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New Technology Research & Development Program
Grant Contract 582-5-70807-0011

Final Deliverable Report

The preparation of this report is based on work funded in part
by the State of Texas through a Grant from the
Texas Commission on Environmental Quality.

Collection and Evaluation of Hybrid and Conventional Delivery Vehicle Emission and Activity Data • TCEQ Contract #582-5-70807-0011

May 2007

Sponsored by Texas Commission on Environmental Quality Texas Emission Reduction Program

LOPEZ GARCIA GROUP

lggroup.com

Collection and Evaluation of Hybrid and Conventional Delivery Vehicle Emission and Activity Data
TCEQ Contract No. 582-5-70807-0011

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Sponsored by:
Texas Commission on Environmental Quality
Texas Emission Reduction Program

May 2007

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The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. This report does not constitute a standard, specification, or regulation or endorsement of a particular technical approach or manufacturer.

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Rolling Frito-Lay Sales, LP (Frito-Lay) and LOPEZGARCIA GROUP, INC. (LGGROUP) do not endorse products or manufacturers. Trade or manufactures' names appear herein solely because they are considered essential to the subject of this report.

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- Rick McCracken – South Texas Fleet Manager (Houston)
- Ray Schwengler – Dedicated driver
- Jim Willis – Dedicated driver

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Acronyms and Abbreviations

ABS	Absolute value
ANOVA	Analysis of variance
ASCII	American Standard Code for Information Interchange
ASTM	American Society for Testing and Materials
COV	Coefficient of Variation
CATI	Clean Air Technologies International, Inc.
CI	Confidence Interval
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DC	Drive Cycle
DFW	Dallas Fort Worth
Dyno	Dynamometer
EPA	Environmental Protection Agency
F	Fahrenheit
FTP	Federal Test Procedure
g/mi	Grams per mile
GPS	Global Positioning System
GVWR	Gross Vehicle Weight Rating
HC	Hydrocarbon
HEV	Hybrid Electric Vehicle
Hz	Hertz
IDI	Indirect-injection
kg	Kilograms
l	Liter
lb	Pound
lb/gal	Pound per gallon
LD	Light Duty
LEV	Low Emissions Vehicle
LGGROUP	LOPEZGARCIA GROUP, Inc
mg/mi	Milligrams per mile
MJ	Megajoule
MPG	Miles per gallon
NEC	Net Energy Change
NiMH	Nickel metal hydride
NO_2	Nitrogen Dioxide
NO_x	Nitrogen Oxides
NREL	National Renewable Energy Laboratory
NTP	Notice to Proceed
O_2	Oxygen
O_3	Ozone
OBD	On-board Diagnostics
PEMS	Portable On-board Emissions Measurement System
PM	Particulate Matter
PPM	Parts per million
psi	Pounds per square inch

REL	Relevance
RH	Relative Humidity
RPM	Revolutions per minute
SAE	Society of Automotive Engineers
SOC	State of Charge
Std Dev	Standard Deviation
SwRI	Southwest Research Institute
TCEQ	Texas Commission on Environmental Quality
TERP	Texas Emissions Reduction Program
UDDS	Urban Dynamometer Driving Schedule
US	United States
V	Volt
VIN	Vehicle Identification Number
Wt	Weight

Abstract

The D/FW and Houston metro areas are currently air quality non-attainment areas for ozone, which means that the air is not within standards set forth by the EPA for ground-level ozone. Ozone is not emitted directly into the air but is formed through complex chemical reactions between precursor emissions of volatile organic compounds (VOC) and oxides of nitrogen (NO_x) in the presence of sunlight. Vehicles have been identified as a major source of NOx emissions, and a number of initiatives are underway to determine the potential to reduce NOx from mobile sources. This emissions study is sponsored by the Texas Commission on Environmental Quality under the Texas Emissions Reduction Project to investigate the potential for hybrid-electric commercial delivery vehicles to reduce harmful emissions and fuel consumption. The study involved three test phases comparing gasoline and diesel powered hybrid-electric trucks to existing conventional gasoline and diesel vehicles. Data was gathered from both dynamometer lab testing under controlled conditions and on-road testing using actual delivery routes.

The first test phase involved vehicle emission and performance testing at the Southwest Research Institute (SwRI) test facility in San Antonio, Texas in a laboratory environment using the heavy duty chassis dynamometer and Federal Test Protocol (FTP). Phase 1 and Phase 3 dynamometer testing followed the test protocol described in SwRI Proposal EVR-4791 "Emissions Testing of Various Delivery Vehicles". SwRI's tests were based on the Federal Test Procedure (FTP) and measured exhaust emissions of PM, NO_x, HC, CO and CO_2 and fuel consumption. Results of the Phase 1 baseline testing indicated that the diesel hybrid got the best miles per gallon with newer diesel truck second. The gas hybrid produced the lowest NO_x emissions with the older diesel truck second.

AVERAGE EMISSION RESULTS DURING PHASE 1 TESTING OVER LD UDDS DRIVE CYCLE

Test Code	HC g/mi	CO g/mi	NOx g/mi	PM mg/mi	CO2 g/mi	MPG	Fuel kg	Miles
Older Baseline Diesel	0.31	1.47	3.46	152	842	12.2	2.02	7.6
Newer Baseline Diesel	0.14	2.30	6.21	75	705	14.6	1.69	7.6
Diesel Hybrid	0.53	2.11	4.98	156	667	15.4	1.60	7.5
Gas Hybrid	0.15	2.51	0.26	7	741	12.0	1.78	7.6

The second phase of testing involved 'real world' emissions and vehicle performance monitoring in the Dallas-Ft. Worth and Houston areas in the Frito-Lay product delivery operation for various fixed delivery routes. During Phase 2 testing, emission/ performance monitors installed in both the base line and hybrid vehicles provided real time data acquisition. The emission monitors measured NO_x, CO, CO_2, hydrocarbon concentrations and the performance monitors (including GPS) provided vehicle speed,

distance and MPG. Phase 2 on-road emission measurement was conducted using a on-board Portable Emissions Measurement System (PEMS), the Montana OEM-2100, provided by Clean Air Technologies International. The key objectives to the Phase 2 testing were to collect real-world vehicle emissions and activity data on Dallas/Fort Worth and Houston area roads using the PEMS; to analyze characteristics of the on-road vehicle emissions and determine the operational factors which play the largest role in fuel consumption and emissions generation; and to compare fuel consumption and NOx emissions between conventional and hybrid vehicles. The Frito-Lay delivery operation was analyzed using GPS, and the data gathered in the analysis were used to select the routes for the Phase 2 testing so that results representative of the Frito-Lay delivery operation were obtained. Results obtained during the on-road testing showed the following:

COMBINED ON-ROAD DATA FOR MPG AND EMISSIONS BY TEST VEHICLE

Test Code	HC g/mi	CO g/mi	NOx g/mi	CO2 g/mi	MPG
Older Baseline Diesel	0.28	2.03	4.22	897	11.0
Newer Baseline Diesel	0.57	2.36	6.05	689	14.7
Diesel Hybrid	0.60	2.34	7.63	706	13.2
Gas Hybrid	0.21	2.65	1.28	916	9.2

Statistical analysis of data collected for each vehicle broken down by route revealed no consistent difference in any particular route over the course of the testing phase of the project.

The third and final phase of testing involved “durability” testing at the SwRI facility upon completion of the on-road testing. The results for the “durability” testing are comparable to the initial baseline testing, as seen in the table below.

AVERAGE EMISSION RESULTS DURING PHASE 3 TESTING OVER LD UDDS DRIVE CYCLE

Test Code	HC g/mi	CO g/mi	NOx g/mi	PM mg/mi	CO2 g/mi	MPG	Fuel kg	Miles
Older Baseline Diesel	0.34	1.65	3.52	137	835	12.3	2.01	7.6
Newer Baseline Diesel	0.12	2.25	6.1	84	724	14.2	1.73	7.5
Baseline Gas	0.03	1.49	0.16	4	801	11.1	1.90	7.5
Diesel Hybrid w/Hybrid Disabled	0.40	4.75	5.81	177	697	14.7	1.67	7.5
Diesel Hybrid in Hybrid Mode	0.41	2.43	4.86	128	632	16.2	1.53	7.6
Gas Hybrid	0.16	2.89	0.37	8	748	11.9	1.80	7.6

A fifth vehicle, a gasoline baseline truck, was added during the project and data gathered during Phase 2 on-road testing and Phase 3 durability testing. The diesel hybrid was also tested on Phase 3 with the hybrid system disabled to ascertain true

"baseline" performance on this truck; however, the engine and automatic-shift manual transmission were not tuned for this application, so the results are not representative of a true baseline vehicle of this engine configuration.

A proposed method to force-rank the vehicles overall through a composite score was developed by calculating a score for each vehicle within the range of the results for each constituent. This score was then multiplied by five and equally added the MPG and NO_x scores for each vehicle to provide a composite score on a zero to ten scale. The lowest total score represents the number one ranked vehicle. The table below ranks the vehicles by this composite score. Using the composite score, the newer baseline diesel vehicle proved to be the overall leader in on-road testing when only MPG and NO_x are considered. Based on the results presented, electric hybrid technology does not appear to improve NO_x emissions or fuel efficiency in this type of application. The results show there appears to be a disproportionate trade-off of fuel efficiency for NO_x emissions depending on which type of fuel is used. Because of this trade-off the reader may draw a different conclusion with a different preference for higher efficiency or lower NO_x emissions.

	MPG		NOx		Composite	Composite
	MPG	Score	g/mi	Score	Score	Rank
Newer Baseline Diesel	14.68	0.00	6.05	0.79	3.98	1
Baseline Gas	8.15	1.00	0.01	0.00	5.00	2
Gas Hybrid	9.19	0.84	1.28	0.17	5.04	3
Older Baseline Diesel	11.00	0.56	4.22	0.55	5.59	4
Diesel Hybrid	13.24	0.22	7.63	1.00	6.11	5

MPG and NO_x Composite Vehicle Ranking for On Road Testing

The results lead to a different conclusion if all emission constituents are used in ranking the vehicles. Due to the diversity in average level and range of the results, a composite score was developed by calculating a score for each vehicle within the range of the results for each constituent with 0 being the best and 1 being the worst. This score was then multiplied by two and equally added for each vehicle to provide a composite score on a one to ten scale. The lowest total score represents the number one ranked vehicle. The table below ranks the vehicles by this composite score. Using the composite score, the baseline gas vehicle proved to be the overall leader in on-road testing when considering all emissions constituents. The hybrid technology did not deliver improved results in this application and actually ranked the two lowest of the five vehicles. Even though the engine/chassis combination used as the base for the gasoline hybrid passed the requirements for EPA certification as a LEV, the changes made to convert it to a series hybrid are believed to have resulted in it's not being able to perform at the same level of emissions of the baseline gas vehicle. The baseline gas vehicle delivered the lowest combined emissions results shown and meets EPA LEV

certification levels as-tested. As a result it ranked best in three of the four emissions constituents. The higher CO_2 output of this vehicle was not sufficiently disproportionate to outweigh the lower emissions in other areas.

	MPG		NOx		HC		CO		CO2		Composite	Composite
	MPG	Score	g/mi	Score	g/mi	Score	g/mi	Score	g/mi	Score	Score	Rank
Baseline Gas	8.15	1.00	0.01	0.00	0.07	0.00	0.52	0.00	964	1.00	4.00	1
Newer Baseline Diesel	14.68	0.00	6.05	0.79	0.57	0.94	2.36	0.86	689	0.00	5.21	2
Older Baseline Diesel	11.00	0.56	4.22	0.55	0.28	0.40	2.03	0.71	897	0.76	5.96	3
Gas Hybrid	9.19	0.84	1.28	0.17	0.21	0.27	2.65	1.00	916	0.83	6.20	4
Diesel Hybrid	13.24	0.22	7.63	1.00	0.60	1.00	2.34	0.85	706	0.06	6.28	5

All Constituent Composite Vehicle Ranking for On Road Testing

It is understood that the results and conclusions presented here are already somewhat "dated" and obsolete for commercially available diesel trucks in 2007 due to the improved emissions levels of 2007 models. All of the diesel engines in the vehicles tested are no longer commercially available as-tested here due to the 2007 changes to the EPA emissions standards for diesel vehicles. The 2007 EPA emissions standards have a 55% reduction (3.3 g/mi to 1.5 g/mi) in allowable NO_x emissions. The tables below are presented with the tested NO_x value for the diesel hybrid reduced by 55% to show the potential improvements under the 2007 EPA emissions standards. It is assumed that a reduction in base level engine emissions will translate proportionately to a "hybridized" diesel engine, and fuel economy, and thus CO_2 is not materially affected. This vehicle is the only diesel vehicle tested here that will have the same engine that is certified to the 2007 EPA emission standards for diesels. Gasoline emissions standards have not changed since the inception of this study so will not be adjusted likewise.

	MPG		NOx		Composite	Composite
	MPG	Score	g/mi	Score	Score	Rank
Diesel Hybrid	13.24	0.22	3.43	0.57	3.95	1
Baseline Gas	8.15	1.00	0.01	0.00	5.00	2
Newer Baseline Diesel	14.68	0.00	6.05	1.00	5.02	3
Gas Hybrid	9.19	0.84	1.28	0.21	5.26	4
Older Baseline Diesel	11.00	0.56	4.22	0.70	6.31	5

MPG and NO_x Composite Vehicle Ranking for On Road Testing with NO_x Adjusted for 2007 EPA Standards

	MPG		NOx		HC		CO		CO2		Composite	Composite
	MPG	Score	g/mi	Score	g/mi	Score	g/mi	Score	g/mi	Score	Score	Rank
Baseline Gas	8.15	1.00	0.01	0.00	0.07	0.00	0.52	0.00	964	1.00	4.00	1
Diesel Hybrid	13.24	0.22	3.43	0.57	0.60	1.00	2.34	0.85	706	0.06	5.41	2
Newer Baseline Diesel	14.68	0.00	6.05	1.00	0.57	0.94	2.36	0.86	689	0.00	5.62	3
Older Baseline Diesel	11.00	0.56	4.22	0.70	0.28	0.40	2.03	0.71	897	0.76	6.25	4
Gas Hybrid	9.19	0.84	1.28	0.21	0.21	0.27	2.65	1.00	916	0.83	6.29	5

All Constituent Composite Vehicle Ranking for On Road Testing with NO_x Adjusted for 2007 EPA Standards

As can be seen in the tables above, it is anticipated that the change in EPA emissions standards will improve the NO_x emissions performance of the diesel hybrid enough to change the original conclusions of the study when only considering MPG and NO_x. Using these anticipated NOx emissions the diesel hybrid would be the preferred vehicle. If all emissions are considered, the baseline gas vehicle would still be preferred where NO_x emissions are of concern. The diesel hybrid would still emit less NO_x than the existing baseline diesels and could be used to replace those when needed where NO_x was not a concern.

In summary, overall, the diesel hybrid does offer improved fuel efficiency versus certain existing vehicles in the Frito-Lay fleet, including older diesels and new gasoline units. While the diesel hybrid did not outperform the newer diesel baseline truck in fuel economy, that 4-cylinder engine configuration is no longer available. The gasoline hybrid showed marginal fuel economy benefit and much higher NO_x versus the current gasoline baseline truck, and lower fuel economy with significantly improved NO_x versus currently used diesel trucks. The diesel hybrid perhaps has an application where higher fuel efficiency is desired and where NO_x emissions are not as much of a concern. With the potential improvements expected with the 2007 EPA emission standards the NO_x impact would be less, but still not low enough make it a good option in areas where NO_x emissions are a concern. Additionally, diesel technology comes at a substantially increased capital cost versus gasoline due the diesel engine and emissions equipment required. Each fleet operator will have to weigh the increased cost against fuel savings and potential emissions reductions incentives based on their annual mileage, current and expected fuel prices, and expected return on investment. Evaluating a 2007-model diesel hybrid with improved NO_x emissions is a recommended area of future study to more fully understand the current fuel efficiency and emissions picture with hybrid-electric delivery trucks.

1.0 Project Background, Objectives, and Overview

1.1 Background of Research

The Dallas/Fort Worth and Houston areas are designated by the Environmental Protection Agency (EPA) as non-attainment regions for ground-level ozone. The criteria for reaching attainment includes passing levels of ground-level ozone. Ozone (O3) is a photochemical oxidant and the key component of smog. While O3 in the upper atmosphere is beneficial to life by shielding the earth from harmful ultraviolet radiation from the sun, high concentrations of O3 at ground level are a major health and environmental concern. O3 is not emitted directly into the air but is formed through complex chemical reactions between precursor emissions of volatile organic compounds (VOC) and oxides of nitrogen (NOx) in the presence of sunlight. These reactions are stimulated by sunlight and temperature so that peak O3 levels occur typically during the warmer times of the year. Both VOCs and NOx are emitted by transportation and industrial sources. VOCs are emitted from sources as diverse as autos and trucks, chemical manufacturing, dry cleaners, paint shops and other sources using solvents.

Non-attainment regions must be in compliance with the current federal standards for ground-level ozone by 2007. These cities and regions are faced with potential loss of federal transportation funds, increased health costs, and other consequences if the compliance mandates are not met. The impact of non-compliance for these cities and regions is estimated to be in the billions of dollars per year. Research has found that a significant portion of the emissions come from mobile sources. In order to meet the quantitative goals in reducing the mobile source emissions, the Texas Commission on Environmental Quality (TCEQ) under the Texas Emission Reduction Program (TERP) has funded grants for the study of emission reduction technologies that have the potential to be used to reduce ozone in the non-attainment regions. A grant request was submitted by Rolling Frito-Lay Sales, LP (Frito-Lay) to TCEQ in July 2004, requesting funds to study the emissions and vehicle performance of conventional gas and diesel vehicles currently in the Frito-Lay fleet versus hybrid gas and diesel vehicles currently available or under development.

1.2 Objectives of Research

The key objectives of this research are to collect real-world vehicle emissions and activity data for typical Frito-Lay route delivery trucks in Dallas/Fort Worth and Houston using Portable Emission Measurement System (PEMS); and to analyze characteristics of the on-road vehicle emissions. The data will be used to determine which of the technologies studied provides the lowest vehicle emissions and best mileage (MPG) with the potential for use in commercial fleets in the near future. The results can be used by companies with fleets of similar-type delivery trucks in two ways: assist in

vehicle replacement and new vehicle purchase decisions to reduce mobile source emissions. An added benefit of this project is to provide emission and vehicle performance information on past and current delivery vehicles which can serve as a benchmark for potential future testing.

1.3 Project Schedule

The grant request was approved and Notice to Proceed (NTP) issued by the TCEQ on May 31, 2005. The schedule listed in the grant proposal was for the completion of the project within 20 months from the NTP. This time period was later extended to 24 months in reaction to truck deliveries later than initially anticipated. The updated testing schedule, reflecting the actual vehicle delivery dates, is provided here (see Table 1-1).The original schedule estimated that the vehicle delivery dates were April 2006 for the Azure Dynamics (formerly Solectria) Gas Hybrid and March 2006 for the International Eaton Diesel Hybrid. However, due to technical problems encountered during vehicle development, Azure substituted a series-type hybrid with the same base engine for this study. The series-type hybrid was delivered in October 2006. Problems were also encountered with development of the International/Eaton Diesel Hybrid. The diesel hybrid truck was delivered in January 2007. Due to the delays in vehicle delivery, the on-road testing schedule was compressed from the originally proposed sixteen weeks to twelve weeks. This change to the on-road testing schedule required revisions to the testing protocol. Instead of using route drivers driving one normal delivery route per day, it was decided that dedicated drivers would be used to drive multiple routes per day to complete the on-road testing on time. In addition, a fifth vehicle (baseline gasoline, representative of current new-vehicle purchases) was added during the on-road testing phase. Despite occasional vehicle and continual emission monitor equipment problems, the emission and vehicle performance testing was completed by the end of April 2007.

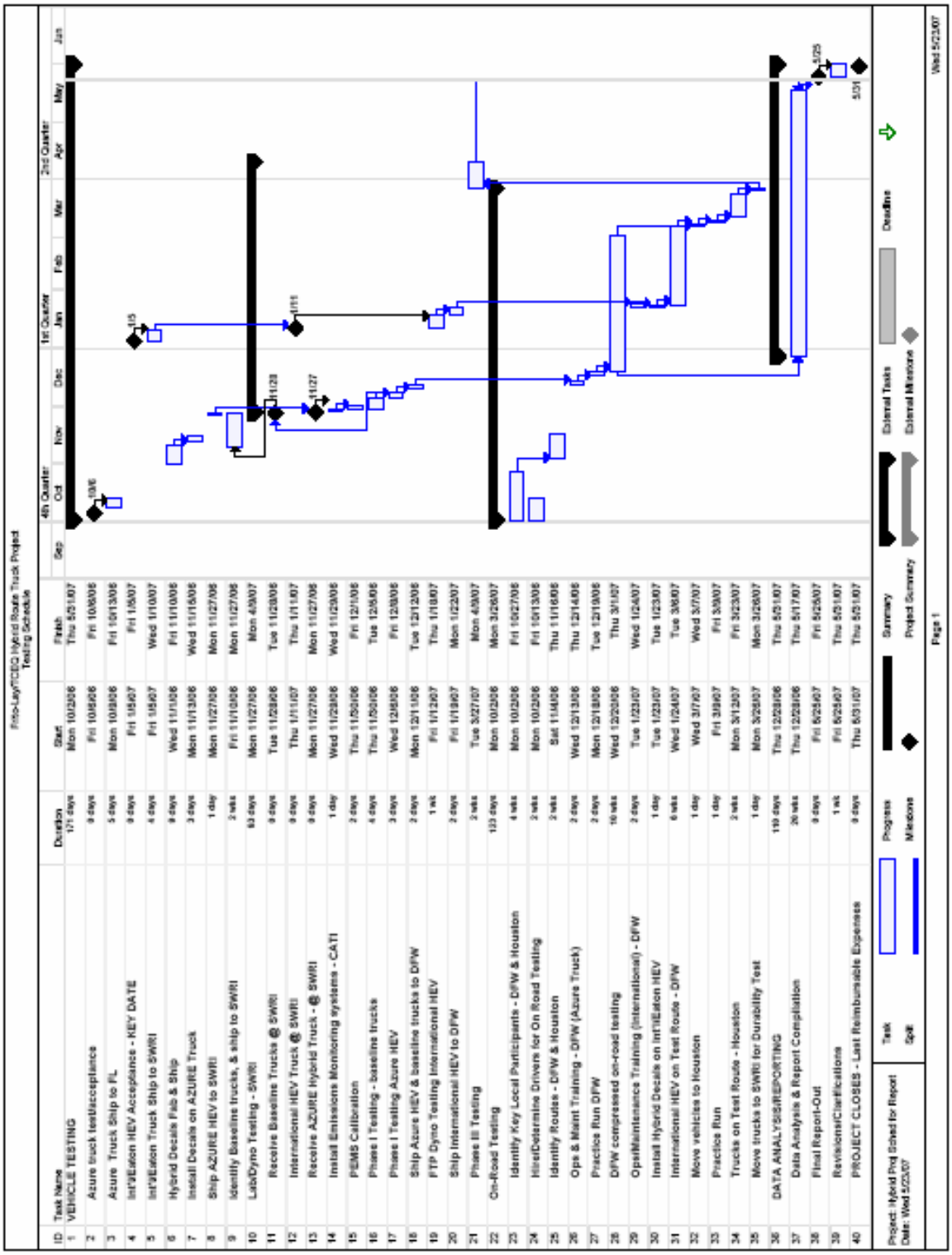


Table 1-1 Project Schedule

1.4 Project Overview

Upon receipt of the NTP from the TCEQ, the gas hybrid and diesel hybrid vehicles trucks were contracted, specifications finalized, vehicles constructed and delivered to Frito-Lay. As noted above, the vehicle construction phase took much longer than anticipated and the project schedule slipped 8-10 months. While the vehicles were under development and construction, a testing protocol was developed by Frito-Lay and LGGROUP. The testing protocol (Appendix A) included the testing schedule, test plan strategy, and data collection and analysis plan. The testing protocol was presented to National Renewable Energy Laboratory (NREL) in November 2006 to gain input from their experience in testing hybrid vehicles. The test protocol was updated with the information acquired from NREL meeting and reissued for use during the testing.

An important component of the protocol was the selection of the drive cycles to be used during the testing. Frito-Lay used GPS data to identify drive cycle information such as average speed, trip length, and speed versus time on the existing fleet. The light-duty (LD) Federal Test Procedure (FTP) Urban Dynamometer Driving Schedule (UDDS) was chosen as the most representative of daily operation by the Frito-Lay delivery vehicles. The LD UDDS drive cycle was used during Phase 1 and Phase 3 testing. The original intention of the Phase 3 testing was to evaluate the results after on-road mileage accumulation. However, since the on-road mileage during this project's timeline was insignificant (roughly 1000 miles), the Phase 3 testing mainly serves as a confirmation of the Phase 1 testing.

