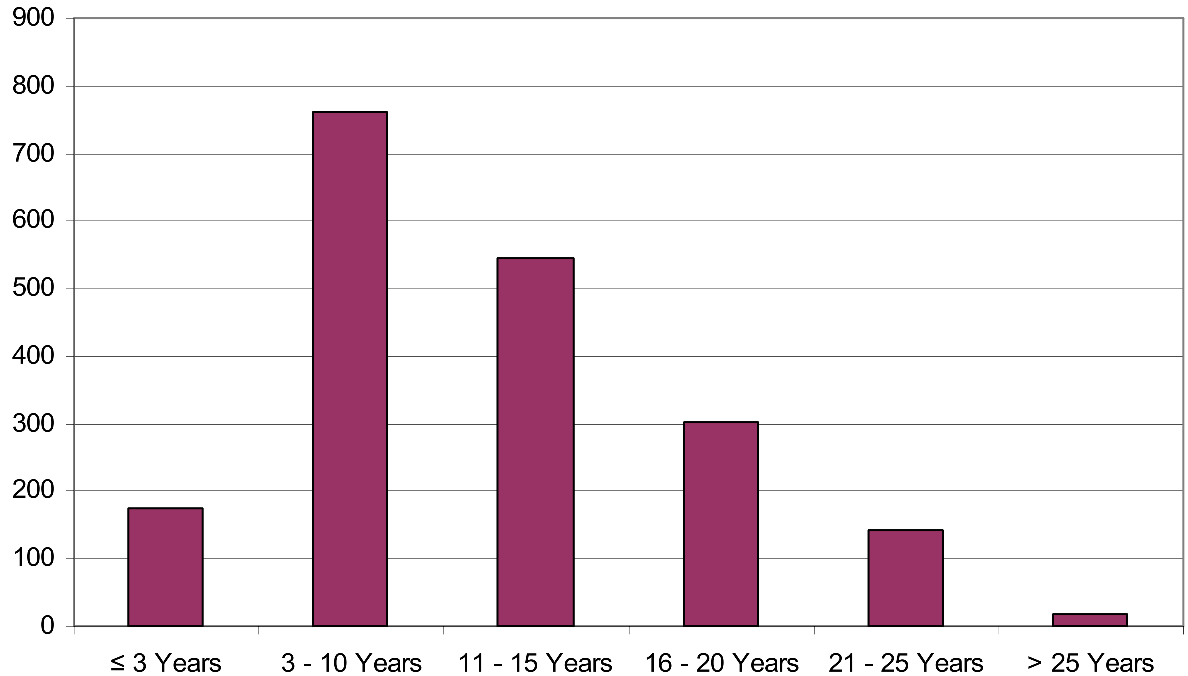


Figure C.3. TxDOT Districts 2, 15, 16, and 18 Age Distribution

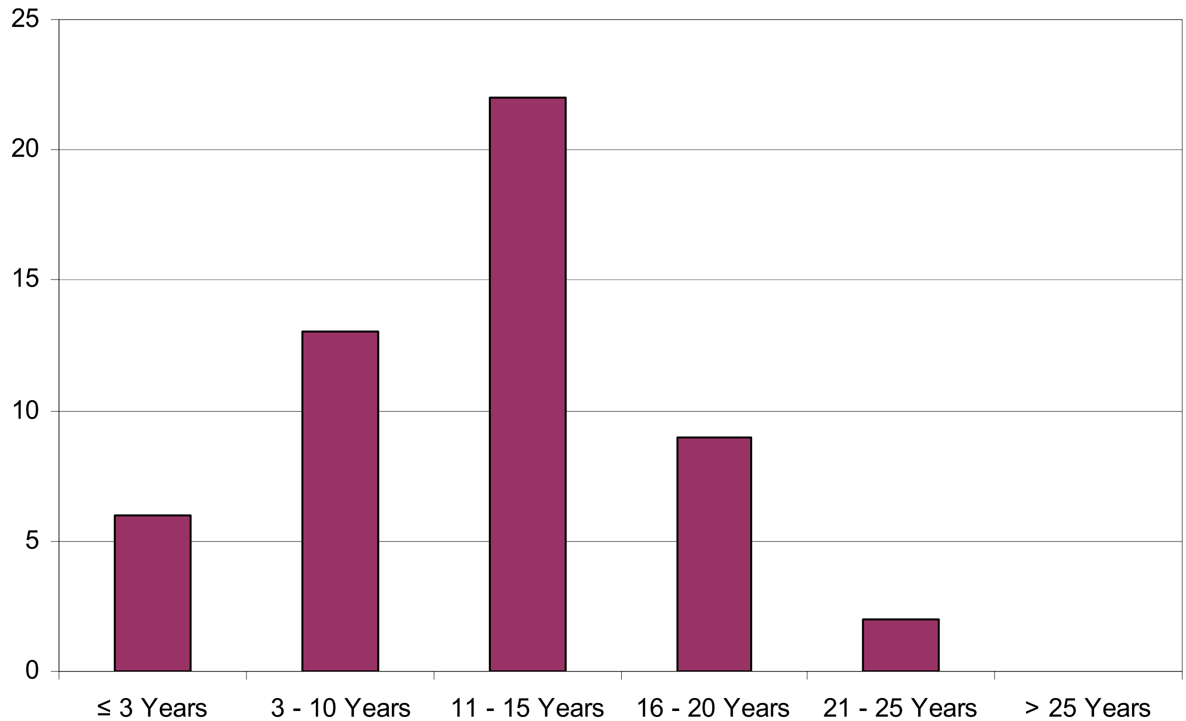


Figure C.4. TxLED Fuel Leak Vehicle Age Distribution

The hypothesis regarding age as a percentage, or distribution of the ages of the vehicles across a particular sample of vehicles will be tested using the Chi-Square test in conjunction with a Contingency Coefficient analysis. The data for TxLED fuel leak vehicles and the TxDOT fleet are set up in a 2x2 matrix as shown in Table C.7. Three years was used to distinguish between new and old vehicles.

Table C.7 Age Comparison of TxLED Fuel Leak Vehicles and TxDOT Fleet

Age (years)	TxLED	Fleet	Total
≤3	6	176	182
>3	46	1771	1817
Total	52	1947	1999

An initial investigation of the data in Table C.6 provides overwhelming evidence that the distribution of fuel leak vehicles and the TxDOT fleet are essentially the same. Looking at new vehicles (≤ 3 years), it can be seen that approximately 10% of the total fuel leak vehicles are new, and approximately 10% of the TxDOT District 2, 15, 16, and 18 fleets are new. This suggests that it will be unable to reject the null hypothesis used in Chi-Square testing; the two samples are from the same population distribution. The Chi-Square analysis results in a value of 0.38 with one degree of freedom. This result means that there is a high probability that any difference in the sample distributions is due to chance alone. Also, this means that any contingency coefficient analysis would provide no significant insight. Any relationship strength implied by the contingency coefficient would have an equal chance of being zero since the coefficient is calculated using the Chi-Square value which in this case, is insignificant.

In addition to the comparison of TxLED-fueled vehicles to the TxDOT fleet, a comparison was made to the conventional diesel fueled vehicles in the baseline year. Table C.8 displays the matrix used for Chi-Square analysis. It appears from the table that the TxLED-fueled vehicles tend to experience more fuel leaks than conventional diesel fueled vehicles. This is a reasonable expectation as vehicles that are designed for conventional diesel fuel would be expected to experience more fuel leaks. Changing the chemical makeup of the fuel used in the vehicles is therefore likely to produce fuel leaks among a wider age range as even the newer vehicles are not all designed with low-sulfur diesel fuel in mind.

Table C.8 Age Comparison of TxLED and Conventional Diesel Fuel Leak Vehicles

Age (years)	TxLED	Conventional Diesel	Total
≤3	6	1	7
>3	46	20	66
Total	52	21	73

The Chi-Square statistic resulting from the analysis is 0.79, far less than the 3.84 required to declare a significant finding at a 95% confidence level. This contradicts intuition and can likely be explained by the sample sizes being evaluated.

Usage Analysis

The usage of the TxDOT diesel fleet is measured by either an odometer or an hourmeter. The usage data provided in the EOS database is total usage over the life of the vehicle. Dividing this life usage number by the age of the vehicle gives an average yearly usage over the life of each vehicle. This number is a measure of the utilization of the vehicle. In this section of the study, the hypothesis to be tested is: due to the wear and tear of frequent use, vehicles having a high yearly usage will tend to have more fuel leaks. This analysis is carried out by comparing the distribution of fuel leak vehicle yearly usage with the TxDOT four-district fleet usage.

A 2x2 Chi-Square and contingency coefficient analysis is carried out for both hourly and mileage vehicles. Values of 500 hours/year and 10,000 miles/year were selected to distinguish between high usage and low usage vehicles. After the separate hourly and mileage analysis, the two will be combined to compare high and low usage vehicles in one analysis.