For the on-road testing phase, data from existing delivery trucks with GPS units was analyzed to determine the average speeds and distance. From this information (see Chapter 4 for specific drive cycle parameters), three representative routes (two in the Dallas/Fort Worth area and one in Houston) were chosen for on-road testing. In summary, the project involved the following steps:

Hybrid vehicle design construction and delivery

↓

Phase 1 - Dynamometer testing at Southwest Research Institute (SwRI) test facility

↓

Phase 2 - On-road testing in the Dallas/Fort Worth and Houston areas

↓

Phase 3 - dynamometer testing at Southwest Research Institute (SwRI) test facility

↓

Data Analysis

↓

Report Preparation and Submission

Four vehicles (older baseline diesel, newer baseline diesel, diesel hybrid, and gas hybrid) were tested during the first phase. The first test phase involved vehicle emission and performance testing at the Southwest Research Institute (SwRI) test facility in a laboratory environment using the heavy duty chassis dynamometer. Five vehicles were testing during the second phase of testing which involved 'real time' emissions monitoring in the Dallas/Fort Worth and Houston areas for various fixed delivery routes. Five vehicles were tested during Phase 3 which involved vehicle emission and performance testing at the SwRI facility upon completion of the 'real time' testing. Information on the test vehicles is provided below in Table 1-2. The older and newer baseline diesel trucks, and gas and diesel hybrids were tested in phase one and all five vehicles shown in Table 1-2 were tested in Phases 2 and 3.

Phase 1 and Phase 3 dynamometer testing followed the test protocol described in SwRI Proposal EVR-4791 "Emissions Testing of Various Delivery Vehicles" (Appendix B). SwRI's test was based on the Federal Test Procedure (FTP) and measured exhaust emissions of PM, NO_x, HC, CO and CO_2 and fuel consumption.

During Phase 2 testing, emission/performance monitors were installed in both the base line and hybrid vehicles to provide real time data acquisition. The NOx, CO, CO_2, and hydrocarbon emissions along with vehicle speed, distance and MPG were monitored. Phase 2 on-road emission/performance measurements were collected with an on-board Portable Emissions Measurement System (PEMS), the Montana OEM-2100. Clean Air Technologies of Buffalo, NY provided the Montana System under contract to Frito-Lay. The Montana OEN 2100 PEMS is capable of measuring second-by-second fuel consumption and emissions readings for diesel and gasoline vehicles.

The key objectives to the Phase 2 testing were to collect real-world vehicle emissions and activity data on Dallas/Fort Worth and Houston area roads using the PEMS; to analyze characteristics of the on-road vehicle emissions and determine the operational factors which play the largest role in fuel consumption and emissions generation; and to compare fuel consumption and NOx emissions between conventional and hybrid vehicles.

Table 1-2
Hybrid Project Test Truck Data

	Older Baseline Diesel	Newer Baseline Diesel	Baseline Gas	Diesel Hybrid	Gas Hybrid
FL Unit #	R70226	R08796	R30222	R13673	RH2006
Year Model	1998	2003	2006-2007	2005	2005
Chassis Manufacturer	General Motors	Workhorse Custom Chassis	Ford Motor Co.	Workhorse Custom Chassis	Workhorse Custom Chassis
Engine Manufacturer	General Motors	Cummins	Ford Motor Co.	International	General Motors
Body Manufacturer	Union City Body Co.	Utilimaster Corp.	Utilimaster Corp.	Utilimaster Corp.	Utilimaster Corp.
Body (Cargo) Length	18 ft	18 ft	18 ft.	18 ft.	16 ft
VIN	1GBHP32Y8W3304305	5B4HP42P553404763	1FCJE39L46HB04103	5B4HPD25363412537	5B4KBD2V063416051
Engine Model	6.5L	ISB4	5.4L	VT275	4.8L
Engine Type	V8	I4, turbo	V8 2V	V6 turbo	V8
Engine Hp	160@3400	170@2600	255@4500	200@2700	270@5200
Engine Torque	292@1700	420@1600	350@2500	440@1800	285@4000
Transmission	GM 4L80E automatic	Allison 1000 automatic	Ford 5R100 automatic	Eaton Hybrid (automated manual)	n/a
Data Link Type	none	J1708	OBDII	J1939	OBDII
Mileage at Test Initiation	235,800	81,100	1,400	1,200	209
Vehicle Test Weights - Dry Wt +50% cargo for Dyno and Road Testing (all weights are lb)					
GVWR as built/tested	10,000	10,000	10,000	10,000	14,500
Dry Weight	8010	7930	7680	9212	9600
Driver	200	200	200	200	200
Fuel (as delivered for testing)	148.5	111.4	297.0	297.0	154.7
TOTAL Weight	8,359	8,241	8,177	9,709	9,955

Note: For the Phase 2 on-roading testing a simulated load was placed in each vehicle representative of approximately one half of the normal daily load expected in Frito-Lay route vehicles.

As a minimum, for road testing, the emission monitor was required to monitor NOx concentrations along with vehicle speed, distance, and MPG as outlined in the original project proposal to TCEQ and contract.

Since the hybrid trucks would be on the road every day during testing, special decals were designed to highlight the hybrid electric nature of the vehicles. It was acknowledged from the beginning of the project that this study was highly visible within and outside the company. After several iterations, a suitable design was developed that described the special nature of these vehicles, recognized hybrid OEM partners and the TCEQ, and successfully meshed with the existing vehicle graphic design.

Figure 1-1 – Special Hybrid Decals on Test Vehicles

1.5 Outline of This Report

The Scope of Work listed under the Grant Activities in the TCEQ Grant Agreement for New Technology Research and Development (Appendix C) includes four tasks. The tasks found in the Agreement are: Task 1: Development and Delivery of Hybrid Vehicles; Task 2: Testing of Existing Fleet and Prototypes Vehicles; Task 3 Data Review and Analyses; and Task 4: Program Management and Reporting.

This report is organized into the following chapters for ease of review. Chapter 1 – Background and Objectives covers Task 1 of the Grant Activities which involves the construction and delivery of two hybrid vehicles. Chapter 2 introduces the equipment that was used to measure and record the emission data during the on-road testing phase as required in 2.2.2 of the Grant Activities. Chapters 3, 4, and 5 cover the Phase 1 testing at SwRI; on-road testing during the vehicle runs on two routes in Dallas/Fort Worth area and two routes in Houston; and Phase 3 testing at SwRI as listed in Task 2 of the Grant Activities. Chapter 6 covers the data review and analysis as described in

Task 3 of the Grant Activities. Chapter 7 describes the conclusions from the vehicle testing and provides recommendations based on the findings of this study as described in Task 3 of the Grant Activities.

1.6 Revisions to the Original Contract

The original contract (No. 582-5-70807-0011) between the Texas Commission on Environmental Quality and Rolling Frito-Lay Sales, LP was executed on May 31, 2005. Over the course of the project, there were several amendments and minor changes to the contract which are listed below:

Date of Change to Contract	Nature of Change to Contract
9/08/05 – Amendment #1	A name change for Frito Lay Project Manager from Pete Silva to Joe Gold was made. Also, a name change for the gas hybrid provider from Solectria to Azure Dynamics was made.
1/13/06 – Amendment #2	A name change was made from Eaton to International as the truck integrator/ supplier and revisions were made to the project schedule.
7/05/07 – Amendment #3	The change from Sensors, Inc. to Clean Air as the Portable Emissions Monitoring System (PEMS) supplier was made as well as a change to leasing versus purchase of the PEMS. Also, another change to the project schedule was made.
11/03/06 – Minor change #1	The description of the Azure Dynamics Corp. vehicle was changed to reflect the vehicle provided (series hybrid).
2/27/07 – Minor change #2	A change in the budget allowed for extra testing at SwRI for the conventional gas and diesel hybrid vehicles.

2.0 On-Road Emissions Data Collection Equipment

The portable emission measurement systems known as the Montana System OEM-2100 (PEMS) was leased from Clean Air Technologies, Inc. (CATI) of Buffalo, NY for the duration of the Phase 2 testing. It is capable of measuring second-by-second fuel consumption and emissions of HC, CO, CO_2, NO_x and PM readings for diesel and gasoline vehicles. The Montana system was used successfully for a Houston Advanced Research Center study "Collection and Evaluation of On-Road Vehicle Emission and Activity Data", April 2004. This chapter introduces the basic features of this equipment.

2.1 Basic Description of Montana OEM-2100 System

The PEMS is designed to measure vehicle mass exhaust emissions under actual on-road driving conditions using vehicle and engine operating data and concentrations of pollutants in exhaust gas sampled from the tailpipe. It is typically installed in the passenger seat or on the vehicle floor, and provides second-by-second information on emissions, fuel consumption, vehicle speed, engine RPM, temperature, throttle position and other engine parameter data measured directly using an array of analytical sensors. The sensors are installed on the applicable engine systems and are then routed to the PEMS. For vehicles with a supported engine computer diagnostic port, engine and vehicle data is acquired using this interface. The diagnostic port interface cable is routed to the unit from the port connector.

Power for the PEMS is drawn from a cigarette lighter outlet or from a cable clamped directly onto the battery. The unit will be securely mounted in the vehicle for the duration of the on-road testing.

Undiluted exhaust gas is sampled from the tailpipe using probes and 20-foot (6-meter) sample lines. For in-vehicle installation, exhaust sample lines can be routed through the vehicle floor or a window and secured to the exhaust system using hose clamps. The concentrations of NO_x, in the exhaust gas are determined by a functional equivalent of a gas analyzer subsystem. At the same time, vehicle speed, engine RPM, intake air mass flow, coolant temperature, and other engine operating parameters are collected using an on-board diagnostics (OBD) connector. If using a sensor array system the engine RPM, intake temperature and intake pressure are measured, vehicle speed is collected using a global positioning system (GPS), and mass air is calculated using engine displacement, a fixed volumetric efficiency and RPM. From the OBD provided or calculated intake air mass flow, known composition of intake air, measured composition of exhaust, and user-supplied composition of fuel, a second by second exhaust mass flow is calculated. Multiplying the exhaust mass flow by the concentrations of different pollutants yields grams per second emission data.

Installation of PEMS exhaust sample lines

2.2 Montana OEM-2100 Features and Specifications

The PEMS has the following features:

- weight is less than 38 lbs.
- power requirements are 12-14 V DC (12 V nominal) and 4-6 amperes from the vehicle electrical system (110V AC adapter included).
- automatic battery backup.
- data capture rate is 1 Hz.
- sample flow is 6 liters/minute nominal for each gas analyzer, 3.8 – 4.0 l/min through PM detector.
- equipment outputs second by second data with 12-second delay.
- On-board diagnostics data rate is 0.6 – 3.5 seconds/frame, depending on the vehicle.
- system computer is an industrial computer with the data interface of IDE compact flash memory, and the user interface is designed as the touch-screen or keyboard/keypad.
- all software is included in the computer.
- real-time text information is displayed and the ASCII comma-delimited text file will be generated for the analysis.
- measured parameters include time, vehicle speed, acceleration, engine RPM, engine coolant temperature, engine load, throttle position, intake air mass flow, exhaust mass flow, fuel consumption, grams per second emissions of NO_x and PM.
- operating temperature and humidity are 25-100 Degree F, 0-90% RH, non-condensing (for ambient conditions); and 40-95 Degree F, 0-90% RH, non-condensing (at instrument location).
- typical installation time is 10 to 20 minutes. The warm-up time of the equipment is limited by the gas analyzer warm-up time. The unit can be moved and installed while running.

- 15 minutes warming-up time are needed for gaseous emissions only and 30 minutes for PM measurements. However, 60 minutes are recommended for optimal accuracy.
- several optional equipment including the Global Positioning System (GPS), the pre-catalyst sampler (requires drilling a hole into exhaust), the heated-sample line, the heavy-duty engine scanner, and the universal sensor array.
- system is typically calibrated using a locally obtained "smog check" calibration gas mix (propane, CO, CO2, NO).

2.3 System Installation

The PEMS unit was placed in the test vehicle and secured in place with adjustable tie down straps. Exhaust sample lines were routed through the cargo area and through the floor and secured to the exhaust system using hose clamps. The sensor array was installed on the applicable engine systems and then routed to the PEMS. Power was drawn from an auxiliary battery in order to maintain power to the PEMS when the vehicle was turned off at the stops.

Installation and start-up of PEMS included six typical steps:

(1) safe and convenient placement of the system;

(2) installation and connection of the sensor array and GPS;

(3) establishing an appropriate source of power;

(4) routing exhaust sample lines for gas concentration measurements;

(5) warm up of the unit for 45 to 60 minutes before testing starts;

(6) obtaining engine data for emissions flow calculation.

The conceptual diagram of system installation is illustrated in Figure 2-1.

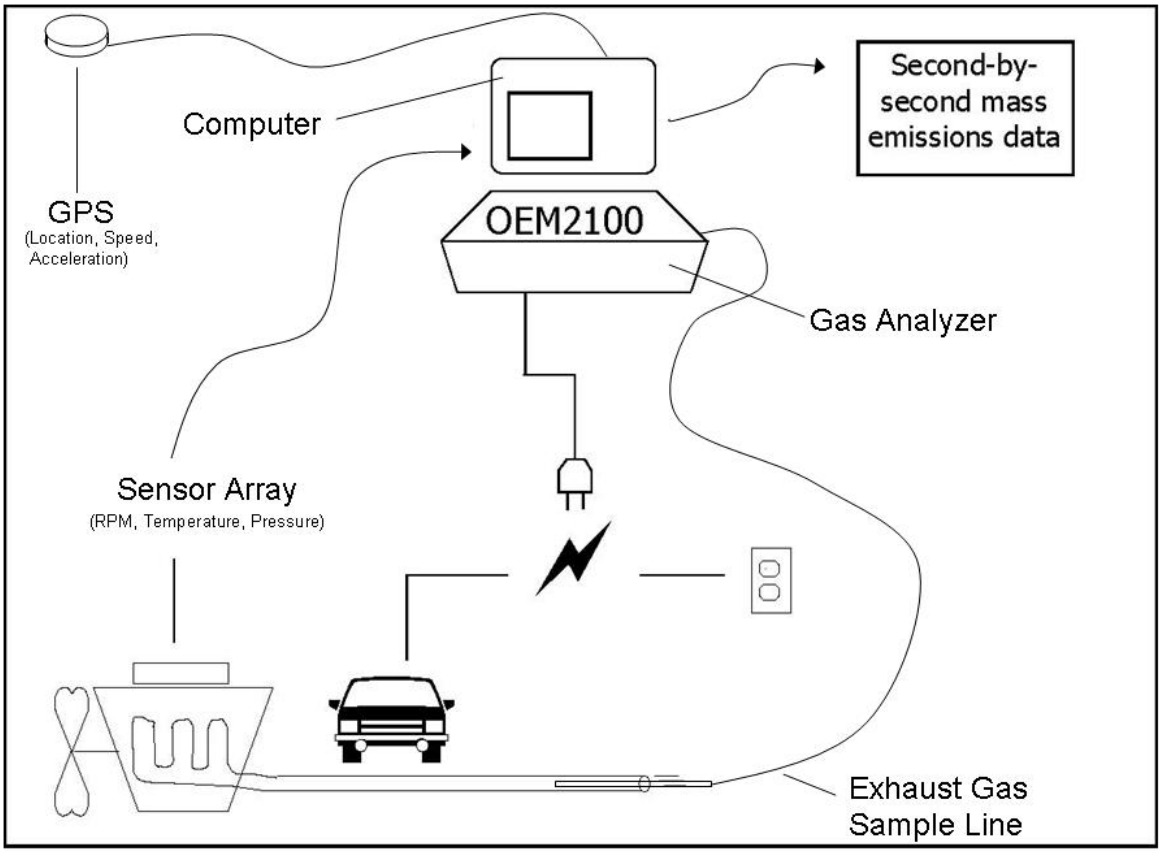


Figure 2-2 Conceptual Diagram of System Installation

An example of the installation for this test is shown in Figure 2-2.

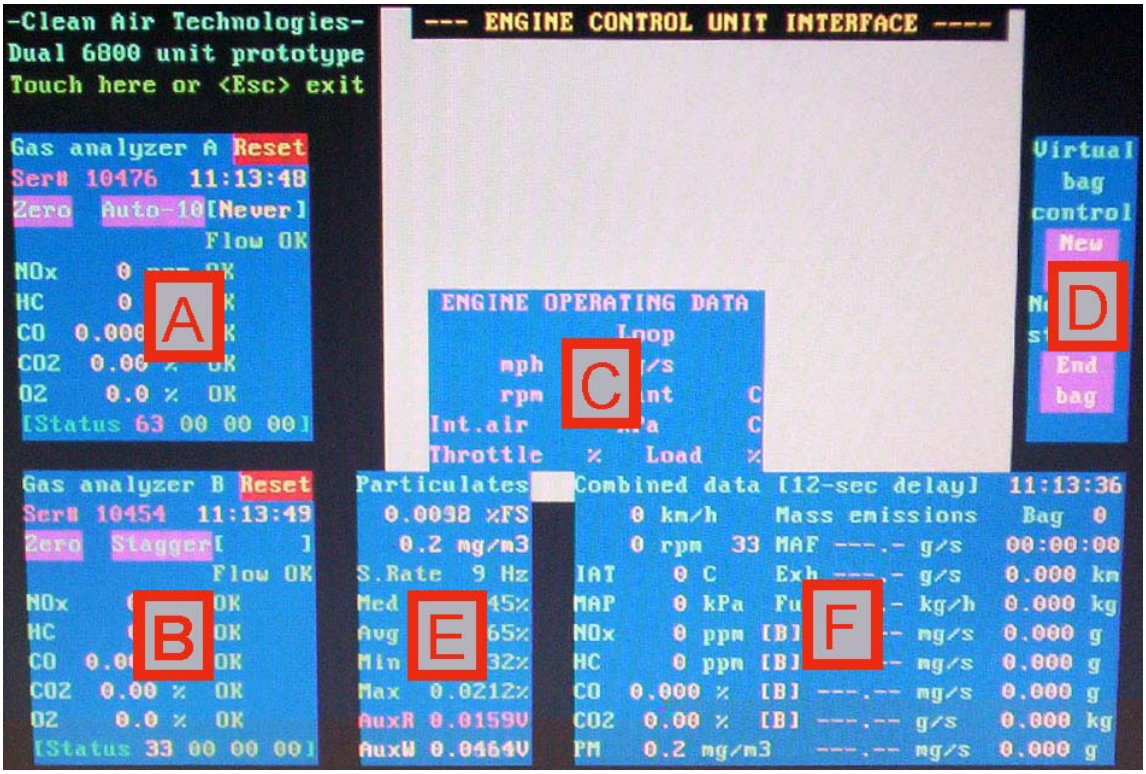
Figure 2-3 PEMS Installation

2.4 System Operation

While operating the PEMS, careful attention to detail is critical for obtaining high quality data. Successful operation of the PEMS requires understanding the system, entering correct set up parameters, periodically checking that the data is in reasonable ranges during real time operation, periodically calibrating the equipment, observing for leaks, pump failures or flooding with condensate, and frequently assuring that the installed hardware has not shifted or been damaged while driving.

There are four major subsystems to the PEMS unit: the computer, the sensor array signal conditioner, the sensor array including the GPS and the dual gas analyzers.

During PEMS operation, one screen, the operation screen shown in Figure 2-3, is used for instrument control and for displaying real time data output. Information is organized functionally, as described in the figure legend. Most functions can be controlled using the touch screen or keyboard.



A is for analyzer A

B is for gas analyzer B

C is for engine interface display

D is for bag control

E is for particulate analyzer display *(not used for this testing)*

F is for combined data display

Figure 2-4 PEMS Operation Screen.

Data is collected in the PEMS in a file with a name based on the date. With the file each segment of the test can be broken into a virtual "bag."

2.5 System Performance

CATI has previously performed comparison testing of the PEMS against laboratory systems from several laboratories using various vehicles and fuels, and have concluded that the PEMS is comparable to laboratory systems. Table 2-1 shows the expected accuracy of the PEMS for emissions. The accuracy for fuel efficiency is dependent on OBD input, if used. When using the sensor array, fuel efficiency is calculated using an assumed, static volumetric efficiency, engine displacement, RPM, the measured CO2 and GPS input for distance. Because volumetric efficiency is not static during normal engine operation, the accuracy of the fuel efficiency calculation will be less.

Gas	Measurement Range	Accuracy	Repeatability	Noise (rms)	Resolution
HC n-Hexane	0 - 2000 ppm 2001 - 1500 ppm 15001 - 30000 ppm	±4 ppm abs. or ±3% rel. ±5% rel. ±8% rel.	±3 ppm abs. or ±2% rel. ±3% rel. ±4% rel.	2 ppm abs. or 0.8% rel.	1 ppm
HC Propane	0 - 4000 ppm 4001 - 30000 ppm 30001 - 60000 ppm	±8 ppm abs. or ±3% rel. ±5% rel. ±8% rel.	±6 ppm abs. or ±2% rel. ±3% rel. ±4% rel.	4 ppm abs. or 0.8% rel.	1 ppm
CO	0.00 - 10.00% 10.01 - 15.00%	±0.02% abs. or ±3% rel. ±5% rel.	±0.02 abs. or ±2% rel. ±3% rel.	0.01% abs. or 0.8% rel.	0.001 vol. %
CO2	0.00 - 16.00% 16.01 - 20.00%	±0.3% abs. or ±3% rel. ±5% rel.	±0.1%abs. or ±2% rel. ±3% rel.	0.1% abs. or 0.8% rel.	0.01 vol. %
NO_x	0-4000 ppm 4001-5000ppm	±25 ppm abs. or ±4% rel. ±5% rel.	±20 ppm abs. or ±3% rel. ±4% rel.	10 ppm abs. or 1% rel.	1 ppm
O2	0.00- 25.00%	±0.1% abs. or ±3% rel.	±0.1% abs. or ±3% rel.	0.1% abs. or 1.5% rel.	0.01 vol. %

Table 2-1 PEMS Specifications for analyzers, gas benches, and sample lines

In order to obtain more accurate results and more closely match lab testing results, an approach for adjusting on-road data was developed to overcome the discrepancy between the assumed and actual volumetric efficiency for a given engine; this approach is highlighted in Section 6.2.

3.0 Phase 1 Dynamometer Testing

The Phase 1 (Baseline) Dynamometer Testing was conducted at SwRI in San Antonio. Four vehicles (see Table 3-1) were tested in December 2006 and January 2007 using the Light-Duty (LD UDDS) Drive Cycle.

The purpose of this work was to determine the effect of each type of hybrid drive system on emissions and vehicle performance in comparison to conventional trucks in a controlled replicable laboratory environment.

Information on the testing setup, data collection, and results are provided in the following sections. Finally, any problems encountered during the data collection were listed. Excerpts of the SwRI Interim Report for Project 12163, Titled "Emissions Testing of Various Delivery Trucks" dated February 7, 2007 are provided in this section with entire report found in Appendix D.

3.1 Data Collection Plan

Two conventional delivery trucks (older baseline diesel and newer baseline diesel) and two different hybrid-electric drive trucks (diesel hybrid and gas hybrid) were tested on the same heavy duty chassis dynamometer. Table 3-1 is a summary of each truck's mechanical configuration and test weight. Exhaust emissions of PM, NOx, HC, CO, and CO2 were measured for each truck. The emission levels of the hybrid trucks were compared to those of the conventional trucks. Fuel economy was calculated for each test using the carbon balance method. Energy balance corrections were considered for each hybrid truck per SAE Recommended Practice J2711 for heavy-duty hybrid drive vehicles.

Table 3-1 Vehicles Testing During Phase 1 Testing

Engine	Drivetrain	Fuel	Test Wt, lb
Older Baseline Diesel, General Motors, 6.5L V8, indirect injection Naturally aspirated	Automatic transmission	Diesel	9,180
Newer Baseline Diesel, Cummins 3.9L In-line 4, direct injection Turbocharged, intercooled	Automatic transmission	Diesel	9,160
Diesel Hybrid, International, 4.5L,V6, direct-injection Turbocharged, intercooled	Parallel Hybrid Electric, NiMH battery Pack, Automated manual transmission	Diesel	10,530
Gas Hybrid, General Motors V8, port injected Naturally aspirated	Series Hybrid Electric NiMH battery pack	Gasoline	10,730

Hybrid electric vehicles are typically equipped with energy storage devices. A difference in the storage device from beginning to end of the test run(a net energy change or NEC) will likely affect the measured emissions and fuel economy data. SAE J2711 was developed to provide a method to correct emissions and fuel economy data if the energy storage device's NEC varied by more than 1 percent of the total fuel energy consumed during the test. SAE J2711 does not recommend correcting data if the NEC is less than 1 percent. The length of the LD UDDS cycle chosen and energy expended by the main engine was sufficiently large that the NEC for each hybrid truck test was less than 1 percent, so no correction was required. The NEC values for each truck are included in this report.

SwRI conducted five hot-start emission tests on each of the four trucks over the same drive cycle, and the average value for each emission was used to compare the relative emission levels of the trucks. The light-duty UDDS (LD UDDS) drive cycle (see Figure 3-1) was chosen to test the trucks, as this drive cycle most closely patterns typical Frito-Lay Drive delivery activity for trucks under 10,000 lbs. Refer to Section 4.0 for a description of drive cycle analysis performed, and figures showing a typical Frito-Lay delivery speed versus time trace. The test plan for this testing is given in Table 3-2. The test weights included the truck's empty weight, fuel weight, driver, and half of the remaining cargo weight capacity. Cargo capacity is assumed at 11,500 pounds GVWR for the hybrid trucks which would be required of future hybrids versus the current 10,000 pounds of the current vehicles do to the increased mass of the drive system batteries, various control pieces, etc. On–road testing was limited to 10,000 pounds to remain legally compliant on total vehicle weight. Since maximum total cargo capacity is 20% of total GVWR, minor adjustment of the total weight would not have significant effect on the fuel economy or emissions results. This information was provided to SwRI by Frito-Lay. SwRI used this test weight and measured frontal area to calculate the road load using EPA's recommended procedure for heavy-duty chassis testing. SwRI used standard testing fuels for this phase of the testing. The diesel fuel had a density of 7.2 lb/gal and a sulfur content of 30 ppm by weight. The gasoline fuel density was 6.2 lb/gal, sulfur content of 21 ppm by weight, and (R+M)/2 octane rating of 93.