Analysis was also performed comparing the usage distribution of TxLED and conventional diesel fueled vehicles. Of the conventional diesel fuel vehicles, 10 had usage measured in miles, 11 were measured in hours. Of the 10 measured in miles, 7 were used 10,000 or fewer miles per year. All of the hourly vehicles were used under 500 hours per year. A Chi-Square statistic was computed for both the hourly and mileage vehicles in comparison with TxLED-fueled vehicles. Neither comparison yielded a significant result at the 95% confidence level.

Hourly Vehicles

The analysis of the vehicles with usage measured in hours/year begins by constructing the 2x2 table to be used in the Chi-Square and contingency coefficient (if warranted) computations. The matrix used in the analysis is shown in Table C.9. It appears that as with age, the distribution of vehicle usage for TxLED fuel leak vehicles is very similar to the TxDOT fleet. Of the TxLED vehicles, 91% are used 500 or fewer hours per year. In the TxDOT fleet, 88% of the hourly measured vehicles are used 500 or fewer hours per year.

Table C.9 Hourly Usage Comparison of TxLED Fuel Leak Vehicles and TxDOT Fleet

Usage (Hours)	TxLED	TxDOT Fleet	Total
≤ 500	29	1000	1029
> 500	3	138	141
Total	32	1138	1170

As expected, the Chi-Square analysis on the data in Table C.9 provided a very low value of 0.22 with one degree of freedom which is much less than the 3.84 to declare a significant finding at the 95% confidence level. Therefore, any difference in the distribution of high and low usage vehicles between TxLED fuel leak vehicles and the TxDOT fleet is likely due to chance alone.

Mileage Vehicles

The analysis undertaken for vehicles with usage measured in miles/year is identical to that for hourly measured vehicles. The table used for the Chi-Square and contingency coefficient analysis is shown in Table C.10.

Table C.10 Mileage Usage Comparison of TxLED Fuel Leak Vehicles and TxDOT Fleet

Usage (Miles)	TxLED	TxDOT Fleet	Total
≤ 10,000	8	543	551
> 10,000	12	266	278
Total	20	809	829

Vehicles with usage measured in miles/year exhibit a much different trend than the hourly vehicles. From Table C.10, only 40% of the TxLED fuel leak vehicles are used less than 10,000 miles per year, while vehicles used less than 10,000 miles per year account for 67% of the TxDOT fleet that has usage measured in miles. Intuitively, it seems likely that such a large difference will be significant. When analysis is carried through, this intuition is reinforced by a Chi-Square value of 6.44 with one degree of freedom, indicating a significant difference in the distributions at a 95% confidence level. The contingency coefficient, C, is then calculated using this significant Chi-Square value, resulting in $C = 0.08$. This indicates a small yet significant relationship between usage and the vehicle sample.

These results would indicate that vehicles with usage less than 10,000 miles per year are less likely to develop fuel leaks and are a good candidate for TxLED use. During the baseline year, 7 vehicles used less than 10,000 miles per year experienced fuel leaks, one more vehicle than during the TxLED year. While this does not indicate that a reduction in fuel leaks would be experienced through continuation of TxLED use, it intuitively implies that a significant increase in fuel leaks in vehicles used 10,000 miles per year or less, between TxLED and conventional diesel fueled vehicles, is unlikely.

Assuming that the majority of vehicles with usage measured in miles are on-road vehicles, those that are used less than 10,000 miles per year are good candidates for continued TxLED use, with respect to the rate of fuel leak occurrence. These vehicles account for 543 out of 1,947 vehicles (28%) in the four districts in this study, which may yield a significant contribution to NOx reduction without an increase in fuel leaks.

General Usage

The final usage analysis includes both hourly and mileage measured vehicles in the same table, divided as in the previously analysis at 500 hours and 10,000 miles, respectively into "low usage" and "high usage" categories. The data used in the analysis is shown in Table C.11. A significant difference seems unlikely in this case as 69% of the TxLED fuel leak vehicles fall into the low usage category and 79% of the TxDOT fleet falls into the same category.

Table C.11 Usage Comparison of TxLED Fuel Leak Vehicles and TxDOT Fleet

Usage (Miles)	TxLED	TxDOT Fleet	Total
Low Usage	37	1543	1580
High Usage	15	404	419
Total	52	1947	1999

Completing the calculations verifies the intuition that the difference in the distribution of the vehicle samples in the usage categories is not significant. A Chi-Square value of 2.00 with one degree of freedom results—less than the 3.84 necessary to declare a significant finding at the 95% confidence level.

Analysis of Fuel Leaks Reported by District

Though TxDOT does require similar maintenance reporting procedures be used across all TxDOT districts, the human factor makes enforcing identical diagnosis and communication of fuel system problems impossible. Each mechanic and operator has a distinct set of experiences that will cause many maintenance problems to be diagnosed and treated differently by different mechanics, especially ones working in very separate geographic locations. Table C.12 displays the number of fuel leaks and the number of other maintenance problems experienced at each district. A Chi-Square test was used to test the null hypothesis that the distribution of fuel leak diagnosis in each district is in line with the overall number of fuel system maintenance problems reported. This test was done to investigate whether a specific district has a higher tendency to report fuel leaks, or if a particular district is experiencing a higher number of fuel leaks.

Table C.12 Fuel Leak and Other Fuel System Maintenance Distributions by District

Location	Fuel Leaks	Other Fuel System ROs	Total
Dallas	18	90	108
San Antonio	28	58	86
Fort Worth	26	88	114
Corpus Christi	1	3	4
Total	73	239	312

The result of the Chi Square analysis, a value of 6.78, for the data in Table C.12 is insignificant at a 95% confidence level with three degrees of freedom. It was therefore unable to reject the null hypothesis, meaning, the fuel leak distribution and the other fuel system maintenance distribution experienced at each district appear to be derived from the same population distribution. Therefore, no specific district seems to be reporting or experiencing an unusual number of fuel leaks compared to the other districts.

Fuel System Component Analysis

The Diesel Task Force (1996) reported that any increase in fuel leaks will likely involve the seals and O-rings within the fuel system. A particular component scrutinized in this study for an increase in fuel leaks was the fuel injector pumps, because of the number of rubber O-rings used to seal diesel fuel injection pumps. As previously noted there was an increase in the number of fuel leaks experienced in the injection system with the use of TxLED. Table C.13 depicts the distribution of fuel leak locations in a 2x2 matrix. Limitations of Chi-Square analysis require that no cells in the matrix have a count of less than one, therefore the data in Table C.13 is aggregated into two categories: fuel injection system, and other. This data only takes into account those fuel leaks that had a location specified; the “N/A” locations are not included in this distribution or analysis.

Table C.13 Fuel Leak Location Distributions

Component	Conventional Diesel	TxLED	Total
Injection System	2	14	16
Other	6	18	24
Total	8	32	40

The analysis provided an insignificant Chi-Square value of 0.94, much less than the 3.84 required to have a significant finding at the 95% confidence level with one degree of freedom. It was therefore unable to reject the null hypothesis. The distribution of fuel leak locations for conventional diesel and TxLED appear to be derived from the same population distribution, implying that any increase in fuel leaks experienced is not significantly component specific.

Analysis of Other—Defined Maintenance Problems

Analysis similar to that of the fuel leak vehicles was undertaken for maintenance problems that were defined in the EOS database, excluding fuel leaks and fuel filter changes. An investigation into the significance in the increase of other-defined maintenance issues yielded an insignificant result. The number of other-defined maintenance problems was analyzed as a percentage of the fleet for conventional diesel and TxLED-fueled vehicles. The Chi-Square statistic resulting from this analysis is 2.91, less than the 3.84 required for a significant finding at the 95% confidence level with one degree of freedom. Therefore, it was unable to reject the null hypothesis that the distribution of other-defined maintenance problems are from the same overall population. This means, changing fuels did not significantly change the distribution of other-defined maintenance problems within the TxDOT fleet.

Summary

The purpose of this section was to investigate the impact of switching to TxLED from conventional diesel fuel in the TxDOT districts of Fort Worth, Dallas, San Antonio, and Corpus Christi. One year of maintenance data for each type of fuel was collected for analysis. Anecdotal evidence suggested that an increase in fuel leaks may be experienced, especially in older vehicles, and often involving the fuel injectors and injector pumps. Having only one year of data for each fuel type limited the scope of the analysis. It did not allow for a distribution of maintenance activities to be developed and rendered it impossible to determine whether the counts experienced in the two data collection years were near their respective population means, or if they are unusual happenings. This limitation made an analysis of variance, to determine whether the number of fuel leaks in each scenario were significantly different, infeasible. Because no distribution of leaks existed, no variance existed.