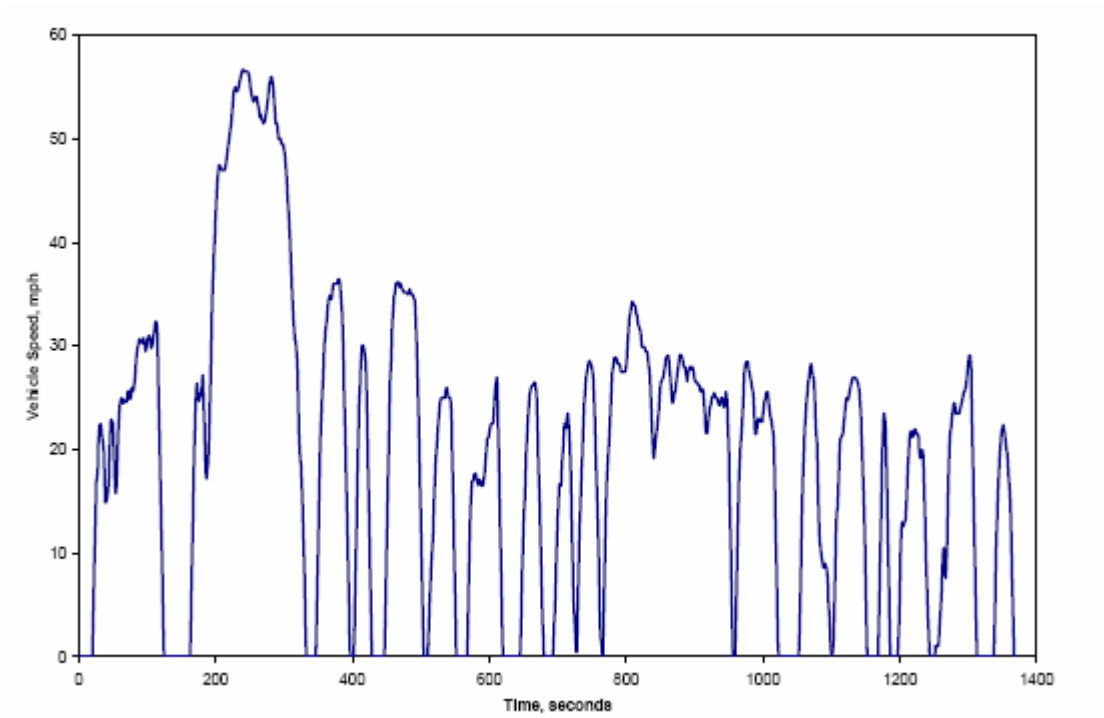


Figure 3-1. Light-Duty Urban Dynamometer Driving Schedule Drive Cycle

Table 3-2. Test Plan for Chassis Testing

Step	Description
1	Install the newer baseline diesel, and isolate fuel system, conduct coastdowns.
2	Conduct two prep runs.
3	Perform five hot-start tests for HC, CO, NOx, PM, and CO2
4	Remove the newer baseline diesel from dynamometer
5	Install the older baseline diesel and isolate fuel system, conduct coastdowns.
6	Conduct two prep runs.
7	Perform five hot-start tests for HC, CO, NOx, PM, and CO2
8	Remove the older baseline diesel from dynamometer
9	Install the gas hybrid, isolate fuel system, conduct coastdowns.
10	Set-up to record battery State of Charge (SOC) for SAE J2711 NEC Correction.
11	Conduct two prep runs.
12	Perform five hot-start tests
13	Remove the gas hybrid from dynamometer
14	Repeat Steps 9 through 13 for diesel hybrid.
15	After completing Part 1, release the trucks for Phase 2 operation and prepare the report for Phase 1 testing.

3.2 Summary of Phase 1 Dynamometer Testing Results

Data collection was conducted in December 2006. The test plan for each vehicle was conducted as shown in Table 3-2. The results for each vehicle are shown below. The SwRI Report is provided in its entirety in Appendix D.

3.2.1 Older baseline diesel - Test Results

This truck, VIN 1GBHP32Y8W3304305, was powered by a 1997 6.5L GM naturally-aspirated, in-direct injected diesel engine and was equipped with an automatic transmission. The truck was installed on the chassis dynamometer and tested at 9,180 lb. Coastdowns for this truck were conducted and are shown in Appendix D. The truck was then driven over the drive cycle once to condition the vehicle for the hot-start testing. After five hot-start tests were conducted, the first test appeared to be an outlier and a sixth test was performed while the truck was still on the dynamometer. However, after using ASTM-E178 criteria, the first test was not an outlier, so it was decided to use all six tests for the average and c.o.v. calculations. The test results for this truck are summarized in Table 3-3.

TABLE 3-3 EMISSION RESULTS FOR OLDER BASELINE DIESEL OVER LD UDDS DRIVE CYCLE

Test Code	HC g/mi	CO g/mi	NOx g/mi	PM mg/mi	CO2 g/mi	MPG	Fuel kg	Miles
4305-H1*	0.35	1.59	2.98	218	852	12.1	2.04	7.6
4305-H2	0.30	1.44	3.11	144	847	12.2	2.03	7.6
4305-H3	0.30	1.44	3.68	133	839	12.3	2.00	7.5
4305-H4	0.30	1.48	3.63	158	838	12.3	2.01	7.6
4305-H5	0.31	1.47	3.74	136	840	12.3	2.02	7.6
4305-H6	0.30	1.41	3.64	126	837	12.3	2.00	7.5
Average =	0.31	1.47	3.46	152	842	12.2	2.02	7.6
c.o.v.[1]	6%	4%	9%	22%	1%	1%	1%	0%

* This test was initially thought to be an outlier during testing, but it was not, using ASTM-E178. This test was used in the average and c.o.v. calculations.
[1] Coefficient of variance.

3.3.2 Newer baseline diesel - Test Results

This truck, VIN 5B4HP42P553404763, was powered by a 2005 3.9L Cummins, turbocharged, intercooled, direct injected diesel engine and was equipped with an automatic transmission. The truck was installed on the chassis dynamometer and tested at 9,160 lb. Coastdowns for this truck were conducted and are provided in Appendix D.

The truck was then driven over the drive cycle once to condition the vehicle for the hot-start testing. The five hot-start tests were conducted with a 20-minute soak in between each test to change emission sample bags and PM filters. The test results for this truck are summarized in Table 3-4.

TABLE 3-4 EMISSION RESULTS FOR NEWER BASELINE DIESEL OVER LD UDDS DRIVE CYCLE

Test Code	HC g/mi	CO g/mi	NOx g/mi	PM mg/mi	CO2 g/mi	MPG	Fuel Kg	Miles
4763-H1	0.15	2.23	6.27	78	715	14.4	1.71	7.5
4763-H2	0.14	2.37	6.30	78	707	14.6	1.70	7.6
4763-H3	0.14	2.32	6.20	74	707	14.6	1.69	7.5
4763-H4	0.16	2.28	6.21	73	701	14.7	1.69	7.6
4763-H5	0.13	2.32	6.07	75	696	14.8	1.68	7.6
Average =	0.14	2.30	6.21	75	705	14.6	1.69	7.6
c.o.v.[1]	6%	2%	1%	3%	1%	1%	1%	0%

[1] Coefficient of variance

3.2.3 Diesel Hybrid – Test Results

This truck, VIN 5B4HPD25363412537, was powered by a 2006 4.5L direct-injected turbocharged diesel engine and was equipped with parallel hybrid drive train using an electric motor between the engine and transmission. The transmission was an Eaton automated manual. The battery pack was nickel metal hydride (NiMH). This vehicle's hybrid system was not completely refined and the engine control unit was not using production software and calibrations, so the results of this truck may not be representative of the final product. The truck was installed on the chassis dynamometer and tested at 10,530 lb. Coastdowns for this truck are shown in Appendix D. The truck was driven over the drive cycle twice to condition the vehicle for the hot-start testing. The emission test results for this truck are summarized in Table 3-5 and the NEC values are summarized in Table 3-6. As described in the Data Collection Plan, the NEC for all of the tests for this truck were less than 1 percent, so no data correction was necessary.

TABLE 3-5 EMISSION RESULTS FOR THE DIESEL HYBRID OVER LD UDDS DRIVE CYCLE

Test Code	HC g/mi	NOx g/mi	PM mg/mi	CO g/mi	CO2 g/mi	Fuel kg	MPG	Miles
F2537-H1	0.56	5.04	181	2.14	679	1.62	15.1	7.5
F2537-H2	0.57	5.00	158	1.94	677	1.63	15.2	7.6
F2537-H3	0.53	5.05	148	2.05	671	1.62	15.3	7.6
F2537-H4	0.49	4.94	139	2.03	654	1.57	15.7	7.6
F2537-H5	0.50	4.86	154	2.38	654	1.57	15.7	7.5
Average =	0.53	4.98	156	2.11	667	1.60	15.4	7.5
c.o.v.	7%	2%	10%	8%	2%	2%	2%	0%

TABLE 3-6 NEC RESULTS FOR THE DIESEL HYBRID OVER LD UDDS DRIVE CYCLE

Test Code	SOC, %		NEC MJ	Fuel Energy, MJ	NEC %
	Start	End			
F2537-H1	51.5	53.0	0.10	71.3	0.0
F2537-H2	53.0	53.0	0.00	71.5	0.0
F2537-H3	53.0	53.0	0.00	71.2	0.0
F2537-H4	53.0	51.5	-0.10	69.2	0.0
F2537-H5	51.5	53.0	0.10	69.0	0.0

3.2.4 Gas Hybrid- Test Results

This truck, VIN 584KP02V063416051, was powered by a 2005 4.8L GM Vortec, port injected gasoline engine and was equipped with series hybrid drivetrain using two electric motors and a nickel metal hydride (NiMH) battery pack. The truck was installed on the chassis dynamometer and tested at 10,730 lb. Coastdowns for this truck are shown in Appendix D. The truck was then driven over the drive cycle once to condition the vehicle for the hot-start testing. As in the previous truck, after five hot-start tests were conducted, the first test appeared to be an outlier and sixth test was conducted. Using ASTM-E178, the NOx result from the first test was an outlier, so the sixth test was used in place of the first test for the average and c.o.v. calculations. The emission test results for this truck are summarized in Table 3-7 and the NEC values are summarized in Table 3-8. As described in the Data Collection Plan, the percent NEC for this truck was less than 1 percent for all of the tests, so no data correction was necessary.

TABLE 3-7. EMISSION RESULTS FOR GAS HYBRID OVER LD UDDS DRIVE CYCLE

Test Code	HC g/mi	CO g/mi	NOx g/mi	PM mg/mi	CO2 g/mi	MPG	Fuel kg	Miles
F6051-H1*	0.15	1.41	1.04	7	765	11.7	1.84	7.6
F6051-H2	0.12	2.21	0.37	10	739	12.0	1.77	7.6
F6051-H3	0.18	2.89	0.23	6	739	12.0	1.78	7.6
F6051-H4	0.15	2.51	0.28	5	748	11.9	1.80	7.6
F6051-H5	0.12	2.59	0.13	6	737	12.1	1.77	7.6
F6051-H6	0.17	2.35	0.28	8	742	12.0	1.79	7.6
Average =	0.15	2.51	0.26	7	741	12.0	1.78	7.6
c.o.v. [1]	19%	10%	34%	27%	1%	1%	1%	0%

* This test was an outlier based on the NOx value using ASTM-E178. This test was not used in the average and c.o.v. calculations.
[1] coefficient of variance

TABLE 3-8 NEC RESULTS FOR THE GAS HYBRID OVER LD UDDS DRIVE CYCLE

Test Code	SOC, %		NEC, MJ (megajoule)	Fuel Energy, MJ	NEC, %
	End	Start			
F6051-H1	61.0	58.5	-0.28	77.2	0.0
F6051-H2	58.5	58.0	-0.06	74.5	0.0
F6051-H3	58.0	56.5	-0.17	74.8	0.0
F6051-H4	56.5	58.0	0.17	75.7	0.0
F6051-H5	58.0	57.5	-0.06	74.5	0.0
F6051-H6	57.5	61.0	0.39	75.1	0.0

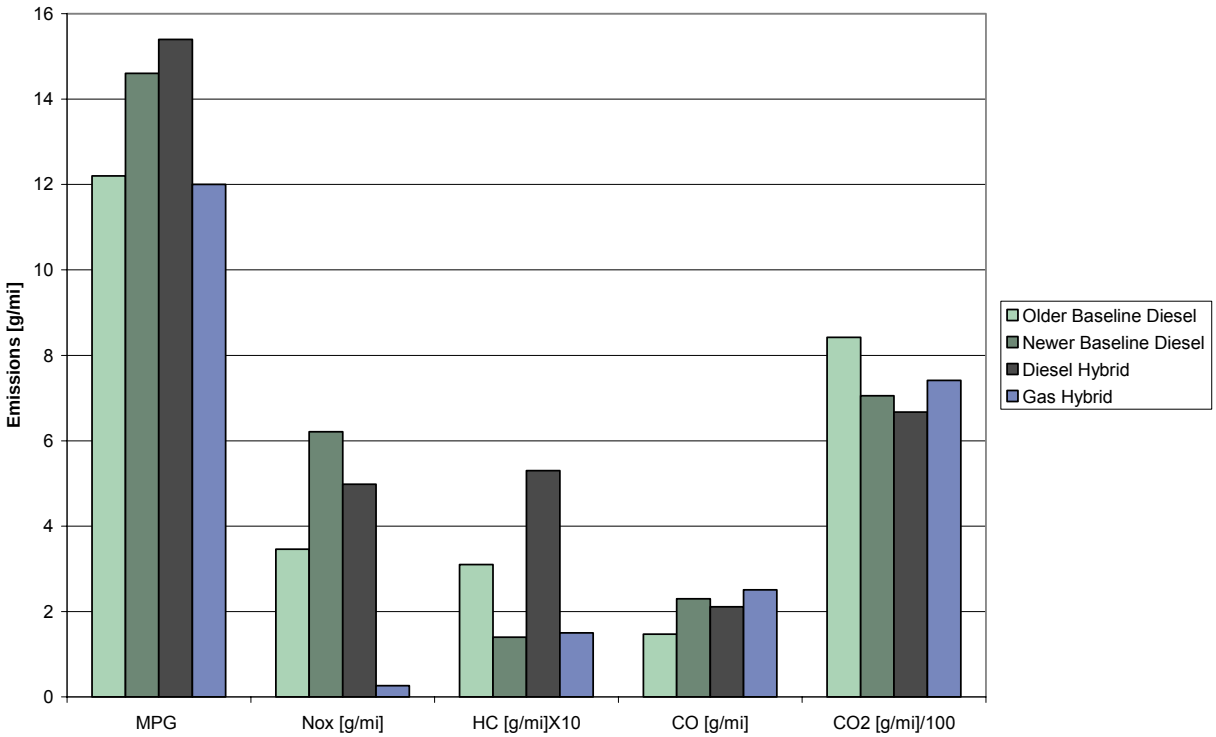
3.3 Summary

Four trucks with different engine and drive train combinations were tested over at least five runs of the same drive cycle. The emissions and fuel economy results were very different. Table 3-9 shows the average emissions values for each truck. Figure 3-10 ranks the trucks by emission and fuel efficiency from lowest to highest.

TABLE 3-9 AVERAGE EMISSION RESULTS FOR EACH TRUCK OVER LD UDDS DRIVE CYCLE

Test Code	HC g/mi	CO g/mi	NOx g/mi	PM mg/mi	CO2 g/mi	MPG	Fuel kg	Miles
Older Baseline Diesel	0.31	1.47	3.46	152	842	12.2	2.02	7.6
Newer Baseline Diesel	0.14	2.30	6.21	75	705	14.6	1.69	7.6
Diesel Hybrid	0.53	2.11	4.98	156	667	15.4	1.60	7.5
Gas Hybrid	0.15	2.51	0.26	7	741	12.0	1.78	7.6

Figure 3-2 Ranking of Trucks by Emissions and Fuel Economy



The newer baseline diesel was equipped with a direct-injection, turbocharged diesel engine with an automatic transmission. The engine was the smallest displacement of the trucks tested. This type of engine configuration and displacement is very fuel efficient compared to the other engine configurations tested, and this truck produced the second highest fuel economy of the four trucks, only the parallel hybrid diesel truck was better. The PM emission for this truck was the lowest of the diesel powered trucks, only the gasoline powered hybrid had a lower level. This truck had the second highest CO emissions, which was somewhat unexpected, since the HC emissions were so low, however, the small displacement may have moved the engine into operating into a region where the air-fuel ratio was richer than at lighter load conditions. Another consequence of the engine's small displacement and high load conditions was high NOx emissions. This truck had the highest NOx emissions of the trucks tested, which was expected.

The older baseline diesel was equipped with indirect-injection (IDI), naturally-aspirated diesel engine with an automatic transmission. The engine had the largest displacement at 6.5L and was the oldest in terms of model year and technology. The truck had the second highest HC emissions and the highest of the three diesel powered trucks. This was likely due to the low-pressure fuel injection system and high cylinder crevice volume, typical of IDI engines. The truck produced the lowest CO and second lowest NOx emissions. Naturally-aspirated engines typically have lower peak cylinder

pressures compared to turbocharged engines and, therefore, the in-cylinder peak temperatures, which cause NOx to form, are lower. Lower NOx often corresponds to higher PM, as was the case for this truck. The older baseline diesel produced the second highest PM emissions. The truck produced the most CO2 emissions.

The gas hybrid produced the lowest emissions except for CO and CO2. The truck was equipped with a gasoline engine with 3-way catalysts and a series hybrid drive train. Gasoline engines also produce almost no PM, even without after treatment, so the low PM number was expected. The truck produced the highest CO emissions, which is likely due to the high CO typical of gasoline engines any time the air-fuel ratio becomes fuel rich. Finally, the truck produced the second highest CO2 emissions and the worst fuel economy of the four tested during Phase 1. In general, gasoline engines are less fuel efficient than diesel engines, especially at light load conditions, so it was not surprising that even with a hybrid drive train, the CO2 emissions were higher than all but the naturally-aspirated older baseline diesel truck.

As noted previously for the diesel hybrid, the hybrid system was not completely refined and the engine control unit was not using production software and calibrations, so the results of this truck may not be representative of the final product. Despite these limitations, the truck produced the lowest CO2 and highest fuel economy of the trucks tested. This truck was equipped with a direct-injection, turbocharged diesel engine with parallel hybrid drive train. The truck produced the highest HC and PM emissions. The truck did have an electric motor in place of a traditional clutch, but the hybrid system was not completely refined. It is difficult to say if these are representative of the final product, as better controls may reduce the observed emission levels.

3.4 Problems Encountered during Data Collection

All trucks were successfully tested and there were no mechanical failures. After emission testing was completed under Phase 1, the trucks were released for use in the field by representatives of Frito-Lay for on road testing of each system. After on-road mileage accumulation, all four trucks returned under Phase 3 for re-testing to quantify any deterioration in performance of each vehicle.

4.0 Phase 2 On-Road Emission Data Collection

In this section, the emission data collection methods will be described. The data collection plan will be introduced first, followed by the data collection procedures. The problems encountered during the data collection procedures will be listed. The final areas to be presented will be summarized observations by the drivers on drivability and lastly observations on data collection.

Figure 4-1 On-Road Testing

4.1 Data Collection Plan

The on-road testing involved 'real world' emissions and vehicle performance monitoring in the Dallas-Fort Worth (DFW) and Houston areas in simulated Frito-Lay product delivery operation for various fixed delivery routes. During testing, emission and performance monitors with GPS were installed in both the base line and hybrid vehicles and provided real time data acquisition. The emission monitors measured NO_x concentrations, vehicle speed, distance and miles per gallon (MPG). On-road emission measurements were done with the PEMS. The key objectives to the on-road testing were to collect real-world vehicle emissions and activity data on DFW and Houston area roads using the PEMS; to analyze characteristics of the on-road vehicle emissions and determine the operational factors which play the largest role in fuel consumption and emissions generation; and to determine the reduction in fuel consumption and NO_x emissions between conventional and hybrid vehicles. The Frito-Lay delivery operation was analyzed using GPS, and the data gathered in the analysis was used to select the routes for the on-road testing so that representative results of the Frito-Lay delivery operation were obtained.

Because of delays in the delivery of the hybrid test vehicles, the testing was taken "offline" from the normal delivery operation. Since a number of replications were required to achieve statistically valid data, this approach allowed for a number of replicates to be run each day, rather than just once, providing much more data on a daily basis. A dummy load of sand was used to simulate the loaded weight of the trucks. On-road testing was performed with a nominal 800 pound sand "cargo" load, which represents half of a typical daily delivery load in current operation. Since a Frito-Lay delivery truck typically leaves full and returns empty, half of the normal load would provide an average cargo weight through daily delivery operation. Every effort was made in the course of test execution and design to closely simulate the normal daily delivery operations to ensure the data gathered was representative of actual delivery activities.

Figure 4-2 Simulated Cargo Load for Test Trucks

Frito-Lay conducted a drive cycle analysis to determine typical route types, mileage, and speeds as shown in Table 4-1 below.

			Distribution Center Pre-Pick			
			Minimum	Average	Maximum	Std
	Speed (Avg)	mph	13.4	21.1	34.6	6.6
	Daily Drive Distance	miles	8.3	26.8	52.6	15.4
	Drive Time Per Day	min	37.3	72.2	122.0	25.0
Time Basis	Crawling (<10 mph)	%	19.8%	31.4%	38.5%	6.6%
	City (0-30 mph)	%	32.6%	53.3%	66.0%	11.4%
	Suburban (30-45 mph)	%	22.1%	35.8%	42.4%	5.4%
	Highway (>45 mph)	%	0.0%	12.7%	45.3%	13.9%
Miles Basis	Crawling (<10 mph)	%	0.9%	4.8%	38.1%	11.1%
	City (0-30 mph)	%	4.7%	15.9%	45.6%	11.7%
	Suburban (30-45 mph)	%	20.0%	60.2%	78.2%	17.9%
	Highway (>45 mph)	%	0.0%	24.0%	75.3%	24.6%
	Total route days		149			
	Total miles		3994			
	# of trucks in sample		11			

Table 4-1 Frito-Lay Existing Fleet Drive Cycle Analysis Summary

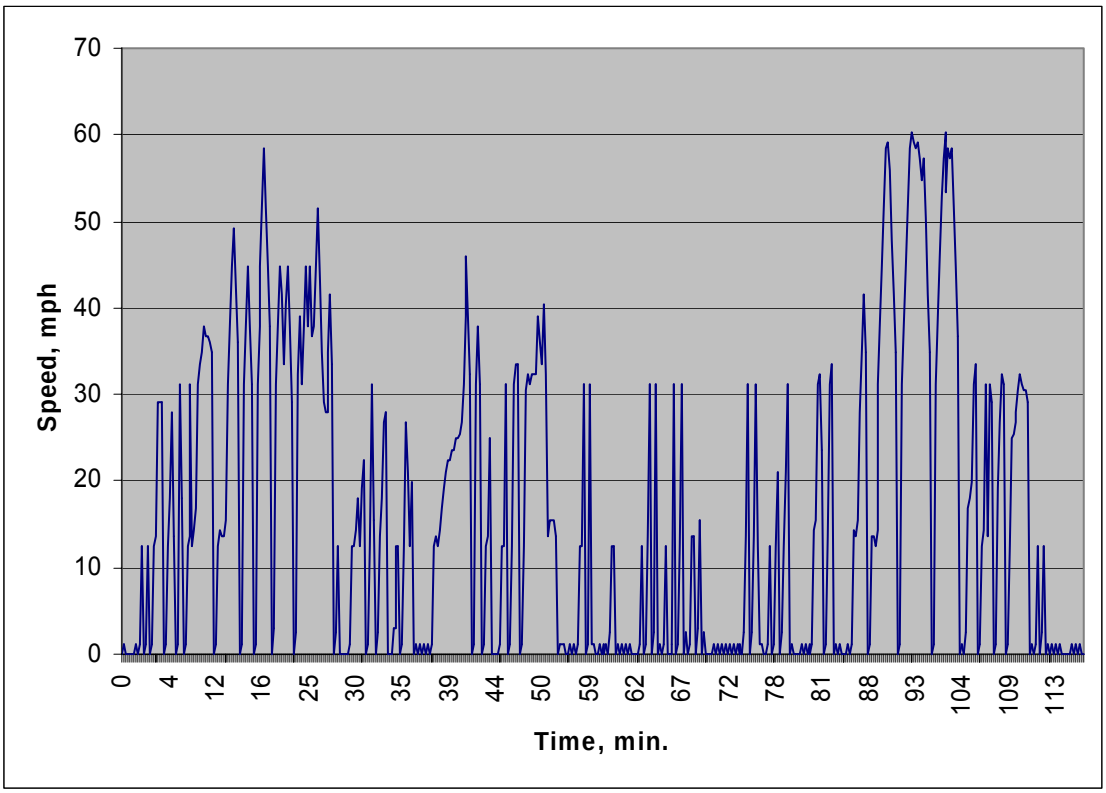


Figure 4-3 Frito-Lay Delivery Truck Drive Cycle Time versus Speed Trace

Using the drive cycle analysis, routes in the DFW and Houston areas were identified for use in the testing. These two metropolitan areas were chosen because they are listed

by EPA as air quality non-attainment areas for zone which id formed through a chemical reaction from oxides of nitrogen (NO_x). Three different routes were chosen to make sure a representative lot of data would be obtained and to determine if the specific route type selected would have an impact on the results. In the DFW area two routes were chosen to represent a suburban type route without freeway driving and an urban route with freeway transit time traveling to the service area and returning to the distribution center. The DFW North suburban route covered surface roads for the entire route, included eight services stops and covered approximately 22 miles. The second route, DFW South, required freeway driving to the service area and return to the distribution center, included nine service stops and covered approximately 28 miles. The Houston route was an urban route without freeway driving, included nine service stops, and covered approximately 14 miles. Each of these routes is considered by driving type to be very representative of the majority of delivery activity within large metropolitan areas. Table 4-2 below shows a comparison of the three routes chosen to the type of routes identified in the original drive cycle analysis. Based on the comparison of drive time, distance, and speed, the routes chosen are considered to be representative of the delivery of routes Frito-Lay uses in their normal business. Maps of all three routes are shown in Appendix E.