However, an analysis of the distribution of the fleet experiencing fuel leaks did uncover a significant finding: the distribution of TxDOT vehicles experiencing fuel leaks was significantly different between conventional diesel and TxLED-fueled vehicles. This finding implies that while it was not possible to determine the distribution of annual fuel leaks and thus, the significance of the difference in magnitude of fuel leaks between conventional diesel and TxLED; the increase in fuel leaks did cause a significant change in the distribution of fuel leaks relative to the TxDOT fleet. This further implies that the increase in fuel leaks is significant.

Though the increase in fuel leaks can be interpreted as statistically significant, the practical importance of the finding is debatable. The percentage increase of the TxDOT fleet, in the four study districts experiencing fuel leaks, is approximately 2%. This is a marginal change that will incur additional costs, though those costs may be transitional in nature. It is possible that the number of fuel leaks experienced in this first year of TxLED use will experience a reduction as the fleet's leaking vehicles are repaired.

Analysis was performed investigating several other facets of the data involving the age and usage. The only significant finding was that low use (≤ 10,000 miles/year) vehicles, with usage measured in miles, tend to have fewer fuel leaks than higher usage vehicles when compared to the distribution of low and high usage vehicles in the TxDOT four district fleets. These may be assumed to be mostly on-road vehicles and account for 28% of the TxDOT diesel fleet in the four districts. The remainder of the analysis regarding age and usage resulted in insignificant findings, leading to the conclusion that with the one exception, there is no significant difference in fuel leak distribution depending upon age and usage.

Other analysis undertaken involved the TxDOT districts reporting fuel leaks on TxLED-fueled vehicles and the locations of fuel leaks in the vehicles. Neither of these analyses provided significant findings, implying that the distribution of fuel leaks among other maintenance problems is the same across all of the study districts. Additionally, the distributions of fuel leak locations relative to the fuel types are from the same population distribution, meaning that any increase in fuel leaks is not component or location specific.

Other maintenance problems were also investigated in a manner identical to fuel leaks. These other maintenance problems were aggregated into one category because of the relatively infrequent occurrence of the problems. These problems included problems with fuel pumps, fuel injectors, fuel injector pumps, fuel kill solenoids, fuel/water separators, and primer pumps. None of the analysis undertaken for other maintenance problems returned significant results. This indicates that there is no relationship between fuel leaks and either age or usage for the other maintenance problems.

C.2. Corrosion

TxLED was investigated as part of a broad study that examined alternative fuels to replace conventional 2D on-road diesel fuel in equipment and trucks operated by TxDOT. This subsection is a summary of conclusions from corrosion tests conducted to study material compatibility. Conventional 2D diesel was used as the basis for comparison. Some results from tests using PuriNOx, another alternative diesel fuel examined in the initial part of this study, will also be included for comparison.

Figure C.2.1 shows a photograph of TxLED and PuriNOx, illustrating the difference in appearance of the two fuels. PuriNOx is an emulsified fuel, containing about 20% water and an additive package, whereas TxLED is not emulsified. Separation is a phenomenon that occurs in PuriNOx and seems to have a significant effect on its corrosion behavior. TxLED does not exhibit separation.

Figure C.2.1. Photograph of a steel specimen in summer-grade PuriNOx (left) and TxLED (right)

C.2.A. Experimental Procedure

Planned interval tests and electrochemical tests were carried out to study the corrosion behavior of steel specimens in diesel fuels. Strips of 1018 steel were used. Planned interval tests involve immersing several sets of specimens in electrolyte solutions, for various periods of time, to determine changes in the alloy corrodibility and solution corrosivity, based on specimen weight changes. In this case, increments of 10 days were chosen for the period of exposure and specimens (as-received and polished) were immersed and examined after 10, 20, 30 and 40 days. In certain cases, extended periods of 50 and 60 days were used.

For electrochemical tests, the potentiostat/galvanostat Model 273 developed by EG&G Princeton Applied Research and related corrosion analysis software, m352, was used. The first step involved sample preparation according to ASTM standard G 5—87, Standard Test Method for Making Potentiostatic and Potentiodynamic Anodic Polarization Measurements. This document specifies the exposed area to be 1 cm^2 with a surface polish of 1 μm diamond paste. The samples were cut from a bar of 1018 steel and ground down to the required size. Grinding and polishing were done to achieve the required surface specifications. Winter-grade PuriNOx, TxLED, and 2D diesel were used as the electrolytes. Standard graphite rods were used as auxiliary electrodes. The Saturated Calomel Electrode (SCE) was used as the reference electrode. Figure C.2.2 shows a typical set-up for electrochemical testing. Electrochemical testing was done in two phases: E_{corr} vs. time was used to obtain a preliminary idea of the corrosion tendency of the steel in the fuels, followed by linear polarization tests to determine the corrosion rates.