Based on the overall drive cycle analysis and categorization of speed ranges as % of time and distance, as well as individual daily drive cycle trace analysis, it was determined that the LD UDDS drive cycle most close matched current delivery drive behavior among the existing standard drive cycles available.

		On-Road Testing Drive Cycle			Frito-Lay Existing Fleet Drive Cycle			LD UDDS
		DFW South	DFW North	Houston	Minimum	Average	Maximum	SWRI
	Speed (Avg)	27.4	25.0	20.9	13.4	21.1	34.6	19.93
	Daily Drive Distance	27.4	21.6	13.7	8.3	26.8	52.6	7.45
	Drive Time Per Day	60.2	53.1	50.7	37.3	72.2	122.0	22.4
Time Basis	Crawling (<10 mph)	16.5%	19.2%	22.3%	19.8%	31.4%	38.5%	11.5%
	City (0-30 mph)	59.2%	56.7%	56.3%	32.6%	53.3%	66.0%	65.2%
	Suburban (30-45 mph)	27.1%	45.1%	19.6%	22.1%	35.8%	42.4%	9.6%
	Highway (>45 mph)	13.7%	0.0%	1.8%	0.0%	12.7%	45.3%	7.6%
Miles Basis	Crawling (<10 mph)	3.4%	4.6%	7.4%	0.9%	4.8%	38.1%	3.0%
	City (0-30 mph)	37.0%	39.3%	50.8%	4.7%	15.9%	45.6%	63.4%
	Suburban (30-45 mph)	35.8%	64.5%	44.0%	20.0%	60.2%	78.2%	16.5%
	Highway (>45 mph)	27.3%	0.0%	5.1%	0.0%	24.0%	75.3%	6.7%

Table 4-2 Road Test Drive Cycle Analysis Comparison

It was anticipated that the on-road testing would require 6 weeks, including 4 weeks of on-road evaluation in the DFW area and 2 weeks in Houston, as well as some “practice” runs in both areas. The actual timing was 18 weeks total due primarily to issues with the PEMS, weather, vehicle preparedness, and the late addition of an additional gas baseline vehicle. Because the gas baseline vehicle was added after the completion of the Houston portion of the testing results are only available for the DFW routes.

Vehicles at Sam Houston Service Center
Houston, TX

Gas Hybrid Truck Leaving for on-road testing, D/FW area

Figure 4-4 Trucks Undergoing On-Road Testing

The on-road test schedule is shown below in Table 4-3. The design rotated both the baseline and the hybrid trucks through the selected routes, and provided for 15 replications per route. Since the project budget allowed for lease of two PEMS, the monitoring equipment had to be alternated between the baseline and the hybrid vehicles during on-road testing. Two vehicles were on the same route each run and followed each other allowing the vehicle pairs to experience the same road conditions. All on road testing was done by the same two drivers through out the testing.

DFW Runs									
		North Run				South Run			
		Gas Hybrid	Newer Baseline Diesel	Diesel Hybrid	Older Baseline Diesel	Gas Hybrid	Newer Baseline Diesel	Diesel Hybrid	Older Baseline Diesel
Week 1	Day 1	4	4	-	-	-	-	-	-
	Day 2	4	4	-	-	-	-	-	-
	Day 3	4	4	-	-	-	-	-	-
	Day 4	3	3	-	-	-	-	-	-
	Day 5	-	-	-	-	4	4	-	-
Week 2	Day 1	-	-	-	-	4	4	-	-
	Day 2	-	-	-	-	4	4	-	-
	Day 3	-	-	-	-	3	3	-	-
	Day 4	-	-	4	4	-	-	-	-
	Day 5	-	-	4	4	-	-	-	-
Week 3	Day 1	-	-	4	4	-	-	-	-
	Day 2	-	-	3	3	-	-	-	-
	Day 3	-	-	-	-	-	-	4	4
	Day 4	-	-	-	-	-	-	4	4
	Day 5	-	-	-	-	-	-	4	4
Week 4	Day 1	-	-	-	-	-	-	3	3
		15	15	15	15	15	15	15	15

Houston Runs					
		Gas Hybrid	Newer Baseline Diesel	Diesel Hybrid	Older Baseline Diesel
Week 5	Day 1	-	-	4	4
	Day 2	-	-	4	4
	Day 3	-	-	4	4
	Day 4	-	-	3	3
	Day 5	4	4	-	-
Week 6	Day 1	4	4	-	-
	Day 2	4	4	-	-
	Day 3	3	3	-	-
		15	15	15	15

DFW Runs Baseline Gas			
		North Run	South Run
Week 7	Day 1	4	-
	Day 2	4	-
	Day 3	4	-
	Day 4	3	-
	Day 5	-	4
Week 8	Day 1	-	4
	Day 2	-	4
	Day 3	-	3
		15	15

Table 4-3 Frito-Lay Hybrid Route Truck Project Road Test Schedule

Figure 4-5 Gasoline Hybrid Truck Operator and Maintenance Training and Preparation for On-Road Testing

In preparation for the on-road testing phase, each hybrid truck supplier provided maintenance and operator training on the hybrid vehicles at Frito-Lay's Fleet Service Center in Fort Worth.

4.2 Data Collection Training

The PEMS is a very sensitive scientific monitoring device, and the road testing team was provided with instructions regarding set-up and operation. In addition close communication with CATI was maintained throughout testing.

After the SWRI lab testing, preliminary tests were conducted in December 2006 using two of the vehicles identified for the on road testing. During the preliminary tests, the RPM sensor occasionally failed to work. Also it was found that the associated GPS system did not perform consistently and the research team determined that more training on applying sensor arrays, system maintenance, and data processing was necessary. A technician from CATI was requested onsite in Fort Worth to assist in equipment repairs and to provide additional training and troubleshooting.

During the site visit, the CATI technician repaired the GPS system, replaced the RPM multiplexer, illustrated the sensor array placement in the engine compartment, and shared CATI's experiences on collection and data processing.

Ongoing support was provided by CATI throughout the testing process. Whenever there was a problem, close communication with the technicians in CATI via phone calls and e-mail was conducted and resolutions to the problems were discussed.

A second onsite visit was required by the CATI technician to resolve additional equipment issues and provide additional instruction for troubleshooting. During the last week of on-road testing a third visit by the CATI technician was required to resolve more equipment issues and to provide on-site support during the final runs to ensure the data collected was correct.

4.3 Data Collection Procedure

Data collection was conducted from January 2007 to April 2007. The Hybrid Project Test Truck Data Sheet (Table 1-2) was used in setting up the PEMS for each truck. For each of the tests, the Daily Vehicle and Run Checklists, as shown in Figure 4-5, were completed to record the testing conditions for data processing purposes and to highlight issues encountered during the runs. A typical completed checklist for each vehicle can be found in Appendix E.

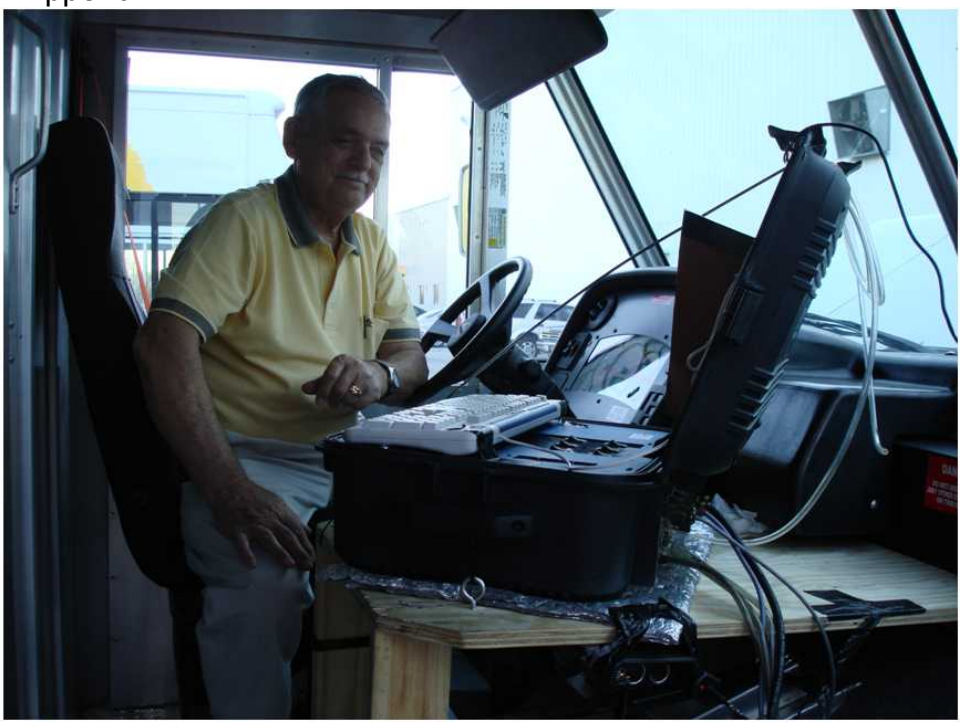


Figure 4-6 Vehicle Driver Readying PEMS for On-Road Test Run

Frito-Lay Hybrid Vehicle Evaluation
Daily Vehicle and Run Checklist

Date:			**Run 1**	**Run 2**	**Run 3**
Vehicle No.:		File Number			
Driver Name:		Bag Number			
Insurance Papers Present		Start Mileage			
Vehicle Registration Present		Route			
Temperature F		Run start time			
Weather (Rainy, Cloudy, Sunny)		Stop 1 key off			
		Mileage			
PRE-RUN INSPECTIONS AND START-UP		Stop 1 key on			
Truck Inspection		Stop 2 key off			
Tire Pressure:		Mileage			
Front Left (Green - Red Corrected) 75 psi		Stop 2 key on			
Front Right (Green - Red Corrected) 75 psi		Stop 3 key off			
Rear Left		Mileage			
Inner (Green - Red Corrected) 75 psi		Stop 3 key on			
Outer (Green - Red Corrected) 75 psi		Stop 4 key off			
Rear Right		Mileage			
Inner (Green - Red Corrected) 75 psi		Stop 4 key on			
Outer (Green - Red Corrected) 75 psi		Stop 5 key off			
Fuel Type		Mileage			
Fuel Gauge Reading		Stop 5 key on			
		Stop 6 key off			
Analyzer Inspection Start-up		Mileage			
Last System Calibration (date)		Stop 6 key on			
Analyser Filter Cleaned (date)		Stop 7 key off			
Battery Charge		Mileage			
Analyser Turned on for Warm Up (time)		Stop 7 key on			
Analyser Start Up		Stop 8 key off			
1. Connect power cable to battery		Mileage			
2. Turn on all 6 switches		Stop 8 key on			
3. Follow prompts on screen		Stop 9 key off			
4. Do not edit any information click 'Y","Y" and enter		Mileage			
5. This should have you at the data screen		Stop 9 key on			
6. Allow the sysytem to warm up for 45 minutes		Stop 10 key off			
7. Complete the rest of the check list items.		Mileage			
Troubleshooting tips		Stop 10 key on			
Verify RPM is reading. If not push "P" key on diesel truck		End Time			
Verify RPM is reading. If not push "S" key on gas hybrid truck		End Mileage			
Verify temperature reading		Total Mileage			
Starting Runs					
1. After system warm up:			**Ending Runs**		
2. Connect exhuast sampling hose to filters on analysers		1. Stop at gate push "-" to stop bag			
3. Start diesel truck and let run for 5 minutes			**Ending day**		
4. Start Hybrid truck and make three laps in the parking lot with gas engine running		1. Press <ESC> to write file			
5. Press <ESC> This creates file number		2. Disconnect exhaust sampling hose			
6. As you pull through the gate push "+" to create bag number		3. Let sampler run 5 minutes and turn unit off			
7. Record time and mileage at each stop using the time from		4. Exchange batteries or hook up charger.			
Notes:					

Figure 4-7 Sample Daily Vehicle and Run Checklist

4.4 Problems Encountered During Data Collection

There were several problems encountered during the data collection process. The data collection and data processing workload was much higher than originally anticipated primarily due vehicle operational problems and the unreliability of the PEMS monitoring equipment. The following provides some of the major problems encountered.

1. Data collection was delayed approximately one week due to lack of up-to-date state registrations and inspections on four of the five test vehicles.

2. During initial start-up, the gas hybrid control program did not function properly requiring two service technician visits to resolve. This episode resulted in the loss of four days initially, but was successfully resolved for the remainder of testing.

3. It was necessary to spend a considerable amount of time repairing the hardware problems encountered with the PEMS. Some of the issues were related to poor workmanship in the electrical assembly, insufficient information on correct set-up and installation of the PEMS and component failures including an irreparable crash on one PEMS during the final weeks of testing.

4. The PEMS program “froze” or “locked up” time after time during the testing with no assignable cause. This increased the workload of data processing in order to “stitch” together data files for an entire run. At times the tests had to be terminated to wait for CATI technicians to provide instructions how to proceed or to arrive on site to effect repairs. Other test delays were caused by the shipment of repair parts from CATI or their vendors. These issues resulted in the delay of almost one month in collecting valid data. In addition one test route in DFW had to be repeated three times before finally obtaining valid data extending the testing by almost three weeks.

4.5 Drivability Observations

In addition to assessing the efficiency and emissions of the hybrid vehicles, the drivers were periodically asked for drivability observations of the trucks. This was accomplished through informal interviews during the road test portion of the project. Below is a summary of those discussions.

Gas Hybrid Drivability Observations:

- Initial driver comments centered on the control systems problems encountered that required a full shut down and reset of the truck. After a service visit and reload of the control program these problems were resolved.
- In electric mode, the vehicle was sensitive to pressure on the accelerator, making creeping and lower speed operation difficult.

- The drivers noted good acceleration from a stop with the electric drive.
- Drivers commented on becoming familiar with hearing the engine turn off and on while moving down the street.
- Drivers commented on becoming familiar with the sound of the engine running at high RPM, but not shifting.
- Drivers discussed the need to adjust driving style to take advantage of electric operation by not flooring the accelerator which causes the gas engine to start before needed.

Diesel Hybrid Drivability Observations:

- There were comments about the need to ensure the parking brake was set whenever leaving the vehicle. This was required since the transmission did not lock when the transmission selector was placed in park.
- During the road testing the motor would idle at high RPM requiring the drivers to stop the vehicle and shift the transmission to park and then return to gear to lower the RPM. This problem was resolved prior to the second round of dynamometer testing (Phase 3).
- The vehicle was sluggish when in non-hybrid mode.
- The drivers expressed concern about the location of the battery pack which was located close to the ground level. The battery could be damaged from high spots in the street and parking lots.

4.6 Data Collection Observations

During and after the on-road testing was complete a review of the data collection process was conducted to determine areas for further study or improvement. Below is a summary of the review with recommendations.

PEMS Equipment

The PEMS equipment provided consistent and repeatable data. As mentioned above, there is opportunity for improvement in the area of mechanical and electrical reliability of the unit wiring and attached components. More thorough explanation of emission and vehicle performance collection methods and use in the performance calculations is needed. The PEMS uses a sensor array that does not provide direct measurement of some parameters and therefore these parameters must be calculated using other measured parameters and static values. To more effectively use the PEMS, the option of the vehicle diagnostics port should be the primary method for collecting engine performance parameters.

Daily Run Review

An end-of-day review should be consistently conducted to ensure observations and daily run checklists are completely filled out, and to determine if there are trends in the data that need to be addressed immediately.

Fuel Efficiency Tracking

The PEMS performs calculations for fuel efficiency based on emissions. Because there are multiple factors that impact the accuracy of this calculation, an alternative method for fuel efficiency should be employed. During this test, fuel purchased was logged on the daily run checklists and electronic fuel purchase records were used. Both of these methods should be reviewed at least weekly to verify accuracy and completeness.

Figure 4-8 Gas Hybrid and Newer Baseline Diesel Trucks in Fort Worth Fleet Service Center Garage during Phase 2 On-Road Testing

5.0 Phase 3 Dynamometer Testing

The Phase 3 testing was conducted at the SwRI facility. Excerpts from the SwRI report are provided in this section. The SwRI report, SwRI Letter Final Report Titled, "Emissions Testing of Various Delivery Trucks", Project 03-12163, dated May 15, 2007 is provided in it's entirety in Appendix F. Table 5-1 lists the vehicles tested and their mechanical configuration and test weight.

TABLE 5-1 TRUCK CONFIGURATION SUMMARY

Truck	Engine	Drivetrain	Fuel	Test Wt, lb.
older baseline diesel	General Motors, 6.5L V8, indirect-injection Naturally aspirated	Automatic transmission	Diesel	9,180
newer baseline diesel	Cummins 3.9L In-line 4, direct-injection, turbocharged, intercooled	Automatic transmission	Diesel	9,160
baseline gas	Ford 5.4L, V8 port-injection, Naturally aspirated	Automatic transmission	Gasoline	9,010
Diesel hybrid	International, 4.5L V6, direct-injection, turbocharged, intercooled	Parallel Hybrid Electric, NiMH battery pack, Automated manual transmission	Diesel	10,530
Diesel hybrid (hybrid disabled)	International, 4.5L V6, direct-injection, turbocharged, intercooled	Automated manual transmission	Diesel	10,530
Gas hybrid	General Motors, 4.8L V8, port-injected Naturally aspirated	Series Hybrid Electric, NiMH battery pack	Gasoline	10,730

The trucks that were tested in December 2006 and January 2007 left SwRI and were operated in the field by Frito-Lay from January 2007 through March 2007. The four trucks returned for chassis dynamometer testing near the end of March 2007. During that time, the diesel hybrid received updates for the hybrid system and engine control to provide better performance and drivability. An idle fuel-control problem was present on this vehicle, caused by is-communication between the hybrid drive controller and the main diesel engine ECM. At idle and very low throttle inputs, while in neutral or electric drive mode, the engine speed would oscillate. This oscillation had the potential effect of increasing fuel use and emissions at periods of low torque demand, but did not materially effect drivability. The engine recalibration performed by International's engineers prior to Phase 3 testing successfully solved the engine speed oscillation and provided

operation more representative of what to expect in a commercially-available vehicle. Therefore, due to the engine calibration state in Phase 3 versus that in Phase 1, more emphasis will be placed on Phase 3 dynamometer test results.

Figure 5-1 Diesel Hybrid Receiving Updated Engine Calibration at Sam Houston Service Center

Frito-Lay also requested that SwRI test the diesel hybrid with the hybrid system disabled and test another truck, a gas baseline, which is representative of a conventional, new vehicle purchase gasoline-powered configuration to compare to the gas hybrid. Table 5-1 is a summary of each truck's mechanical configuration and test weight. Exhaust emissions of PM, NO_x, HC, CO, and CO_2 were measured for each truck. The emissions levels of the hybrid trucks were compared to those of the conventional trucks. Fuel economy was calculated for each test using the carbon balance method. Energy balance corrections were considered for each hybrid truck per SAE Recommended Practice J2711 for heavy-duty, hybrid-drive vehicles.

5.1 Data Collection Plan

The purpose of this work was to determine the effect of each type of hybrid drive system on emissions in comparison to conventional trucks. SwRI conducted five hot-start emission tests on each of five trucks over the same drive cycle, and the

average value for each emission was used to compare the relative emission levels of the trucks. Frito-Lay chose to test the trucks over the same LD UDDS drive cycle that was used in the Phase 1 testing described in Chapter 3.0. The test plan for Phase 3 is given in Table 5-2. Frito-Lay provided the test weights used by SwRI using the sum of each truck's dry empty weight, fuel weight, driver, and half of the remaining cargo weight capacity. SwRI used this test weight and measured frontal area to calculate the road load using EPA's recommended procedure for heavy-duty chassis testing. The diesel trucks were fueled with ultra-low sulfur diesel with a density of 7.2 lb/gal. The gasoline truck used commercially-available gasoline with a density of 6.2 lb/gal.

TABLE 5-2 TEST PLAN FOR CHASSIS TESTING

Step	Description
1	Install newer baseline diesel, isolate fuel system, conduct coastdowns.
2	Conduct two prep runs.
3	Perform five hot-start tests for HC, CO, NOx, PM, and CO2.
4	Remove newer baseline diesel from dynamometer.
5	Repeat Steps 1 through 4 for older baseline diesel.
6	Install gas hybrid with test fuel in on-board fuel tank, conduct coastdowns.
7	Set-up to record battery State of Charge (SOC) for SAE J2711 NEC correction.
8	Conduct two prep runs.
9	Perform five hot-start tests for HC, CO, NOx, PM, and CO2.
10	Remove gas hybrid from dynamometer.
11	Install diesel hybrid and isolate fuel system, conduct coastdowns.
12	Set-up to record battery State of Charge (SOC) for SAE J2711 NEC correction.
13	Conduct two prep runs.
14	Perform five hot-start tests for HC, CO, NOx, PM, and CO2.
15	Disable hybrid drive system on diesel hybrid
16	Repeat Steps 3 and 4.
17	Remove diesel hybrid from dynamometer.
18	Install baseline gas with test fuel in on-board fuel tank, conduct coastdowns.
19	Repeat Steps 14 through 16 for baseline gas.
20	Prepare final report.

5.2 TEST RESULTS

The following sections describe each vehicle's installation, coastdown, and emissions results. In the case of the hybrid trucks, a table with the NEC value for each test is included in the corresponding sections.

5.2.1 Older diesel baseline - Test Results

The older diesel baseline, VIN 1GBHP32Y8W3304305, was powered by a 1997 6.5L GM naturally-aspirated, indirect injected diesel engine and was equipped with an automatic transmission. The truck was installed on the chassis dynamometer and tested at 9,180 lb. Coastdowns for this truck were conducted and are described in the report provided in Appendix F. The truck was then driven over the drive cycle once to condition the vehicle for the hot-start testing. The five hot-start tests were conducted, and the test results for older diesel baseline are summarized in Table 5-3.

TABLE 5-3 EMISSION RESULTS FOR OLDER BASELINE DIESEL OVER LD UDDS DRIVE CYCLE

Test Code	HC, g/mi	CO, g/mi	NO_x, g/mi	PM, mg/mi	CO_2, g/mi	MPG	Fuel, kg	Miles
4305B-H1	0.37	1.70	3.52	147	834	12.4	1.99	7.53
4305B-H2	0.33	1.58	3.55	126	830	12.4	1.99	7.55
4305B-H3	0.35	1.68	3.49	135	836	12.3	2.06	7.77
4305B-H4	0.33	1.67	3.50	143	840	12.3	2.03	7.61
4305B-H5	0.33	1.61	3.52	137	835	12.3	1.99	7.52
Average =	**0.34**	**1.65**	**3.52**	**137**	**835**	**12.3**	**2.01**	**7.60**
c.o.v.	5%	3%	1%	6%	0%	0%	2%	1%

5.2.2 Newer diesel baseline - Test Results

The newer baseline diesel, VIN 5B4HP42P553404763, was powered by a 2005 3.9L Cummins, turbocharged, intercooled, direct injected diesel engine and was equipped with an automatic transmission. The truck was installed on the chassis dynamometer and tested at 9,160 lb. Coastdowns for this truck are shown in the report provided in Appendix F. The truck was then driven over the drive cycle once to condition the vehicle for the hot-start testing. The five hot-start tests were conducted with a 20-minute soak in between each test to change emission sample bags and PM filters. The test results for newer diesel baseline are summarized in Table 5-4.

TABLE 5-4 EMISSION RESULTS FOR NEWER BASELINE DIESEL OVER LD UDDS DRIVE CYCLE

Test Code	HC, g/mi	CO, g/mi	NOx, g/mi	PM, mg/mi	CO2, g/mi	MPG	Fuel, kg	Miles
4763B-H1	0.13	2.25	6.14	89	724	14.2	1.73	7.54
4763B-H2	0.12	2.30	6.17	82	727	14.2	1.74	7.54
4763B-H3	0.11	2.26	6.14	86	723	14.3	1.73	7.55
4763B-H4	0.14	2.22	6.19	82	722	14.3	1.73	7.55
4763B-H5	0.12	2.23	6.12	83	722	14.2	1.73	7.54
Average =	**0.12**	**2.25**	**6.15**	**84**	**724**	**14.2**	**1.73**	**7.54**
c.o.v.	9%	1%	3%	4%	1%	1%	1%	0%

5.2.3 Baseline gas – Test Results

Gas baseline, VIN 1FCJE39L46HB04103, was powered by a 2005 5.4L Ford, port injected gasoline engine and was equipped with an automatic transmission. The truck was installed on the chassis dynamometer and tested at 9,010 lb. Information on coastdowns for this truck are provided in Appendix F. The truck

was then driven over the drive cycle twice to condition the vehicle for the hot-start testing. The five hot-start tests were conducted with a 20-minute soak in between each test to change emission sample bags and PM filters. The test results for the truck are summarized in Table 5-5.

TABLE 5-5 EMISSION RESULTS FOR BASELINE GAS OVER LD UDDS DRIVE CYCLE

Test Code	HC, g/mi	CO, g/mi	NO_x, g/mi	PM, mg/mi	CO_2, g/mi	MPG	Fuel, kg	Miles
F4103-H1	0.00	1.17	0.21	5	804	11.1	1.91	7.52
F4103-H2	0.05	1.35	0.19	4	798	11.2	1.90	7.51
F4103-H3	0.01	1.86	0.17	3	805	11.1	1.91	7.49
F4103-H4	0.03	1.59	0.16	3	802	11.1	1.91	7.52
F4103-H5	0.04	1.47	0.08	3	797	11.2	1.89	7.50
Average =	**0.03**	**1.49**	**0.16**	**4**	**801**	**11.1**	**1.90**	**7.51**
c.o.v.	67%	17%	30%	23%	0%	0%	1%	0%

5.2.4 Diesel hybrid – Test Results

Diesel hybrid, VIN 5B4HPD25363412537, was powered by a 2006 4.5L direct-injected turbocharged diesel engine and was equipped with parallel hybrid drivetrain using an electric motor between the engine and transmission. The transmission was an Eaton automated manual. The battery pack was nickel metal hydride (NiMH). The truck was installed on the chassis dynamometer and

tested at 10,530 lb. Information on the coastdowns for this truck are provided in Appendix F. The truck was driven over the drive cycle twice to condition the vehicle for the hot-start testing. The emission test results and NEC values are summarized in Table 5-6 and in Table 5-7. As described in the introduction, the NEC for all of the tests for this truck were less than 1 percent, so no data correction was necessary.

TABLE 5-6 EMISSION RESULTS FOR DIESEL HYBRID OVER LD UDDS DRIVE CYCLE

Test Code	HC, g/mi	CO, g/mi	NOx, g/mi	PM, mg/mi	CO2, g/mi	MPG	Fuel, kg	Miles
F2537B-H1	0.42	2.37	4.87	126	632	16.2	1.53	7.60
F2537B-H2	0.41	2.32	4.76	124	634	16.2	1.53	7.58
F2537B-H3	0.41	2.49	4.78	123	627	16.4	1.51	7.57
F2537B-H4	0.41	2.49	4.82	135	635	16.2	1.53	7.55
F2537B-H5	0.40	2.48	5.04	132	634	16.2	1.53	7.60
Average =	**0.41**	**2.43**	**4.86**	**128**	**632**	**16.2**	**1.53**	**7.58**
c.o.v.	2%	3%	2%	4%	0%	0%	1%	0%

TABLE 5-7 NEC RESULTS FOR DIESEL HYBRID OVER LD UDDS DRIVE CYCLE

Test Code	SOC, %		NEC MJ	Fuel Energy, MJ	NEC %
	Start	End			
F2537B-H1	54.0	52.0	-0.13	67.2	-0.2
F2537B-H2	52.0	54.0	0.13	67.2	0.2
F2537B-H3	57.0	53.0	-0.26	66.5	-0.4
F2537B-H4	53.0	54.0	0.06	67.1	0.1
F2537B-H5	54.0	52.0	-0.13	67.5	-0.2

The hybrid diesel was the only truck modified before returning for Phase 3 testing. It was noted that in the Phase 1 testing (described in Chapter 3.0) that the truck's hybrid system control software was not fully developed and that the engine control unit (ECU) did not correctly receive torque commands from the hybrid controller. Both of those issues were addressed while the truck was operated in the field. During the Phase 3 testing, emissions of HC, and NOx were reduced by 23, and 18 percent, respectively, compared to Phase 1 testing. CO emissions increased by 15 percent. Fuel economy improved by 5 percent compared to the Phase 1 testing.

At Frito-Lay's request, the truck was also tested with the hybrid system disabled. Although it was recognized that the vehicle would be lighter and the driveline inertia would be less without a hybrid system, no attempt was made to compensate or correct for the differences. The hybrid system was disabled by disconnecting the high-voltage battery cable from the pack at the connector. The testing in this configuration was conducted using the same procedure used in hybrid mode. The results of this testing is summarized in Table 5-8. With the hybrid system disabled, the emissions of HC were nearly identical, however, CO emissions nearly doubled, NOx increased 20 percent, and PM increased by 38 percent, compared to the hybrid configuration. Fuel economy was nearly 10 percent worse with the hybrid system disabled. It was discovered through the course of testing that the engine and automatic-shift manual transmission were not tuned for this non-hybrid operation, so the truck had some difficulty following the speed/time trace on the LD UDDS cycle. The results here are not representative of a true baseline vehicle of this engine configuration and are not discussed further in the Conclusions.

TABLE 5-8. EMISSION RESULTS FOR DIESEL HYBRID WITH HYBRID SYSTEM DISABLED OVER LD UDDS DRIVE CYCLE

Test Code	HC, g/mi	CO, g/mi	NOx, g/mi	PM, g/mi	CO2, g/mi	MPG	Fuel, kg	Miles
F2537C-H1	0.42	5.02	5.74	190	704	14.5	1.68	7.45
F2537C-H2	0.40	4.64	5.80	169	698	14.7	1.67	7.50
F2537C-H3	0.40	4.78	5.78	174	691	14.8	1.66	7.50
F2537C-H4	0.40	4.75	5.90	181	698	14.7	1.67	7.47
F2537C-H5	0.40	4.57	5.86	173	693	14.7	1.66	7.48
Average =	0.40	4.75	5.81	177	697	14.7	1.67	7.48
c.o.v.	2%	4%	1%	5%	1%	1%	1%	0%

5.2.5 Gas Hybrid - Test Results

Gas Hybrid, VIN 584KP02V063416051, was powered by a 2005 4.8L GM Vortec, port injected gasoline engine and was equipped with series hybrid drivetrain using two electric motors and a nickel metal hydride (NiMH) battery pack. The truck was installed on the chassis dynamometer and tested at 10,730 lb. Coastdowns for this truck were conducted and the truck was then driven over the drive cycle once to condition the vehicle for the hot-start testing. As in the previous truck, after five hot-start tests were conducted, the third test appeared to be an outlier based on the NOx value using ASTM-E-178. This test was not used in the average and coefficient of variance calculations. The emission test

results and NEC values for gas hybrid are summarized in Table 5-9 and in Table 5-10. As shown in Table 5-10, the percent NEC for this truck were less than 1 for all of the tests, so no data correction was necessary.

TABLE 5-9 EMISSION RESULTS FOR GAS HYBRID OVER LD UDDS DRIVE CYCLE

Test Code	HC, g/mi	CO, g/mi	NOx, g/mi	PM, mg/mi	CO2, g/mi	MPG	Fuel, kg	Miles
F6051B-H1	0.19	3.93	0.18	10	755	11.7	1.82	7.56
F6051B-H2	0.14	2.44	0.25	10	756	11.8	1.81	7.54
F6051B-H3*	0.12	1.67	0.95	4	738	12.1	1.77	7.55
F6051B-H4	0.15	2.48	0.25	9	743	12.0	1.78	7.56
F6051B-H5	0.21	3.92	0.21	8	751	11.8	1.81	7.55
Average =	0.17	3.19	0.22	9	751	11.8	1.80	7.55
c.o.v.	18%	26%	15%	13%	1%	1%	1%	0%
* This test was an outlier based on the NOx value using ASTM-E178. This test was not used in the average and c.o.v. calculations.								

TABLE 5-10 NEC RESULTS FOR GAS HYBRID OVER LD UDDS DRIVE CYCLE

Test Code	SOC, %		NEC, MJ	Fuel Energy, MJ	NEC, %
	Start	End			
F6051B-H1	57.0	56.5	-0.06	79.9	0.0
F6051B-H2	56.5	58.0	0.17	79.6	0.0
F6051B-H3	58.0	57.5	-0.06	77.7	0.0
F6051B-H4	57.5	56.5	-0.11	78.5	0.0
F6051B-H5	56.5	58.0	0.17	79.4	0.0

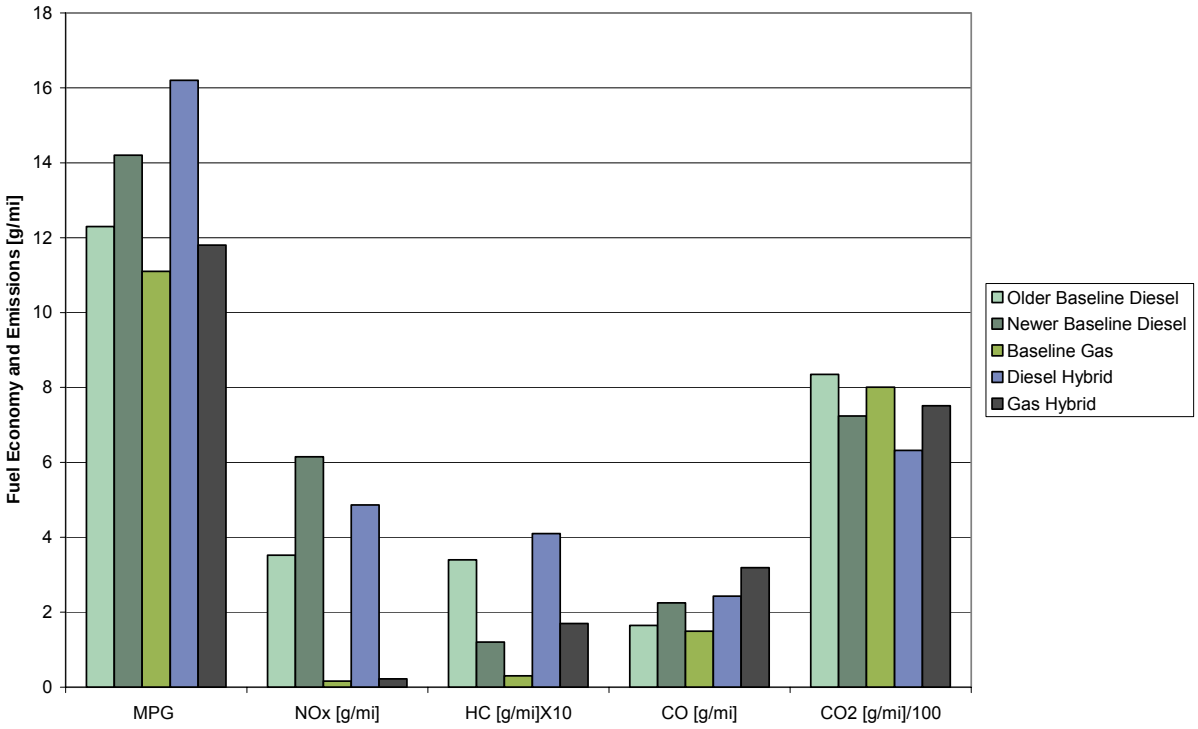
5.3 SUMMARY

The Phase 3 testing of this project was successfully completed. Six different truck configurations were tested including the newer diesel hybrid, older diesel hybrid and gas hybrid that were tested as they were configured during the Phase 1 testing. The diesel hybrid was re-calibrated between the Phase 1 and Phase 3 testing and was tested as both a hybrid and a conventional truck. The gas baseline was also added during the Phase 2 testing. The gas baseline was added to provide a baseline comparison to the gasoline hybrid. Table 5-11 shows the Phase 3 average emissions values for each truck, and Figure 5-1 shows the trucks ranked by emissions and fuel economy.

TABLE 5-11 AVERAGE EMISSION RESULTS FOR EACH TRUCK OVER LD UDDS DRIVE CYCLE

Truck	HC, g/mi	CO, g/mi	NOx, g/mi	PM, mg/mi	CO2, g/mi	MPG	Fuel, kg	Miles
older baseline diesel	0.34	1.65	3.52	137	835	12.3	2.01	7.60
newer baseline diesel	0.12	2.25	6.15	84	724	14.2	1.73	7.54
baseline gas	0.03	1.49	0.16	4	801	11.1	1.90	7.51
diesel hybrid	0.41	2.43	4.86	128	632	16.2	1.53	7.58
diesel w/hybrid disabled	0.40	4.75	5.81	177	697	14.7	1.67	7.48
gas hybrid	0.16	2.89	0.37	8	748	11.9	1.80	7.55

Figure 5-1 Ranking of Trucks by Emissions and Fuel Economy



All of the trucks produced low HC and CO emissions, which are typically not issues for diesel engines and gasoline engines with catalyst systems. The gasoline trucks were equipped with three-way catalyst systems; and therefore, produced very low NOx emissions. However, the gasoline trucks also produced the worst fuel economy. The diesel trucks produced the highest NOx emissions and best fuel economy. Of the diesel

trucks, the newer baseline diesel produced the most NOx, followed by the hybrid diesel, the hybrid diesel (with the hybrid system disabled), and older diesel baseline.

The gasoline engines also produced almost no PM, which is typical of gasoline engine operation, even without after treatment. Of the diesels, the diesel hybrid with the hybrid disabled produced the most PM, followed by the older baseline diesel, the diesel hybrid, and the newer baseline diesel.

The hybrid systems improved fuel economy between 7 and 10 percent compared to similar configurations. The NOx emissions of the diesel hybrid was nearly 1 g/mile less, a 16 percent reduction, compare to the new diesel baseline. The gasoline hybrid produced 0.21 g/mile more NOx, a two fold increase, than the gasoline baseline. It should be noted that the diesel hybrid with the hybrid disabled was tested with the intent to use the data as a baseline for comparison to the diesel hybrid. However, it was deemed that the diesel hybrid with the hybrid disabled did not function properly in the diesel mode. Therefore, the testing data were collected for this vehicle, but was not further evaluated with the other Phase 3 testing data.

6.0 Analysis and Evaluations

This section provides the analysis and evaluations of the emission data collected on-road with the PEMS and in the laboratory through dynamometer testing. Data analysis procedures will be explained and emissions measurements collected on the road will be compared to laboratory data. Projections for emissions and fuel consumption reductions will be explored in Section 7, Conclusions.

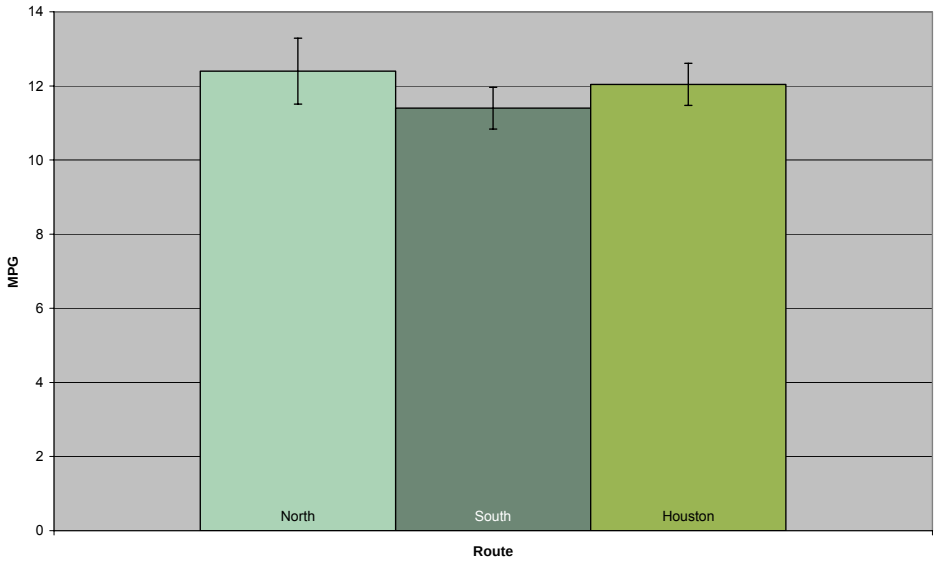
6.1 Procedures on Data Analysis and Evaluations

Data collected through the PEMS were evaluated at multiple time scales over the course of the study. During the testing phase, data were examined at a small time scale (i.e. second-by-second and averaged individual test run data) in order to ensure accuracy of data and complete sensor operation. During initial data analysis it was determined that second-by-second data were unnecessary and inconsistent with the scope and intent of the project, therefore averages of data from each test run were chosen.

Quality Control on data included examination of all summary results and further examination of second-by-second data wherever results deviated excessively from averages for any of the measured emissions. Test runs which were found to deviate excessively from the average and have an assignable cause were discarded and re-run when possible.

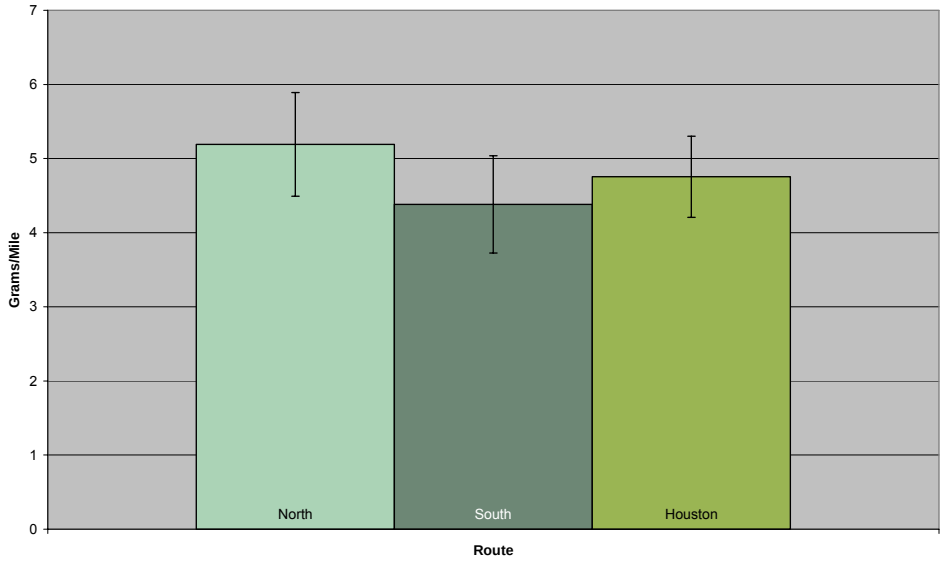
Statistical analysis of data, including single factor analysis of variance (ANOVA) and pair-wise T tests were calculated for each vehicle, broken down by each of the three on-road routes in order to determine whether a specific route and its unique characteristics such as number of stops, local traffic patterns, average speed, etc. had an effect on fuel economy or emissions. Analysis of results indicated no statistical difference in any particular route over the course of the on-road testing phase of the project as demonstrated in figures 6-1 and 6-2. Therefore, for the purposes of this report, data from all three routes traveled during testing (DFW South, DFW North, and Houston) were combined in order to provide more statistical resolution for the overall results.

Figure 6-1 Comparison of Routes by Fuel Economy



*Error bars represent 95% confidence intervals.

Figure 6-2 Comparison of Routes by NOx Emissions



*Error bars represent 95% confidence intervals.

Additionally, results from Phase 1 and Phase 3 testing were compared by means of pair-wise T tests in order to examine any changes that took place during the course of testing due to mileage accumulation. All vehicles were tested in this manner with the exception of the baseline gasoline truck, which was added to the study after Phase 1 testing. The original intent of executing Phase 3 testing at the time of project proposal

submission was to evaluate truck "durability," or any degradation in performance after significant road miles had been logged in Phase 2 testing. This approach was well-intentioned but not feasible, however, given the low mileage typically diven by Frito-Lay delivery trucks (<15,000 miles per year) and the overall grant project timeline. With today's engine and emissions equipment durability, several years worth of delivery operation and/or road testing would be required to accumulate sufficient mileage to truly evaluate "durability" performance of drivetrain and emissions components on hybrid or conventional vehicles.

Although all vehicles exhibited statistically significant differences ($p \leq 0.05$) in fuel economy and the various emissions constituents between Phase 1 and 3, the differences were not consistent within a vehicle or within a given exhaust constituent between vehicles. Only the diesel hybrid vehicle had a specific assignable cause for the observed differences, (i.e, the engine recalibration that was required to address the idle and low-speed performance issues). It is believed that the Phase 3 results after the engine recalibration or more indicative of representative performance of that truck. In all cases, including the diesel hybrid, NO_x emissions showed no statistically significant change between dynamometer testing phases. Comparisons of Phase 1 and Phase 3 testing results for fuel economy (Figure 6-3), NO_x emissions (Figure 6-4), and HC, CO, and PM (Figure 6-5) indicate minor variation of results of dynamometer testing that are presumed to be due to changes in ambient conditions between test phases, normal variation in dynamometer test setup and execution, and normal variation in engine performance and control.

Figure 6-3 Fuel Economy Phase 1 & 3 Comparison

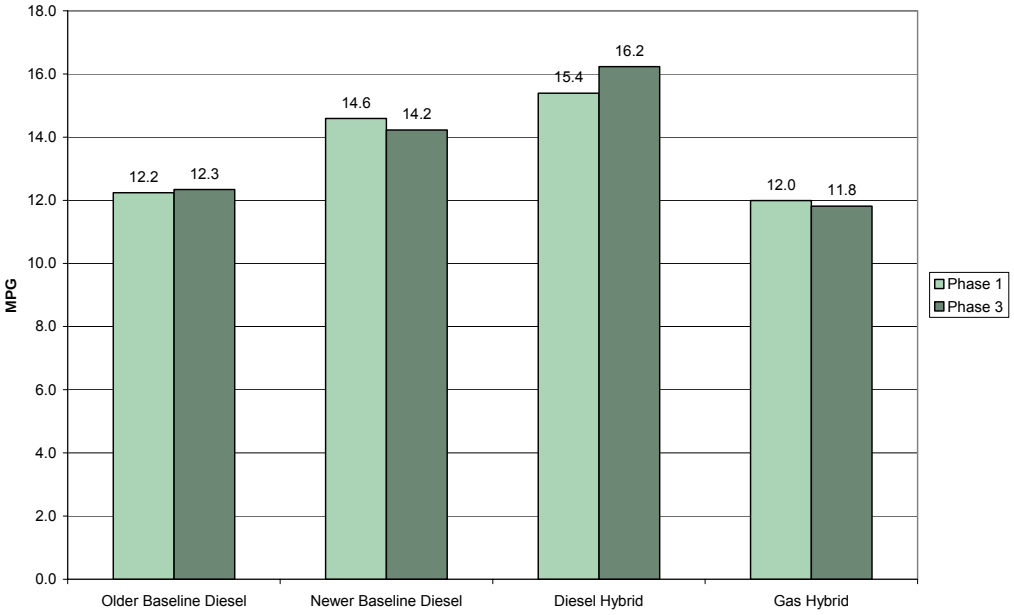


Figure 6-4 NOx Emissions Phase 1 & 3 Comparison

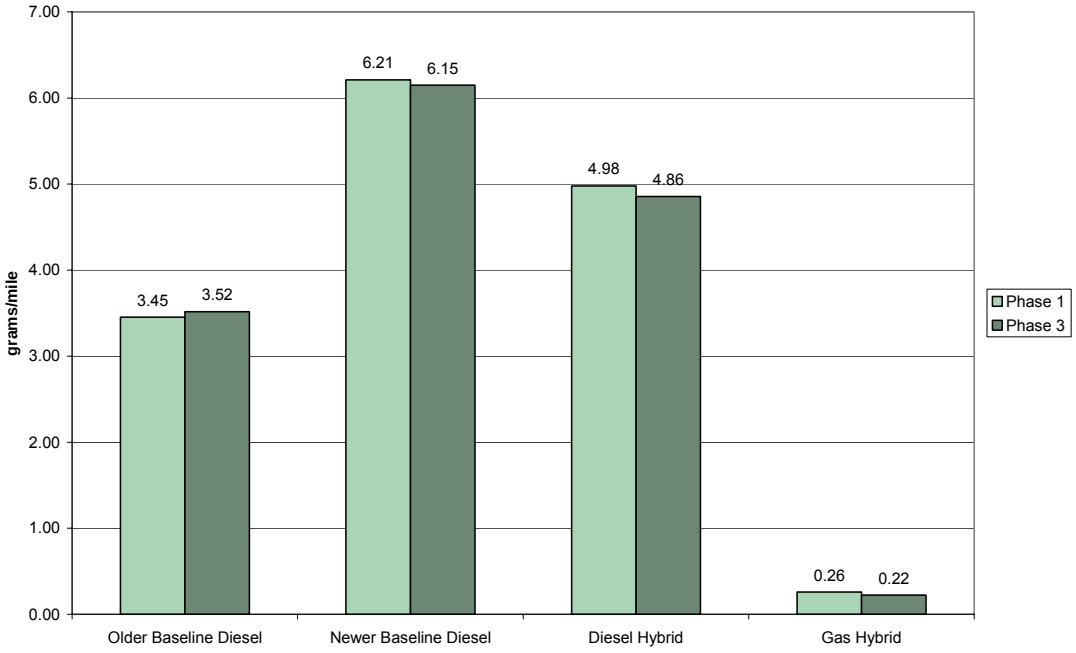
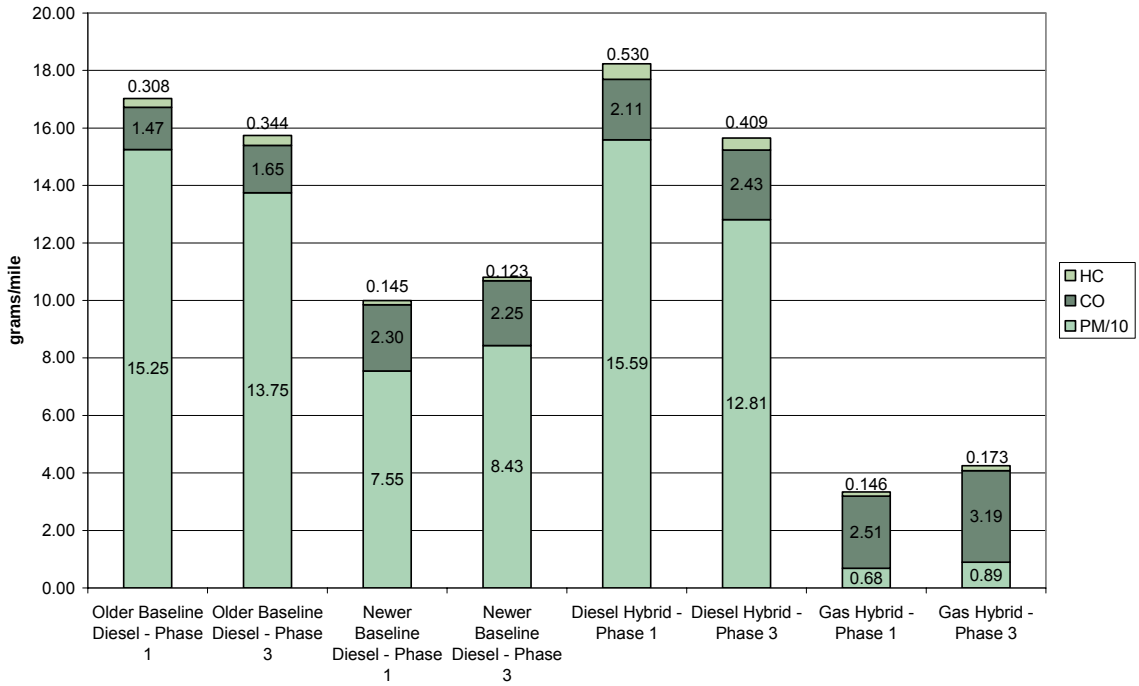


Figure 6-5 HC, CO and PM Phase 1 & 3 Comparison



*Results for particulate matter (PM) are reduced by one order of magnitude for illustration purposes.
For this reason, Phase 1 and Phase 3 Lab test results will be reported and evaluated as

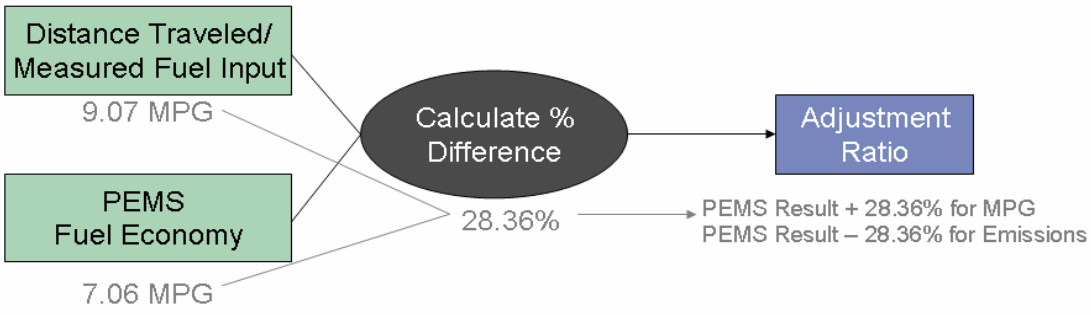
an average of the two test phases with the exception of the diesel hybrid, for which only Phase 3 test results will be used.