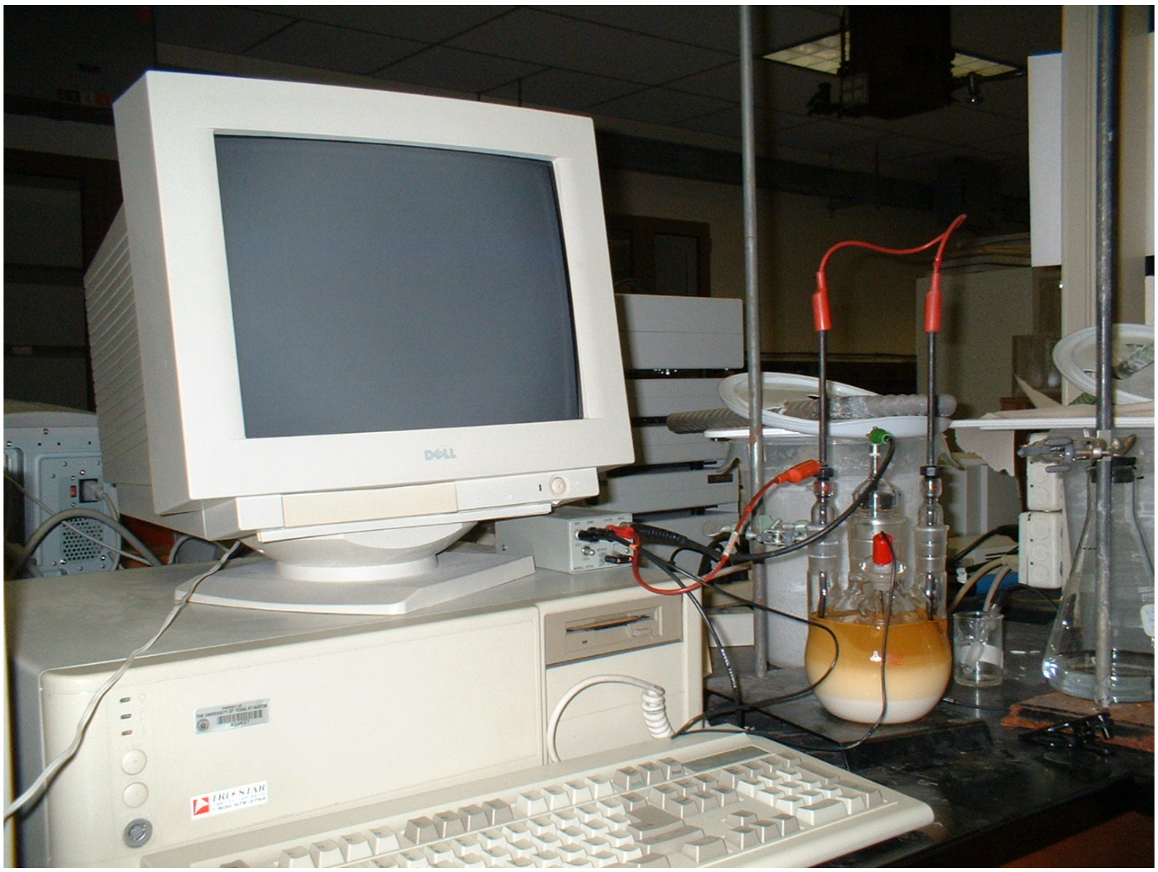


Figure C.2.2. Set-up for Electrochemical Tests showing steel in the winter-grade PuriNOx.

C.2.B. Results and Discussion

Figure C.2.3 shows specimens from planned interval tests involving pure 2D diesel, winter-grade PuriNOx and TxLED. As can be seen, corrosion products are noticeable only on the uppermost portion of the specimen that was immersed in winter-grade PuriNOx. For the more than 40-day period of testing, pure 2D diesel and TxLED did not cause the steel to corrode. Even though there was noticeable corrosion on the specimens that had been immersed in the winter-grade PuriNOx, weight changes for those specimens as well as those immersed in TxLED and

2D diesel were negligible. It was not possible to determine corrosion rates using linear polarization due to the very high resistivity of the solutions.

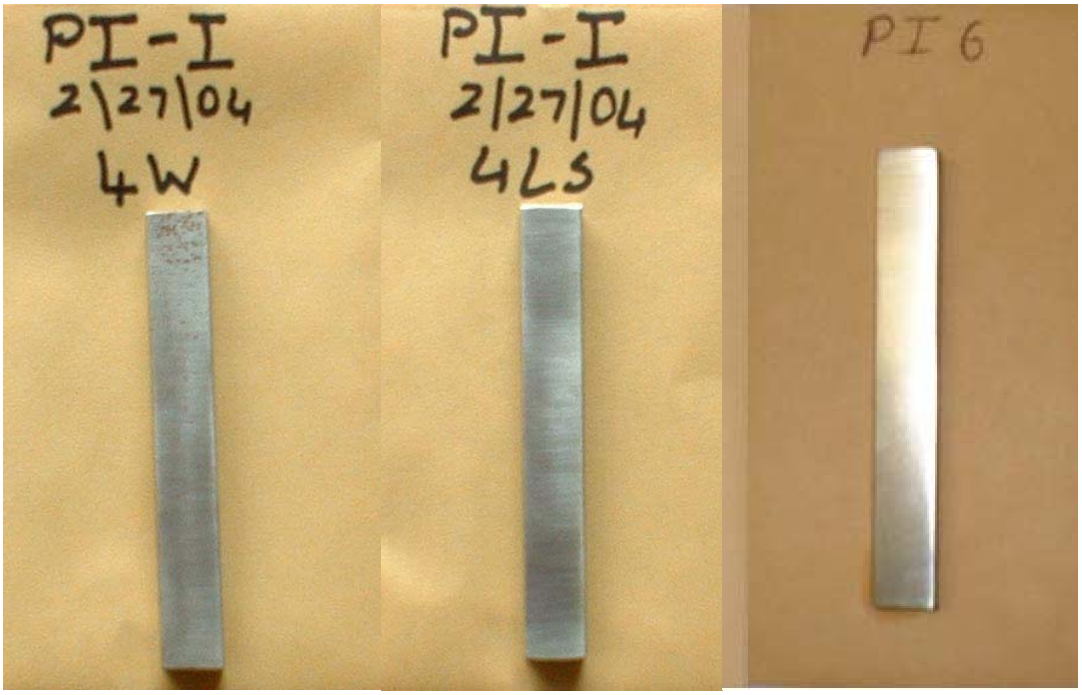


Figure C.2.3. Specimens immersed in winter-grade PuriNOx (l), TxLED (c), and 2D diesel(r) for 30 days.

Figure C.2.4 shows a plot of E_{corr} (mV) vs. time (s) for 1018 steel in TxLED. E_{corr} gives an idea of the corrosion tendency. More negative numbers suggest that the system is more active from a corrosion perspective and more positive numbers indicate more noble behavior. Several 24-hour runs of the test were done. Twenty-four hours seemed to be sufficient for the system to stabilize and provide constant values for E_{corr}. The value of E_{corr} was found to be approximately –1.3 mV vs. SCE for steel in TxLED.