6.2 Data Accuracy and calibration of PEMS results

During the course of on-road testing it was found that while data received from the PEMS were precise and repeatable, they were not inherently accurate. The source of this error was discovered to be caused by one or more constants used by the PEMS in calculations of total airflow or fuel consumption. Comparison of PEMS-derived fuel consumption and CO_2 output against data published by the US Department of Energy (http://www.eia.doe.gov/oiaf/1605/factors.html) led to the determination that the PEMS-assumed Volumetric Efficiency and not fuel composition was responsible for inaccuracy in the data as-taken. The PEMS does not directly measure fuel flow or air flow rate on the engine being tested; the air flow rate is inferred or calculated using an average assumed volumetric efficiency, RPM measurement, and known displacement of the engine. Since volumetric efficiency is a function of engine speed and load at a given time, using the nominal value of 95% in this case yields very generalized results which are potentially accurate at only one point in the engine's operation. Also, only the best performing naturally aspirated engines approach 95% volumetric efficiency, and even then, this peak efficiency is at a limited speed and load combination. As a note, the PEMS system did use a manifold pressure sensor to bias the calculation on the forced-induction turbodiesel engines; the system still used the assumed 95% base volumetric efficiency in the flow calculation.

Since this assumed Volumetric Efficiency was in turn used to calculate the volume of air flowing through the engine at any given time, and all emissions measurements use this total engine and exhaust flow as a dilution factor, all subsequent emissions calculations are affected. In order to correct for these differences an adjustment factor was computed based on the difference between MPG calculations from the PEMS and actual mileage over measured fuel volumes for each vehicle. This adjustment factor was then applied to summary data for each of the tested vehicles. An asterisk after PEMS indicates that results have had the adjustment factor applied.

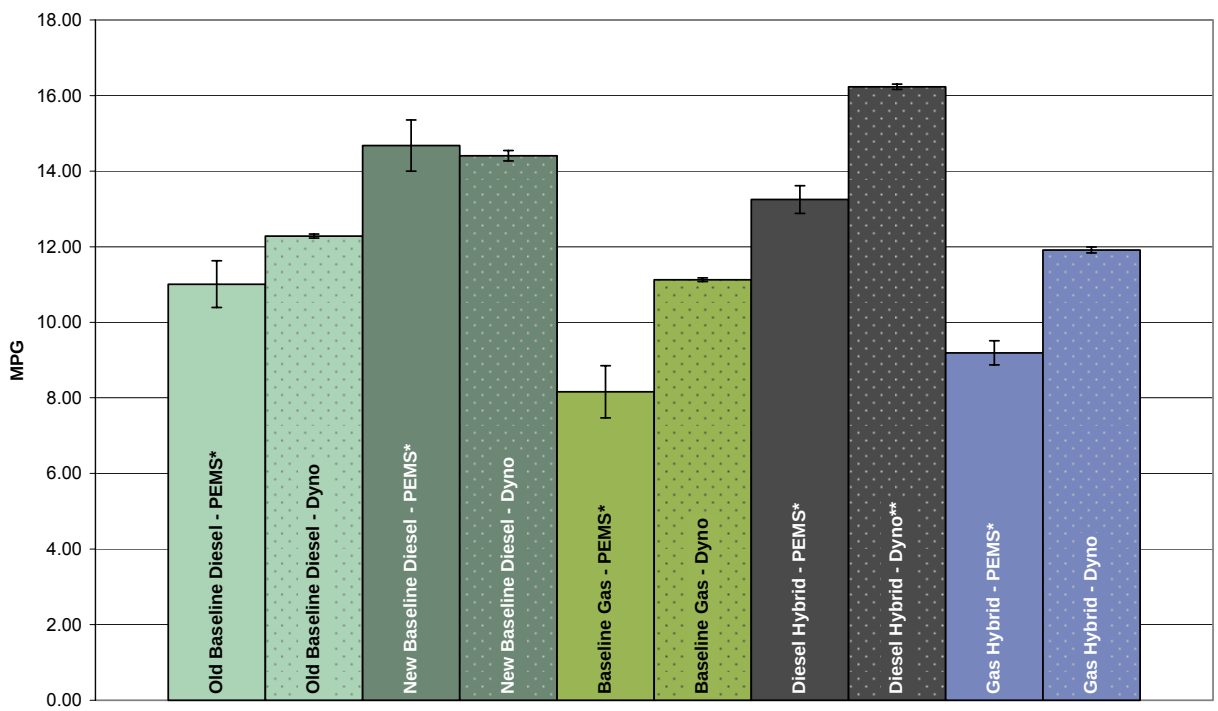
Figure 6-6 PEMS Data Correction



6.3 Combined Results

The following figures present data from on-road testing alongside dynamometer results. In addition to comparisons of average data presented in the following graphs, ANOVAs were conducted on PEMS summary data in order to confirm statistical validity of vehicle test results. ANOVA results amongst vehicles for each of the tested variables showed high degrees of statistical significance where $p \leq 7.6E-10$. Generally, p-values less than 0.05, which indicates that the results have a 95% probability that they are not due to random chance, are accepted for scientific investigations. The figures below present averages of dynamometer results from Phase 1 and Phase 3 of the study with the exception of the diesel hybrid vehicle for which only Phase 3 results are shown due to ECU calibrations performed subsequent to Phase 2 testing. Results were combined in order to afford greatest representation of data and increased statistical resolution. For both PEMS and dynamometer testing 95% confidence intervals were calculated and appear as error bars in the following figures.

Figure 6-7 Fuel Economy

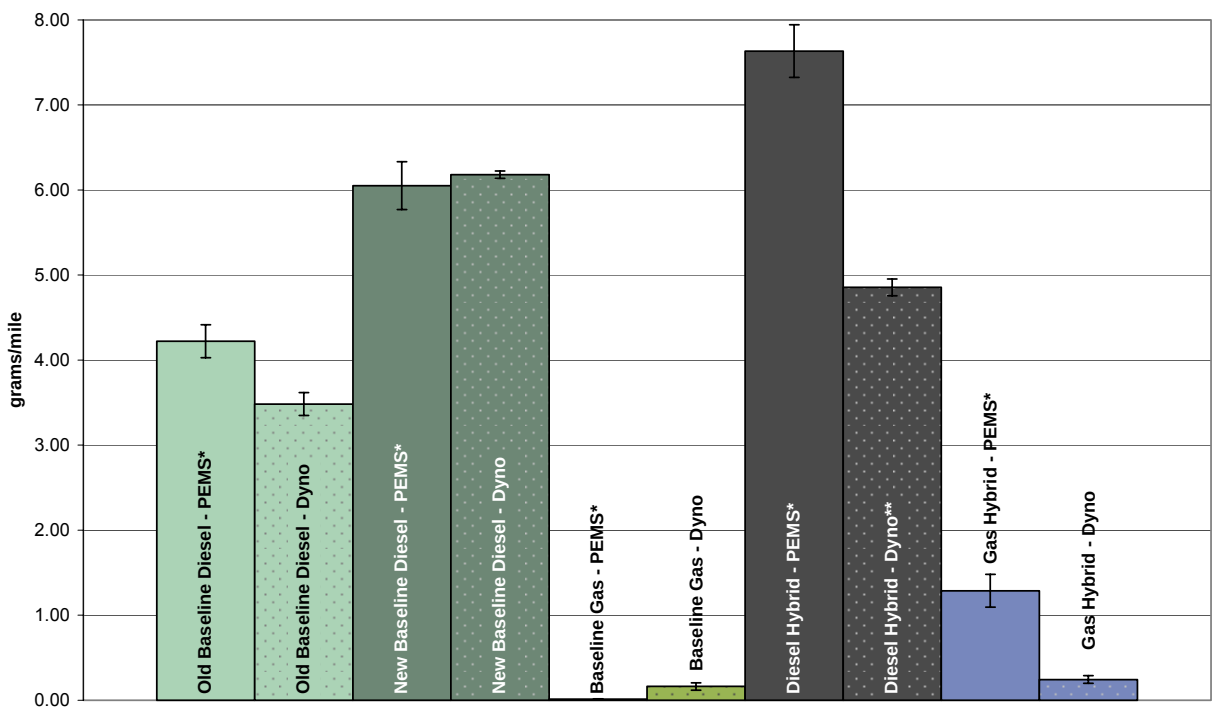


Mean	11.01	12.28	14.68	14.41	8.16	11.12	13.25	16.23	9.19	11.91
Std Dev	2.18	0.09	2.32	0.22	2.25	0.05	1.28	0.08	1.12	0.12
95% CI	0.62	0.05	0.68	0.14	0.69	0.05	0.37	0.07	0.32	0.08
CoV (%)	19.81	0.72	15.80	1.52	27.60	0.49	9.66	0.47	12.21	1.02

* Adjusted PEMS data; see explanation in Section 6.2. **Diesel Hybrid Dyno results from Phase 3 testing only.

The highest fuel economy in on-road testing was seen in the newer baseline diesel with 14.68 MPG. This was unexpected given that the Diesel hybrid exhibited the highest fuel economy in both Phase 1 and 3 testing. Overall, fuel economy was greater in dynamometer than in on-road testing with the exception of the newer baseline diesel which exhibited slightly increased performance in real-world conditions. As expected the gasoline vehicles fared worse given the lower inherent efficiency of gasoline engines and the fuel's lower energy content versus diesel. Presumably, differences in the MPG and emissions from lab to real world are due to the difference between the driver habits on-road and in the lab, as well as the basic drive cycle used on road versus the LD UDDS used on the dynamometer. The on-road drive cycle and driver's characteristics are potentially more aggressive than those used in the lab. Additionally, there were differences in temperature and humidity over the course of on-road testing which are known to affect vehicle performance. Combustion air fed to the vehicles' engines during lab testing is of controlled temperature and humidity, whereas the ambient air during on-road testing varied significantly.

Figure 6-8 NOx Emissions

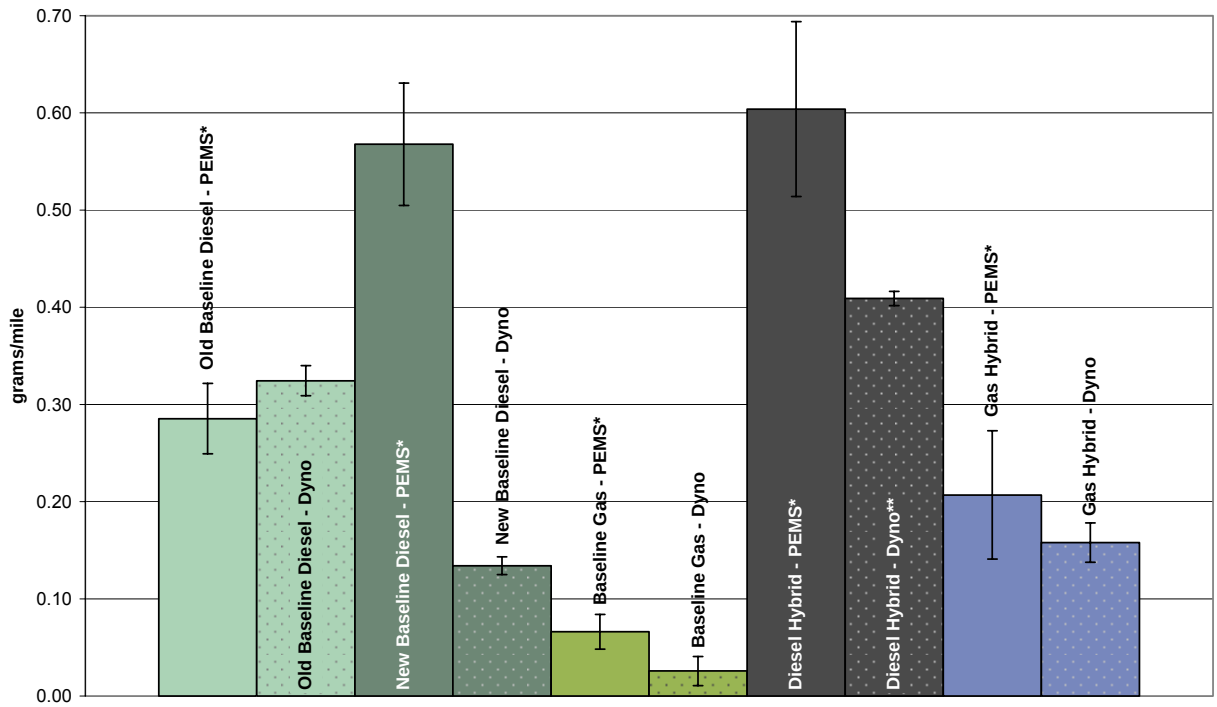


Mean	4.22	3.48	6.05	6.22	0.01	0.15	7.63	4.86	1.29	0.38
Std Dev	0.68	0.23	0.96	0.15	0.01	0.05	1.08	0.11	0.69	0.31
95% CI	0.19	0.13	0.28	0.09	0.00	0.04	0.31	0.10	0.19	0.18
CoV (%)	16.21	6.53	15.86	2.45	73.61	33.88	14.17	2.33%	53.50	81.89

* Adjusted PEMS data; see explanation in Section 6.2. **Diesel Hybrid Dyno results from Phase 3 testing only.

Lowest NO_x emissions in on-road and dynamometer testing were seen from the baseline gas vehicle at 0.01 g/mi and 0.15 g/mi respectively. Overall, on-road NO_x emissions were higher than the lab/dynamometer results for 4 of the 5 vehicles tested. It is suspected that the increased NO_x of the hybrid compared to the baseline vehicles is likely due to the intermittent nature of engine use. The differences in NO_x emissions in lab versus on-road testing is likely due to the drastic increase in the number of starts and stops over the course of a test run which contribute to the decreased effectiveness of emissions control systems. The on-road testing consisted of a number of stops which included turning off and restarting the engine, whereas the engine was running for the full duration of the testing in the lab. The gasoline hybrid engine-off capability at stops and low speeds was active both on the road the dynamometer.

Figure 6-9 Hydrocarbon Emissions



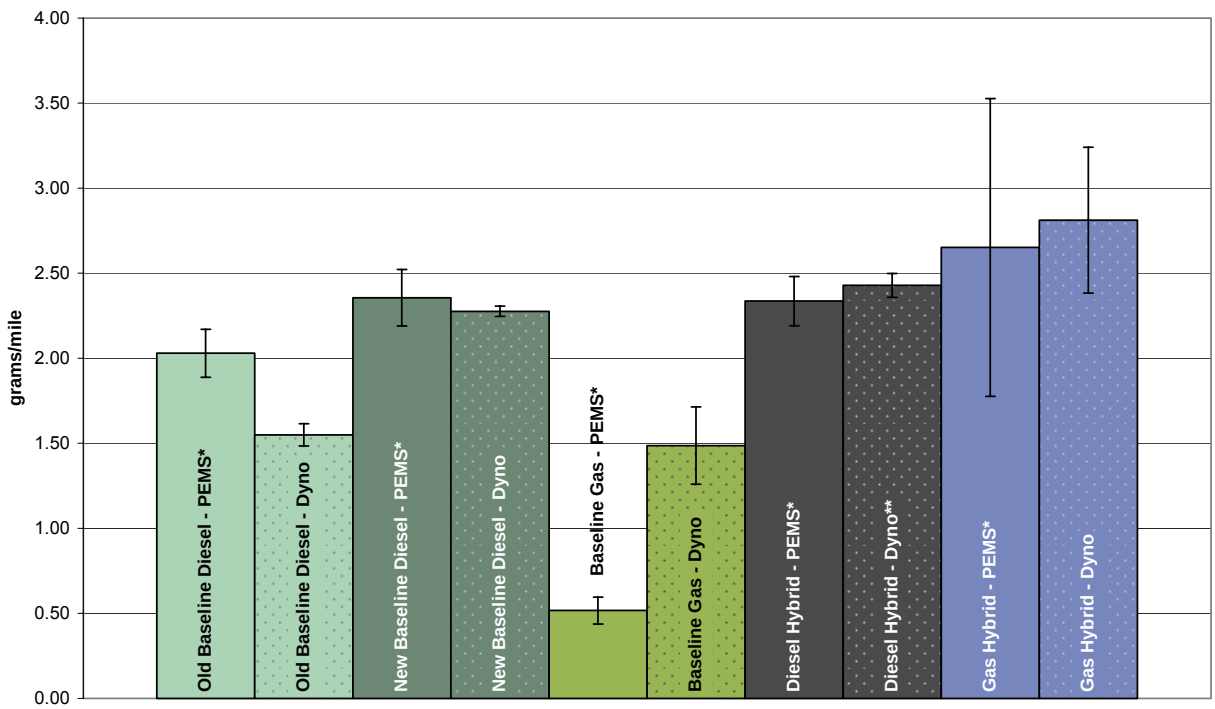
Mean	0.29	0.32	0.57	0.13	0.07	0.03	0.60	0.41	0.21	0.16
Std Dev	0.13	0.03	0.22	0.01	0.06	0.02	0.31	0.01	0.24	0.03
95% CI	0.04	0.02	0.06	0.01	0.02	0.01	0.09	0.01	0.07	0.02
CoV (%)	44.79	8.04	37.95	11.02	87.86	66.56	52.12	2.07	114.01	19.61

* Adjusted PEMS data; see explanation in Section 6.2. **Diesel Hybrid Dyno results from Phase 3 testing only.

The baseline gas vehicle produced the lowest hydrocarbon emissions of any of the tested vehicles with 0.07 g/mi and 0.03 g/mi in on-road and dynamometer testing,

respectively. Trends in emissions between dynamometer and PEMS testing for hybrid vehicles were consistent with those seen for NO_x emissions, and are likely due to identical factors which caused increases in NO_x emissions. Careful analysis and examination failed to elucidate a cause for the dramatic difference in hydrocarbon emissions between lab and on-road testing of the newer baseline diesel.

Figure 6-10 Carbon Monoxide Emissions

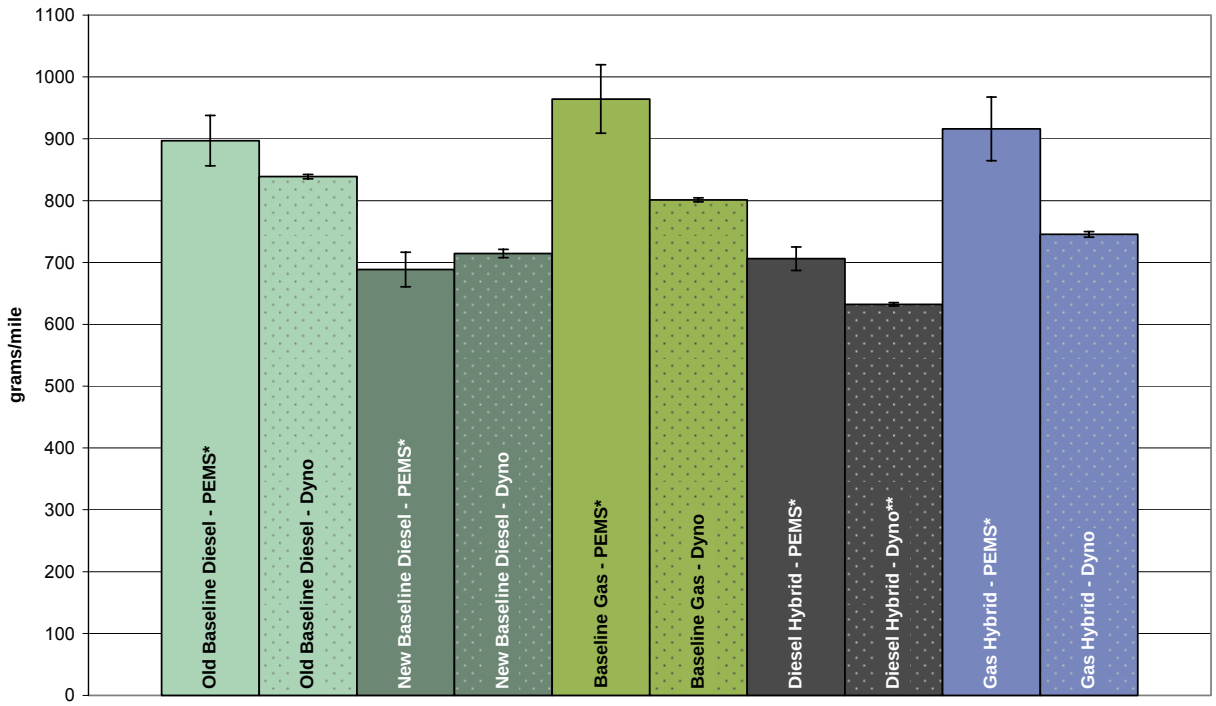


Mean	2.03	1.55	2.36	2.28	0.52	1.49	2.34	2.43	2.65	2.81
Std Dev	0.50	0.11	0.57	0.05	0.26	0.26	0.51	0.08	3.13	0.66
95% CI	0.14	0.06	0.17	0.03	0.08	0.23	0.14	0.07	0.88	0.43
CoV (%)	24.58	7.09	24.21	2.13	50.15	17.44	21.67	3.29	117.98	23.33

* Adjusted PEMS data; see explanation in Section 6.2. **Diesel Hybrid Dyno results from Phase 3 testing only.

Lowest carbon monoxide emissions in on-road and dynamometer testing were seen in the baseline gas vehicle at 0.52 g/mi and 1.49 g/mi respectively. All of the trucks emitted lower amounts of CO in the lab than measured on-road with the exception of the diesel hybrid, where results were nearly identical, and the baseline gas truck, which produced considerably less CO in on-road testing. Overall the gas hybrid produced the highest amount of CO of any of the tested vehicles. As previously addressed, this is likely due to decreased performance of emission control technologies in intermittent applications.

Figure 6-11 Carbon Dioxide Emissions



Mean	897	839	689	714	964	801	706	632	916	745
Std Dev	144	6	96	11	181	4	66	3	184	7
95% CI	41	4	28	7	55	3	19	3	51	5
CoV (%)	16.08	0.72	13.89	1.52	18.77	0.47	9.38	0.49	20.05	0.93

* Adjusted PEMS data; see explanation in Section 6.2. **Diesel Hybrid Dyno results from Phase 3 testing only.

Carbon dioxide emissions rankings were consistent with those presented for fuel economy with the newer baseline diesel performing best in on-road testing at 689 g/mi and the diesel hybrid performing best on the dynamometer with 632 g/mi.

6.4 Summary of Results

In summary, the newer baseline diesel exhibited the greatest performance in on-road testing for fuel economy, while outperformed by the diesel hybrid in lab testing. The baseline gasoline truck produced the lowest emissions of NO_x, hydrocarbons, and carbon monoxide in both on-road and dynamometer testing. Carbon dioxide emissions were least for the newer baseline diesel and diesel hybrid in on-road and dynamometer testing, respectively.