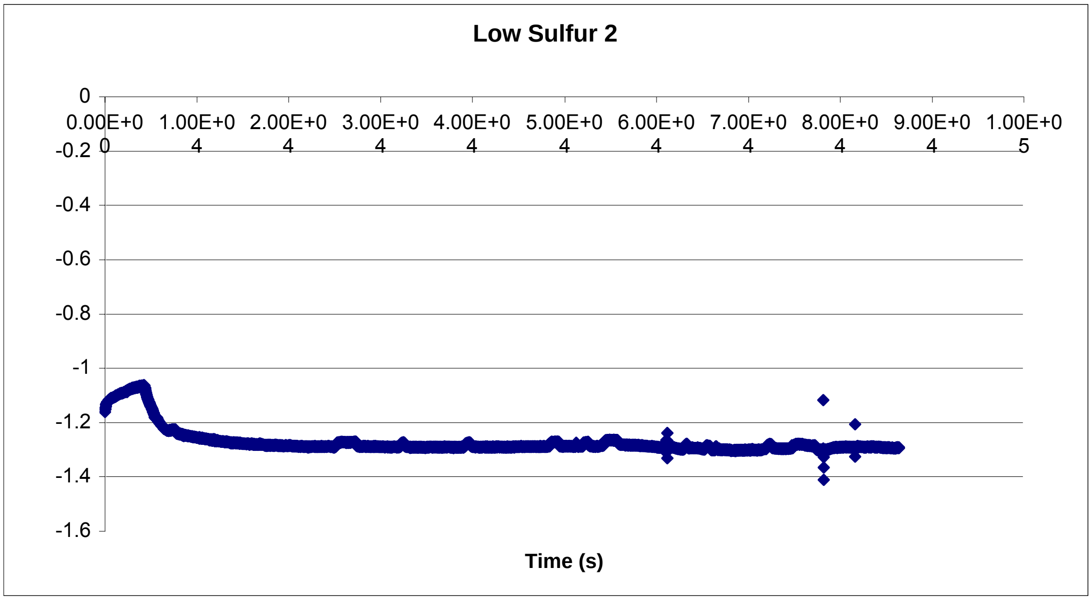


Figure C.2.4. Plot of E_{corr} (mV) vs. time (s) for the TxLED-1018 steel system.

C.2.C. Summary and Conclusions Regarding Corrosion

Based on the data collected and visual observations during and after the planned interval tests, it can be concluded that there was very little corrosion activity when steel was exposed to TxLED. Even after a lengthy period of immersion, no corrosion products were observed on the steel. Moreover, the value of E_{corr} in this case was not very negative, and actually close to zero. Low alloy steels in seawater, for example, exhibit a corrosion potential of around –600 mV vs SCE.

In addition, the phenomenon of separation did not occur in TxLED. This contrasts with PuriNOx, for which separation did occur after a relatively short period of exposure, and corrosion seemed to accompany that separation with corrosion products forming at the separation interface.

Appendix D. Fuel Properties

The properties of TxLED and of the "certification" version of 2D on-road diesel are provided in Table D.1. These properties were measured at Southwest Research Institute.

Table D.1. Properties of TxLED and of 2D Diesel Fuel

Test	method	units	TxLED	2D cert.	TxDOT specs for ULSD min	TxDOT specs for ULSD max
Lubricity: ball-on-cylinder lubricant evaluation (BOCLE) - scuffing load	D6078	grams	3450	4050	3100	-
Lubricity: high frequency reciprocating rig (HFRR)	D6079	scar size. mm	0.360	0.545	-	0.45
Sulfur by UV	D5453	ppm	2.5	377	-	15
Sulfur content by X-ray	D2622	ppm	<10	405	-	15
Cetane Number	D613	[-]	50.5	46.8	48	-
Total aromatics	D5186	wt. %	5.9	33.4	-	10
Mono aromatics	D5186	wt. %	5.4	23.9	-	-
Polynuclear aromatics (PNA)	D5186	wt. %	0.5	9.5	-	-
Heating Value (net)	D240	BTU/lb	18549.0	18336.4	-	-
Heating Value (gross)	D240	BTU/lb	19821.7	19535.2	-	-
Elemental analysis, carbon	D5291	wt. %	86.48	87.72	-	-
Elemental analysis, hydrogen	D5291	wt. %	13.95	13.14	-	-
API gravity at 60 °F	D4052	API°	35.9	36.6	32.0	-
Specific gravity at 60 °F	D4052	[-]	0.8454	0.8419	-	-
Density at 15.5 °C	D4052	g/mL	0.8449	0.8414	-	-
Flash point	D93	°F	199	154	130	-
Flash point	D93	°C	92.8	67.8	-	-
Viscosity, kinematic at 40 °C	D445	cSt	3.201	2.254	1.4	3.6
Ash content	D482	wt. %	<0.001	<0.001	-	0.01
Water and sediment	D1796	vol. %	<0.02	<0.02	-	<0.05
Distillation curve, IBP	D2887	°C	159.2	121.5	-	-
Distillation curve, T5	D2887	°C	195.3	164.6	-	-
Distillation curve, T10	D2887	°C	211.7	185	-	-
Distillation curve, T15	D2887	°C	221.4	201.4	-	-
Distillation curve, T20	D2887	°C	230.0	214.9	-	-
Distillation curve, T30	D2887	°C	244.0	233.7	-	-
Distillation curve, T40	D2887	°C	255.7	249.9	-	-
Distillation curve, T50	D2887	°C	269.0	262.4	-	report
Distillation curve, T60	D2887	°C	281.1	274.7	-	-
Distillation curve, T70	D2887	°C	294.3	289.4	-	-
Distillation curve, T80	D2887	°C	308.6	305.3	-	-
Distillation curve, T90	D2887	°C	328.8	321.3	282.2	337.7
Distillation curve, T95	D2887	°C	342.9	334.6	-	-
Distillation curve, EBP	D2887	°C	380.0	368.2	-	357.2

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