7.0 Conclusions

The conclusions brought forth here are offered by the authors of this report based on the data presented in Section 6. While the conclusions are considered by the authors to be valid for the use of this class of hybrid commercial vehicles, the reader may draw differing or additional conclusions from the data.

Potential insight and learning from the test procedure and data presented here may be viewed from several perspectives. First, was the test protocol that was developed and executed valid, representative, and comprehensive enough to capture performance of the commercial conventional and hybrid trucks in the 10,000 lb GVWR weight class? This question is addressed in Section 7.1.1. Secondly, is there sufficient consistency between on-road testing and lab testing that future studies may perform one or the other in order to gain valid performance insight while minimizing expense and effort? This is addressed in Section 7.1.2. Lastly and most importantly, do currently available hybrid-electric commercial chassis offer significantly reduced emissions and fuel consumption versus their conventional counterparts? This last question is addressed in Section 7.5

7.1 Test Validity

7.1.1 Route Type

Three different routes were selected for the on-road testing, with the expectation that the individual route chosen may have an impact on performance. All three routes were considered to be somewhat close to the average, or representative of routes driven by Frito-Lay's product delivery trucks. The test results show all three routes provided results consistent with each other in terms of fuel efficiency and emissions. This can be interpreted one of two ways: 1) performance of these vehicles is not sensitive to the individual route characteristics and drive cycle (speed, stops and starts, etc), or 2) the routes chosen were indeed very close to the average and not sufficiently different from each other to display a difference in the results. The authors believe the latter situation was present, as it is widely known in the industry that vehicle performance and efficiency, especially with hybrids using regenerative braking, is very sensitive to the drive cycle, or speed versus time trace that a vehicle undergoes in operation.

In addition, although the test results between the lab and the on-road testing were close in general and consistent vehicle-to-vehicle, there were some significant differences seen. The goal in designing the test program was to choose a standard drive cycle that could be executed under the FTP that was closest to the Frito-Lay average, while keeping in mind that there are many variables that are different between the lab and on-road testing: measurement method (PEMS vs. lab bag samples), ambient conditions, drive cycle, and driver behavior/technique. Considering these potential differences it is believed the LD UDDS was the correct choice of standard drive cycle given the test results presented here, and results likely would not have been closer by using another

standard duty cycle in the lab. Given more time and expense to study the sensitivity of performance to drive cycle, more on-road routes may be tested at both ends of the expected range of average speed and stop/start frequency to evaluate the full range of expected performance from the vehicles.

Although the PEMS data collection equipment is seen by the industry as an accepted method of gathering on-road, real-time emissions data (and the data usually reported as-is from the instruments), validity of the testing and data gathered here was called into question by the team when an initial look at the fuel consumption and emissions results showed a difference of more than 100% in fuel consumption versus both the fuel purchase and fill-up tracking method and the SwRI lab results. When the PEMS operating principle and emissions calculation algorithms were more fully understood to be linked to the volumetric efficiency assumption, the only obvious link to be used as an adjustment factor was fuel consumed and CO2 emitted per gallon of fuel burned. The assumption is that the same bias can be applied to all other emissions data for a given vehicle equally. A more accurate way to gather PEMS data would be to directly measure air flow or fuel flow either from dedicated meters or from the vehicles ECU, and use this second-by second data to calculate the exhaust dilution factor that determines the emissions concentrations and emissions rates per mile. While this approach is recommended for any future testing, the team believes the results here are valid as a whole.

With the run-to-run repeatability seen within a specific route, and the consistency seen in the results between the trucks in the study, the team believes the testing was designed and executed to the best of human ability at the time, and should be considered valid test results that are representative of the hybrid and conventional commercial trucks available today.

7.1.2 Lab versus On-Road Testing

Lab testing is very expensive but the most accurate and repeatable; inherent compromises are the selection of a drive cycle that is thought to be representative of on-road activity, and standard lab conditions in terms of temperature and humidity which may be rarely experienced on the road. The benefit to having lab tested vehicles on a standard drive cycle is the ability to compare relative performance of future vehicles under similar standard conditions.

In most of the vehicles tested, there was a consistent directional difference between the lab and on-road testing. The amount of the difference varied by vehicle, but presumably, vehicle performance measured on-road is more indicative how one might actually expect the vehicles to perform in day-to-day operation. The on-road testing will be used to form the conclusions that follow in order to reflect the expected results in a “real world” setting. The authors do not propose that one type of testing may be a substitute for the other; which type of testing to perform, or both, will depend on the objective of a given study and the resources available.

7.2 Fuel Efficiency and Emissions

In general, the on-road testing showed higher values for CO_2, CO, HC, and NO_x as compared to lab dynamometer testing. For MPG and CO_2 there is a statistical difference between the two testing methods; this is not unexpected due to factors cited earlier. The overall conclusions presented here will be drawn using the results of the on-road testing and will not consider the dynamometer testing phases in order to reflect the "real world" results. Table 7-1 shows a summary of the combined on-road data for fuel efficiency and emissions for each test vehicle.

	MPG	Nox [g/mi]	HC [g/mi]	CO [g/mi]	CO2 [g/mi]
Older Baseline Diesel	11.0	4.22	0.28	2.03	897
Newer Baseline Diesel	14.7	6.05	0.57	2.36	689
Baseline Gas	8.2	0.01	0.07	0.52	964
Diesel Hybrid	13.2	7.63	0.60	2.34	706
Gas Hybrid	9.2	1.28	0.21	2.65	916

Table 7-1 Combined On-road Data for MPG and Emissions by Test Vehicle

7.2.1 Fuel Economy

Highest fuel economy in on-road testing was seen in the newer baseline diesel with 14.7 MPG, and the diesel hybrid performed best in dynamometer testing with 15.8 MPG. Overall, fuel economy was greater in dynamometer than in on-road testing with the exception of the newer baseline diesel which exhibited slightly increased performance in real-world conditions. The hybrids can offer improved fuel economy versus baseline trucks in the study, depending on the basis of comparison. In general, the gasoline hybrid did not deliver the 30-50% improved fuel economy estimated prior to testing. The fuel economy of the gasoline hybrid was worse than all of the existing baseline diesel trucks, and only marginally better (12.2%) than the baseline gasoline truck, which is Frito-Lay's current new-vehicle purchase. The diesel hybrid does offer improved fuel efficiency versus gasoline baseline and some diesel baseline trucks, at 37.9% improvement over the current Frito-Lay gasoline powered truck and 16.7% improvement over the older diesel. Table 7-2 is a relative comparison matrix that shows the change expected when replacing a vehicle from the top of the matrix with a vehicle on the left side of the matrix.

	Older Baseline Diesel	Newer Baseline Diesel	Baseline Gas	Diesel Hybrid	Gas Hybrid
Older Baseline Diesel		-33.6%	25.5%	-20.0%	16.4%
Newer Baseline Diesel	25.2%		44.2%	10.2%	37.4%
Baseline Gas	-34.1%	-79.3%		-61.0%	-12.2%
Diesel Hybrid	16.7%	-11.4%	37.9%		30.3%
Gas Hybrid	-19.6%	-59.8%	10.9%	-43.5%	

Table 7-2 MPG Vehicle to Vehicle Comparison for On Road Testing

7.2.2 NOx Emissions

Lowest NO_x emissions in on-road and dynamometer testing were seen in the baseline gas vehicle. The gasoline hybrid emitted 99.2% more NO_x than the baseline gasoline vehicle. Even though engine/chassis combination used as the base for the gasoline hybrid passed the requirements for EPA certification as a Low Emission Vehicle (LEV), the changes made to convert it to a series hybrid are believed to have resulted in it's not being able to perform at the same level of emissions of the baseline gas vehicle. The team believes this was primary due to the cyclical operation of the engine in response to the speed demands on the vehicle and state of charge on the battery. The on/off operation does not allow the catalytic converter to reach and maintain optimum temperature. In addition the baseline gasoline truck which is Frito-Lay's current new-vehicle purchase is an EPA certified LEV in the configuration tested here. The diesel hybrid emitted 44.7% more NO_x than the lowest baseline diesel. The diesel hybrid, with it's sequential turbochargers uses high combustion chamber pressures to improve power and fuel efficiency but results in higher NO_x emissions. In addition, the diesel hybrid's automatic transmission creates a fluctuating load on the engine during acceleration compared to the automatic transmissions in the baseline trucks which may be affecting NO_x emissions levels. High engine load and lean combustion are the primary factors for NO_x formation in exhaust. With the testing executed in this study, it is not possible to determine with certainty the primary contributing factor for the higher NO_x emissions for the diesel hybrid truck. The baseline diesels performed as expected given they were produced under EPA emission standards at the time of manufacture that allowed for higher emissions. Table 7-3 is a relative comparison matrix that shows the change expected when replacing a vehicle from the top of the matrix with a vehicle on the left side of the matrix. Overall, the gas versus diesel results are consistent with expectations, as the gasoline trucks' 3-way catalyst serves to significantly reduce tailpipe NOx emissions compared to the diesels.

Conclusion: The team believes replacement of any baseline diesel vehicle with the gas hybrid can reduce NO_x emissions, but the best option for reducing NO_x emissions to the lowest level would be the baseline gas vehicle.

	Older Baseline Diesel	Newer Baseline Diesel	Baseline Gas	Diesel Hybrid	Gas Hybrid
Older Baseline Diesel		-43.4%	99.8%	-80.8%	69.7%
Newer Baseline Diesel	30.2%		99.8%	-26.1%	78.8%
Baseline Gas	-42100.0%	-60400.0%		-76200.0%	-12700.0%
Diesel Hybrid	44.7%	20.7%	99.9%		83.2%
Gas Hybrid	-229.7%	-372.7%	99.2%	-496.1%	

Table 7-3 NO_x Vehicle to Vehicle Comparison for On Road Testing

7.2.3 Hydrocarbon Emissions

The baseline gas vehicle produced the lowest hydrocarbon numbers of any of the tested vehicles with 0.07 g/mi and 0.03 g/mi in on-road and dynamometer testing, respectively. The gasoline hybrid did exhibit higher HC (66.7%) versus the gasoline baseline truck, despite the engine-off feature when at a stop or light load. This is presumably due to the many more times that the gasoline engine is started in response to the speed demands on the vehicle and state of charge on the battery; each time the engine is started, the engine controls runs the engine slightly rich to heat the catalytic converter to operating temperature. The on/off operation does not allow the catalytic converter to reach and maintain optimum temperature. Even though engine/chassis combination used as the base for the gasoline hybrid passed the requirements for EPA certification as a LEV) the changes made to convert it to a series hybrid potentially have resulted in it not being able to perform at the same level of emissions of the baseline gas vehicle. The baseline gasoline truck which is Frito-Lay's current new-vehicle purchase is certified as an EPA LEV. As expected the diesel trucks all emitted more hydrocarbons than the gas vehicles. The hybrid diesel was higher than either of the baseline diesels. Table 7-4 is a relative comparison matrix that shows the change expected when replacing a vehicle from the top of the matrix with a vehicle on the left side of the matrix.

Conclusion: The team believes replacement of any baseline diesel vehicle with the gas hybrid can reduce hydrocarbon emissions, but the best option for reducing emissions would be the baseline gas vehicle.

	Older Baseline Diesel	Newer Baseline Diesel	Baseline Gas	Diesel Hybrid	Gas Hybrid
Older Baseline Diesel		-103.6%	75.0%	-114.3%	25.0%
Newer Baseline Diesel	50.9%		87.7%	-5.3%	63.2%
Baseline Gas	-300.0%	-714.3%		-757.1%	-200.0%
Diesel Hybrid	53.3%	5.0%	88.3%		65.0%
Gas Hybrid	-33.3%	-171.4%	66.7%	-185.7%	

Table 7-4 Hydrocarbon Vehicle to Vehicle Comparison for On Road Testing

7.2.4 Carbon Monoxide Emissions

Lowest carbon monoxide emissions in on-road and dynamometer testing were seen in the baseline gas vehicle at 0.52 g/mi and 1.49 g/mi respectively. The hybrid trucks emitted the highest levels of CO of the five trucks in the Phase 2 on-road testing. The gas hybrid was 80.4% higher than the baseline gasoline truck, while the diesel hybrid truck was 13.2% higher than the best performing baseline diesel. Table 7-5 is a relative comparison matrix that shows the change expected when replacing a vehicle from the top of the matrix with a vehicle on the left side of the matrix.

Conclusion: Carbon monoxide emissions were not reduced using the hybrid vehicles and were actually higher than the baseline trucks.

	Older Baseline Diesel	Newer Baseline Diesel	Baseline Gas	Diesel Hybrid	Gas Hybrid
Older Baseline Diesel		-16.3%	74.4%	-15.3%	-30.5%
Newer Baseline Diesel	14.0%		78.0%	0.8%	-12.3%
Baseline Gas	-290.4%	-353.8%		-350.0%	-409.6%
Diesel Hybrid	13.2%	-0.9%	77.8%		-13.2%
Gas Hybrid	23.4%	10.9%	80.4%	11.7%	

Table 7-5 Carbon Monoxide Vehicle to Vehicle Comparison for On Road Testing

7.2.5 Carbon Dioxide Emissions

Carbon dioxide emissions rankings were consistent with those presented for fuel economy with the newer baseline diesel performing best in on-road testing at 689 g/mi and the diesel hybrid performing best on the dynamometer with 632 g/mi. This is generally as expected given the inherent efficiency difference between gasoline and diesel engines. Carbon Dioxide is not considered as noxious as the other emissions here that produce immediate respiratory or other acute symptoms in individuals; however carbon dioxide is believed to be key factor in rise of global temperatures and is

a concern when evaluating the overall emissions "cleanliness" of various vehicle options. CO_2 can be estimated fairly closely for an individual vehicle or a full fleet of vehicles by calculating the gallons of fuel burned per mile or per year and the carbon dioxide emissions factor for a given fuel type (8.87 kg/gal for gasoline and 10.15 kg/gal for diesel). In this case, there is clearly a large tradeoff between the gas and diesel engines between NO_x and CO_2. Table 7-6 is a relative comparison matrix that shows the change in CO_2 expected when replacing a vehicle from the top of the matrix with a vehicle on the left side of the matrix.

	Older Baseline Diesel	Newer Baseline Diesel	Baseline Gas	Diesel Hybrid	Gas Hybrid
Older Baseline Diesel		23.2%	-7.5%	21.3%	-2.1%
Newer Baseline Diesel	-30.2%		-39.9%	-2.5%	-32.9%
Baseline Gas	7.0%	28.5%		26.8%	5.0%
Diesel Hybrid	-27.1%	2.4%	-36.5%		-29.7%
Gas Hybrid	2.1%	24.8%	-5.2%	22.9%	

Table 7-6 Carbon Dioxide Vehicle to Vehicle Comparison for On Road Testing

7.3 Drivability Assessment

Overall, the hybrid trucks drove and rode similar to the baseline vehicles. The drivability of the hybrids was very good overall, and showed a high degree of refinement. Only a few minor issues were seen with each hybrid truck, and were successfully addressed through vendor support visits. The research team believes the operational difference noted (sounds, throttle response, acceleration, engine-off operation, driving style, etc.) would not present a concern for drivers transitioning from a baseline vehicle to a hybrid vehicle. The diesel hybrid with its automated manual transmission exhibited a larger difference versus current Frito-Lay delivery trucks, which are equipped with automatic transmissions. Additionally, the engine-off operation on the gasoline hybrid took some getting used to by the drivers. Overall, after a short learning period, the drivers reported acceptable drivability and quickly adapted to each vehicle's particular driving characteristics. In order to fully take advantage of the hybrid trucks' regenerative braking capability and achieve the optimum fuel efficiency, the vehicle operators would have to be taught specific hybrid truck driving techniques.

7.4 Conclusion

7.4.1 Proposed Ranking of Vehicles Tested

A proposed method to force-rank the vehicles overall through a composite score was developed by calculating a score for each vehicle within the range of the results for

each constituent. This score was then multiplied by five and equally added the MPG and NO_x scores for each vehicle to provide a composite score on a zero to ten scale. The lowest total score represents the number one ranked vehicle. Table 7-7 ranks the vehicles by this composite score. Using the composite score, the newer baseline diesel vehicle proved to be the overall leader in on-road testing when only MPG and NO_x are considered. Based on the results presented, electric hybrid technology does not appear to improve NO_x emissions or fuel efficiency in this type of application. The results show there appears to be a disproportionate trade-off of fuel efficiency for NO_x emissions depending on which type of fuel is used. Because of this trade-off the reader may draw a different conclusion with a different preference for higher efficiency or lower NO_x emissions.

	MPG		NOx		Composite	Composite
	MPG	Score	g/mi	Score	Score	Rank
Newer Baseline Diesel	14.68	0.00	6.05	0.79	3.98	1
Baseline Gas	8.15	1.00	0.01	0.00	5.00	2
Gas Hybrid	9.19	0.84	1.28	0.17	5.04	3
Older Baseline Diesel	11.00	0.56	4.22	0.55	5.59	4
Diesel Hybrid	13.24	0.22	7.63	1.00	6.11	5

Table 7-7 MPG and NO_x Composite Vehicle Ranking for On Road Testing

The results lead to a different conclusion if all emission constituents are used in ranking the vehicles. Due to the diversity in average level and range of the results, a composite score was developed by calculating a score for each vehicle within the range of the results for each constituent with 0 being the best and 1 being the worst. This score was then multiplied by two and equally added for each vehicle to provide a composite score on a one to ten scale. The lowest total score represents the number one ranked vehicle. Table 7-8 the ranks the vehicles by this composite score. Using the composite score, the baseline gas vehicle proved to be the overall leader in on-road testing when considering all emissions constituents. The hybrid technology did not deliver improved results in this application and actually ranked the two lowest of the five vehicles. Even though the engine/chassis combination used as the base for the gasoline hybrid passed the requirements for EPA certification as a LEV, the changes made to convert it to a series hybrid are believed to have resulted in it's not being able to perform at the same level of emissions of the baseline gas vehicle. The baseline gas vehicle delivered the lowest combined emissions results shown and meets EPA LEV certification levels as-tested. As a result it ranked best in three of the four emissions constituents. The higher CO_2 output of this vehicle was not sufficiently disproportionate to outweigh the lower emissions in other areas.

	MPG		NOx		HC		CO		CO2		Composite	Composite
	MPG	Score	g/mi	Score	g/mi	Score	g/mi	Score	g/mi	Score	Score	Rank
Baseline Gas	8.15	1.00	0.01	0.00	0.07	0.00	0.52	0.00	964	1.00	4.00	1
Newer Baseline Diesel	14.68	0.00	6.05	0.79	0.57	0.94	2.36	0.86	689	0.00	5.21	2
Older Baseline Diesel	11.00	0.56	4.22	0.55	0.28	0.40	2.03	0.71	897	0.76	5.96	3
Gas Hybrid	9.19	0.84	1.28	0.17	0.21	0.27	2.65	1.00	916	0.83	6.20	4
Diesel Hybrid	13.24	0.22	7.63	1.00	0.60	1.00	2.34	0.85	706	0.06	6.28	5

Table 7-8 All Constituent Composite Vehicle Ranking for On Road Testing

This ranking exercise is presented only as a guide to assess the proportionality of tradeoffs of the various emissions components, and the potential best balance or compromise overall between the tradeoffs in emissions. The drawback to this methodology is that all emissions constituents are weighted equally here in terms of harmfulness; however, it is believed that since the ranking method compares the relative and not absolute performance of each vehicle, it is at least directionally useful.

7.4.2 Summary for Vehicles Tested Adjusted for 2007 EPA Standards

It is understood that the results and conclusions presented here are already somewhat "dated" and obsolete for commercially available diesel trucks in 2007 due to the improved emissions levels of 2007 models. All of the diesel engines in the vehicles tested are no longer commercially available as-tested here due to the 2007 changes to the EPA emissions standards for diesel vehicles. The 2007 EPA emissions standards have a 55% reduction (3.3 g/mi to 1.5 g/mi) in allowable NO_x emissions. Tables 7-9 and 7-10 are presented with the tested NO_x value for the diesel hybrid reduced by 55% to show the potential improvements under the 2007 EPA emissions standards. It is assumed that a reduction in base level engine emissions will translate proportionately to a "hybridized" diesel engine, and fuel economy, and thus CO_2 is not materially affected. This vehicle is the only diesel vehicle tested here that will have the same engine that is certified to the 2007 EPA emission standards for diesels. Gasoline emissions standards have not changed since the inception of this study so will not be adjusted likewise.

	MPG		NOx		Composite	Composite
	MPG	Score	g/mi	Score	Score	Rank
Diesel Hybrid	13.24	0.22	3.43	0.57	3.95	1
Baseline Gas	8.15	1.00	0.01	0.00	5.00	2
Newer Baseline Diesel	14.68	0.00	6.05	1.00	5.02	3
Gas Hybrid	9.19	0.84	1.28	0.21	5.26	4
Older Baseline Diesel	11.00	0.56	4.22	0.70	6.31	5

Table 7-9 MPG and NO_x Composite Vehicle Ranking for On Road Testing with NO_x Adjusted for 2007 EPA Standards

	MPG		NOx		HC		CO		CO2		Composite	Composite
	MPG	Score	g/mi	Score	g/mi	Score	g/mi	Score	g/mi	Score	Score	Rank
Baseline Gas	8.15	1.00	0.01	0.00	0.07	0.00	0.52	0.00	964	1.00	4.00	1
Diesel Hybrid	13.24	0.22	3.43	0.57	0.60	1.00	2.34	0.85	706	0.06	5.41	2
Newer Baseline Diesel	14.68	0.00	6.05	1.00	0.57	0.94	2.36	0.86	689	0.00	5.62	3
Older Baseline Diesel	11.00	0.56	4.22	0.70	0.28	0.40	2.03	0.71	897	0.76	6.25	4
Gas Hybrid	9.19	0.84	1.28	0.21	0.21	0.27	2.65	1.00	916	0.83	6.29	5

Table 7-10 All Constituent Composite Vehicle Ranking for On Road Testing with NO_x Adjusted for 2007 EPA Standards

As can be seen in the tables above, it is anticipated that the change in EPA emissions standards will improve the NO_x emissions performance of the diesel hybrid enough to change the original conclusions of the study in Section 7.4.1 when only considering MPG and NO_x. Using these anticipated NOx emissions the diesel hybrid would be the preferred vehicle. If all emissions are considered, the baseline gas vehicle would still be preferred where NO_x emissions are of concern. The diesel hybrid would still emit less NO_x than the existing baseline diesels and could be used to replace those when needed where NO_x was not a concern.

7.4.3 Summary

In summary, overall, the diesel hybrid does offer improved fuel efficiency versus certain existing vehicles in the Frito-Lay fleet, including older diesels and new gasoline units. While the diesel hybrid did not outperform the newer diesel baseline truck in fuel economy, that 4-cylinder engine configuration is no longer available. The gasoline hybrid showed marginal fuel economy benefit and much higher NO_x versus the current gasoline baseline truck, and lower fuel economy with significantly improved NO_x versus currently used diesel trucks. The diesel hybrid perhaps has an application where higher fuel efficiency is desired and where NO_x emissions are not as much of a concern. With the potential improvements expected with the 2007 EPA emission standards the NO_x impact would be less, but still not low enough make it a good option in areas where NO_x emissions are a concern. Additionally, diesel technology comes at a substantially increased capital cost versus gasoline due the diesel engine and emissions equipment required. Each fleet operator will have to weigh the increased cost against fuel savings and potential emissions reductions incentives based on their annual mileage, current and expected fuel prices, and expected return on investment. Evaluating a 2007-model diesel hybrid with improved NO_x emissions is a recommended area of future study to more fully understand the current fuel efficiency and emissions picture with hybrid-electric delivery trucks.

7.5 Projected Fuel Consumption and Emissions

Projections for emissions and fuel consumption were calculated for all test vehicles based on an average yearly use of 15,000 miles. The purpose of these projections is to provide a snapshot of the environmental impact of the vehicles tested in one year's normal on-road operation and are shown in Table 7-11. Given the data presented in

this report, projections may be made for fuel savings and emissions avoidance for any combination of new-purchase vehicle options and existing baseline truck replacement candidates.

	Gallons Used	NO_X [lbs]	HC [lbs]	CO [lbs]	CO2 [tons]
Older Baseline Diesel	1363.6	139.6	9.3	67.1	14.8
Newer Baseline Diesel	1021.8	200.1	18.8	78.0	11.4
Baseline Gas	1840.5	0.4	2.2	17.2	15.9
Diesel Hybrid	1132.9	252.3	19.8	77.4	11.7
Gas Hybrid	1632.2	42.3	6.9	87.6	15.1

Table 7-11 Example: Annual Fuel Consumption and Emissions Estimates

Appendix A

Frito-Lay Testing Protocol

Frito-Lay Hybrid Vehicle Testing Protocol
August 2006

1) Abstract

2) Testing Schedule

3) Test Plan Strategy

   a) Overview
   b) Phase 1
   c) Phase 2
   d) Phase 3

4) Data Collection and Analysis

   a) On-Road Testing/Data Collection

   b) Data Collection Equipment

   c) Data Collection Training

      i) Data Collection Plan

      ii) Data Collection Training

      iii) Analysis and Evaluations
         (1) Procedures
         (2) Examples

5) APPENDIX

   a) Driver's Survey/Log

   b) Project Schedule

   c) Data Collection Equipment

      (a) Basic Description of the PEMS
      (b) PEMS Features
      (c) PEMS System Installation
      (d) System Operation
      (e) System Comparison
      (f) System Recommendation

1) Abstract

The hybrid electric drive train technology is seen as a way to significantly improve fuel efficiency and reduce harmful vehicle exhaust emissions. While hybrid technology is in widespread use in the automotive industry, it is still in its infancy in the commercial vehicle industry. Frito-Lay has been selected by the Texas Commission on Environmental Quality (TCEQ) to build and test two hybrid electric delivery vehicles in order to evaluate the fuel efficiency and emissions benefits as well as provide a demonstration of the viability of the technology in day-to-day commercial use. One diesel-electric and one gasoline-electric hybrid delivery truck will be produced and tested both on the dynamometer under controlled conditions as well as in real-world delivery operations. Results will be compared to existing diesel trucks which are typical for the delivery operation. This project is funded by a grant from the TCEQ under the Texas Emissions Reduction Program (TERP). A proposed testing protocol has been developed to evaluate vehicle performance and emissions on the conventional diesel delivery trucks and hybrid gas and diesel delivery trucks, and must be submitted to TCEQ for approval prior to testing initiation. The test protocol will cover all phases of testing.

The first test phase will involve vehicle emission and performance testing at the Southwest Research Institute (SwRI) test facility in San Antonio, Texas in a laboratory environment using the heavy duty chassis dynamometer and Federal Test Protocol (FTP). Phase 1 and Phase 3 dynamometer testing will follow the test protocol described in SWRI Proposal EVR-4791 “Emissions Testing of Various Delivery Vehicles’. SwRI’s test will be based on the Federal Test Protocol (FTP) and measure exhaust emissions of PM, NOx, HC, CO and CO2. Both SwRI’s Proposal EVR-4791 and their Test/QA Plan are attached.

The second phase of testing will involve ‘real world’ emissions and vehicle performance monitoring in the Dallas-Ft. Worth and Houston areas in simulated Frito-Lay product delivery operation for various fixed delivery routes. During Phase 2 testing, emission and performance monitors installed in both the base line and hybrid vehicles will provide real time data acquisition. The emission monitors will measure NOx concentrations and the performance monitors will provide vehicle speed, distance and MPG. Phase 2 on-road emission measurement will be done with a Portable On-board Emissions Measurement System (PEMS), the Montana OEM-2100. The key objectives to the Phase 2 testing are to collect real-world vehicle emissions and activity data on Dallas and Houston area roads using the PEMS; to analyze characteristics of the on-road vehicle emissions and determine the operational factors which play the largest role in fuel consumption and emissions generation; and to determine the reduction in fuel consumption and NOx emissions between conventional and hybrid vehicles. The Frito-Lay delivery operation has been analyzed using GPS, and the data gathered in the analysis will be used to select the routes for the Phase 2 testing so that results representative of the Frito-Lay delivery operation are obtained.

Because of delays in the delivery of the hybrid test vehicles, the testing will be taken “offline” from the normal delivery operation. Since a number of replications are required to achieve statistically valid data, this approach allows for a number of replicates to be run each day,

rather than just once, providing much more data on a daily basis. A dummy load of water or other material will be used to simulate the starting loaded weight of the trucks, and the ballast weight will be reduced during the course of the simulated route run. Every effort will be made in the course of test execution and design to closely simulate the normal daily delivery operations to ensure the data gathered is representative of actual delivery activities.

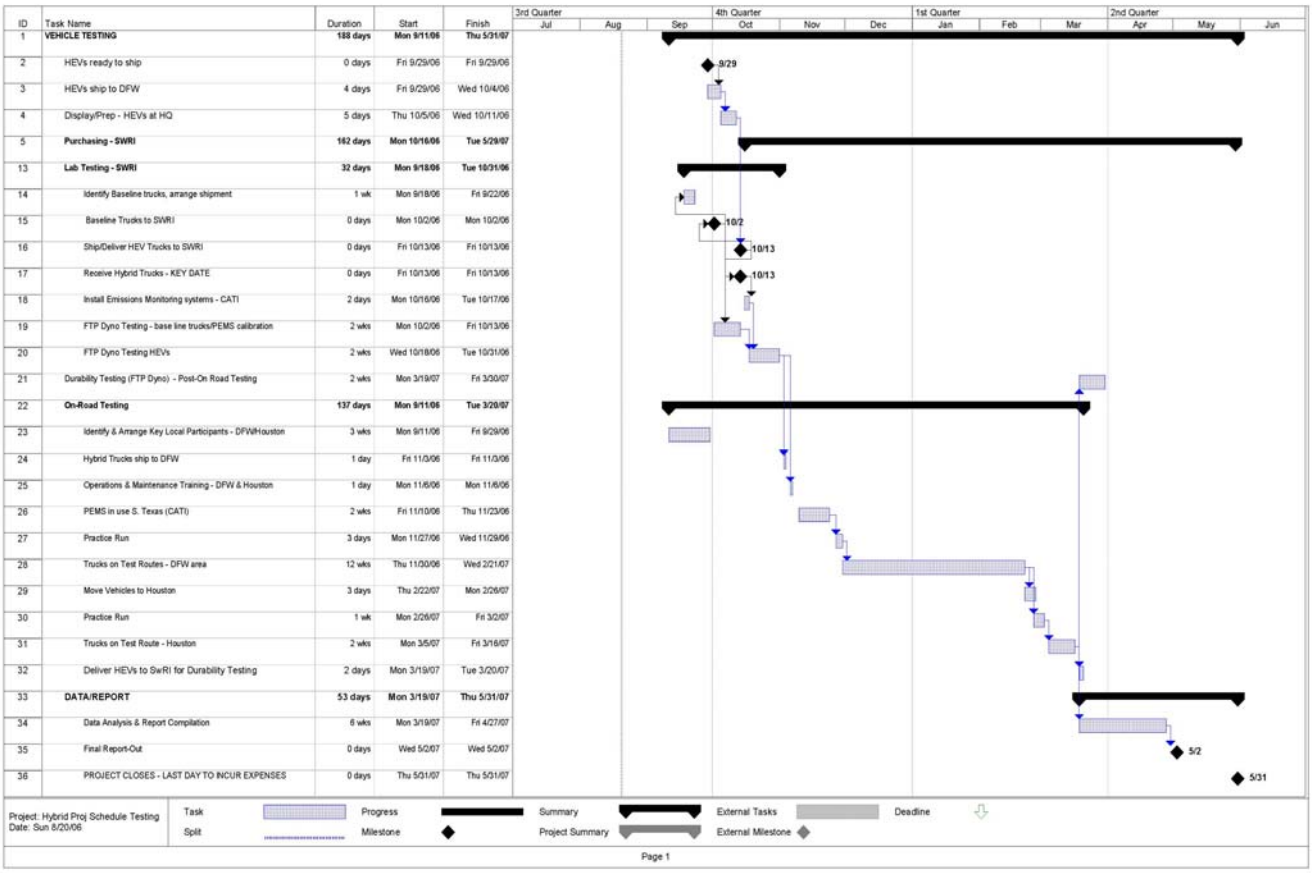
The third and final phase of testing will involve "durability" testing at the SwRI facility upon completion of the 'real time' testing, which is an evaluation of emissions and fuel consumption performance of the vehicles after mileage has accumulated on the units.

The proposed testing protocol has been reviewed with the National Renewable Energy Lab's Advanced Heavy Hybrid team in Golden, Colorado for input. The test protocol described here incorporates NREL's experience and learnings with executing similar type projects in other industry segments.

2) Testing Schedule

The hybrid vehicles will be delivered early in October 2006 and will be engaged in the testing protocol shortly thereafter.

The following is a detailed project schedule for testing of the hybrid and baseline trucks as well as the data gathering and reporting phases of the project.



ID	Task Name	Duration	Start	Finish
1	**VEHICLE TESTING**	**188 days**	**Mon 9/11/06**	**Thu 5/31/07**
2	HEVs ready to ship	0 days	Fri 9/29/06	Fri 9/29/06
3	HEVs ship to DFW	4 days	Fri 9/29/06	Wed 10/4/06
4	Display/Prep - HEVs at HQ	5 days	Thu 10/5/06	Wed 10/11/06
5	**Purchasing - SWRI**	**162 days**	**Mon 10/16/06**	**Tue 5/29/07**
13	**Lab Testing - SWRI**	**32 days**	**Mon 9/18/06**	**Tue 10/31/06**
14	Identify Baseline trucks, arrange shipment	1 wk	Mon 9/18/06	Fri 9/22/06
15	Baseline Trucks to SWRI	0 days	Mon 10/2/06	Mon 10/2/06
16	Ship/Deliver HEV Trucks to SWRI	0 days	Fri 10/13/06	Fri 10/13/06
17	Receive Hybrid Trucks - KEY DATE	0 days	Fri 10/13/06	Fri 10/13/06
18	Install Emissions Monitoring systems - CATI	2 days	Mon 10/16/06	Tue 10/17/06
19	FTP Dyno Testing - base line trucks/PEMS calibration	2 wks	Mon 10/2/06	Fri 10/13/06
20	FTP Dyno Testing HEVs	2 wks	Wed 10/18/06	Tue 10/31/06
21	Durability Testing (FTP Dyno) - Post-On Road Testing	2 wks	Mon 3/19/07	Fri 3/30/07
22	**On-Road Testing**	**137 days**	**Mon 9/11/06**	**Tue 3/20/07**
23	Identify & Arrange Key Local Participants - DFW/Houston	3 wks	Mon 9/11/06	Fri 9/29/06
24	Hybrid Trucks ship to DFW	1 day	Fri 11/3/06	Fri 11/3/06
25	Operations & Maintenance Training - DFW & Houston	1 day	Mon 11/6/06	Mon 11/6/06
26	PEMS in use S. Texas (CATI)	2 wks	Fri 11/10/06	Thu 11/23/06
27	Practice Run	3 days	Mon 11/27/06	Wed 11/29/06
28	Trucks on Test Routes - DFW area	12 wks	Thu 11/30/06	Wed 2/21/07
29	Move Vehicles to Houston	3 days	Thu 2/22/07	Mon 2/26/07
30	Practice Run	1 wk	Mon 2/26/07	Fri 3/2/07
31	Trucks on Test Route - Houston	2 wks	Mon 3/5/07	Fri 3/16/07
32	Deliver HEVs to SwRI for Durability Testing	2 days	Mon 3/19/07	Tue 3/20/07
33	**DATA/REPORT**	**53 days**	**Mon 3/19/07**	**Thu 5/31/07**
34	Data Analysis & Report Compilation	6 wks	Mon 3/19/07	Fri 4/27/07
35	Final Report-Out	0 days	Wed 5/2/07	Wed 5/2/07
36	PROJECT CLOSES - LAST DAY TO INCUR EXPENSES	0 days	Thu 5/31/07	Thu 5/31/07

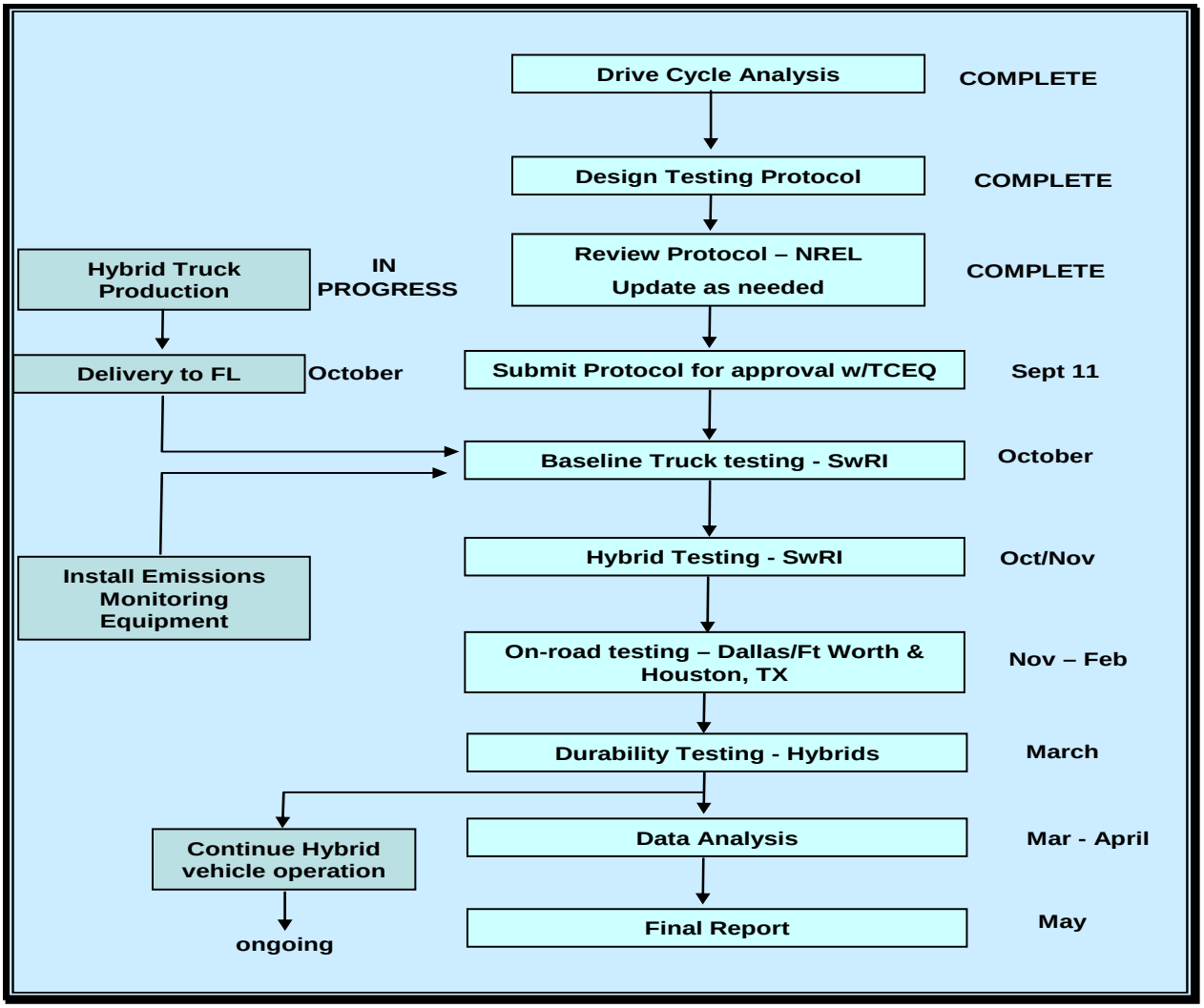
It is anticipated that the on-road testing will require 10 weeks, including 8 weeks of on-road evaluation in the DFW area and 2 weeks on Houston, as well as some "practice" runs in both areas. If variability in test results or technical problems dictates that more on-road testing is required, the schedule will be adjusted accordingly. It is acknowledged that the project has a hard deadline of May 31, 2007, after which no reimbursable expenses may be incurred.

3) Test Plan Strategy

Testing of the hybrid and baseline vehicles will be broken down into 3 phases:

Phase 1 – Initial Laboratory Evaluation
Phase 2 – On-Road Evaluation
Phase 3 – Durability Testing (Lab)

An overview of the testing and data analysis strategy is shown below:



Since each hybrid truck is a new vehicle, it is important to ensure that each truck's engine is broken in prior to testing initiation. In addition to the mileage accumulated during drive train check-out and calibration/tuning, the vehicles will be driven from their assembly point if more miles are required. It is anticipated that both trucks will have at least 2,000 break-in miles prior to test initiation. No time is allotted in the overall schedule for break-in mileage accumulation.

Baseline Vehicles: A key part of this test program involves comparing emissions and fuel efficiency to existing vehicles currently being used for product delivery operations. A baseline diesel older vehicle will be selected from good running condition candidates for retirement. It will be 8 to 10 years old with 100,000 to 150,000 miles on it. A baseline diesel newer vehicle will be selected from good running condition trucks. It will be 2 to 3 years old with 30,000 to 50,000 miles on it.

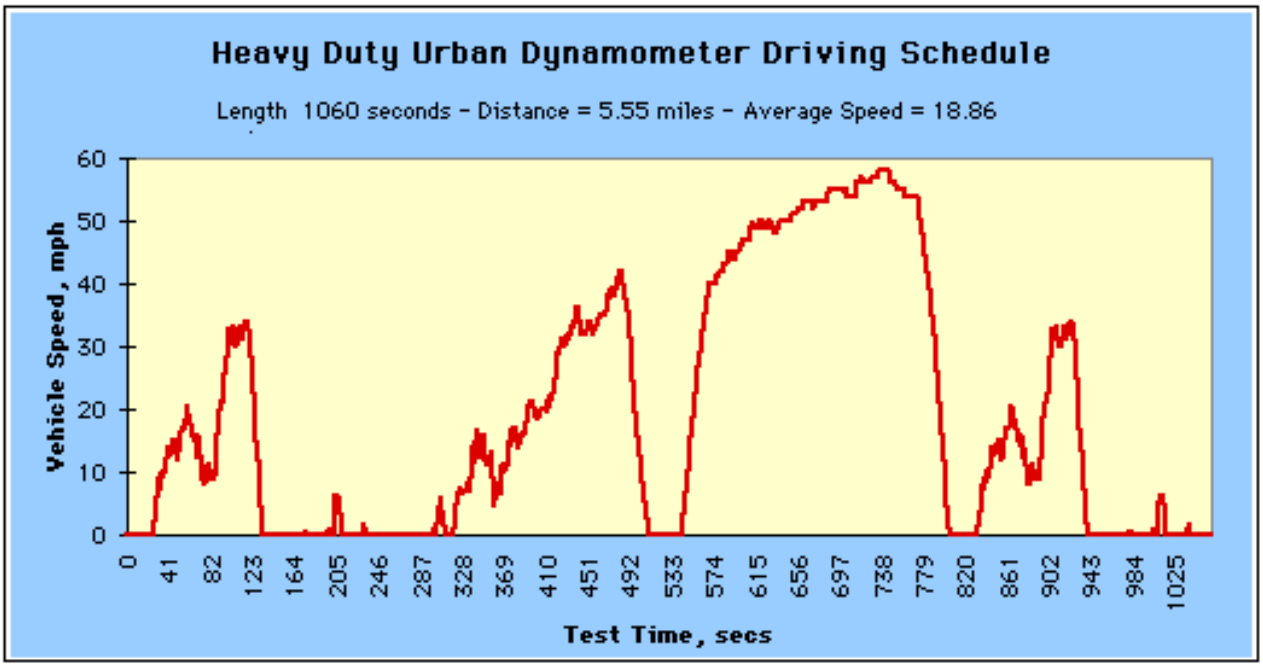
In order to select the delivery routes for the Phase 2 testing that would produce results representative of the Frito-Lay delivery operation, it was apparent that data from existing Frito-Lay delivery activities must be gathered and analyzed. Using data from GPS units installed on existing delivery trucks, a number of different route types were analyzed for speed, distance,

speed distribution, drive time, etc. (Drive Cycle Analysis). In addition to using this data for selection of on-road test routes, it was very insightful and useful in understanding the delivery system and test parameters that should be used in other phases of this study. A more detailed explanation of the existing delivery system analysis will follow in the Phase 2 Testing section.

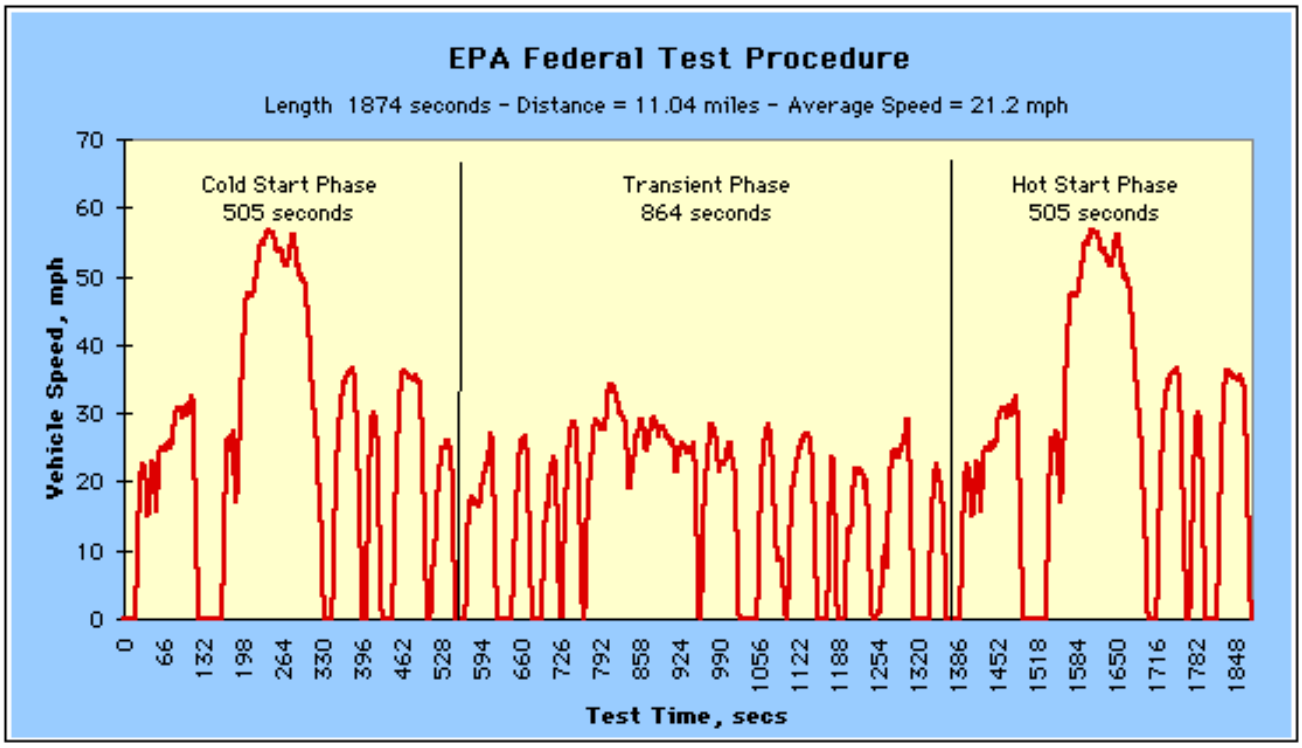
PHASE 1

Phase 1 will consist of running both the baseline and hybrid vehicles on the heavy-duty chassis dynamometer at Southwest Research Institute in San Antonio. During Phase 1 testing, the baseline vehicles will be tested first, followed by the hybrids. The testing is scheduled back-to-back to minimize lab & dynamometer setup time and expense. All vehicles will be run through the Federal Test Protocol (FTP), which uses a standardized time versus-speed trace that corresponds to a typical trip on the road for this type of vehicle. Under the FTP, there are two potential time-versus-speed traces, the Heavy Duty Urban Dynamometer Driving Schedule (HD-UDDS) and the Urban Dynamometer Driving Schedule (UDDS).

FTP Heavy Duty Urban Dynamometer Driving Schedule (HD-UDDS):



FTP Urban Dynamometer Driving Schedule (UDDS):



Typically, the HD-UDDS schedule is used for heavy trucks and buses in standardized testing, and the UDDS used for passenger cars and light trucks. However, after analysis, it was discovered that the UDDS schedule matches more closely with the average or typical Frito-Lay delivery route in terms of average speed, trip length, speed-versus time acceleration signature, etc. During the test program review with NREL, it was agreed that the driving schedule more closely matched to actual operation should be used to obtain lab results that are more indicative of real-world performance. One potential limiting factor would be the ability of our Class 2 vehicles to follow the more aggressive time/speed trace of the UDDS. Upon review of this question with Azure Dynamics, supplier of the gas-electric hybrid truck for this study, Azure indicated that they have run these types and classes of trucks on the UDDS trace with no issues.

Therefore, it is proposed that the UDDS schedule be used for the FTP dynamometer testing at Southwest Research Institute. Southwest Research Institute has indicated that they are capable and ready to run either of these driving schedules for Phase 1 and 3 testing.

During the FTP testing, all emissions will be measured, including CO, CO_2, NO_x, and PM. In addition, fuel use will be recorded and calculated using the carbon balance method in keeping with the FTP.

PHASE 2

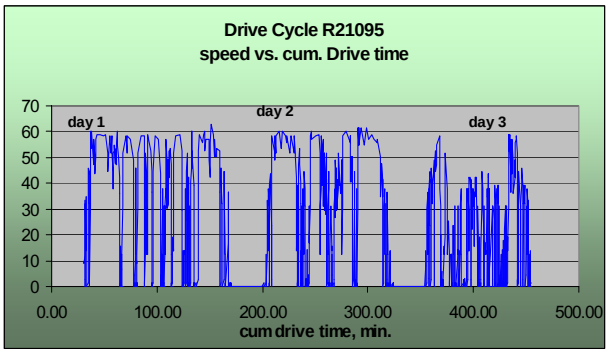
Phase 2 testing, the on-road portion, is the most involved part of the hybrid vehicle evaluation. Many factors in every day driving affect vehicle performance, efficiency, and emissions, including weather, trip distance, traffic patterns, driver habits and behavior, and

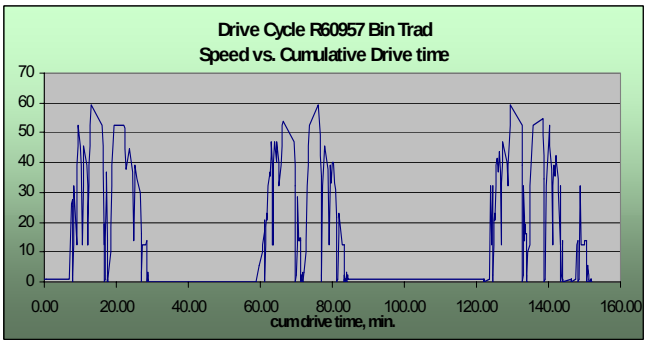
vehicle loading. In performing real-world testing, every attempt to isolate and/or record and document the factors must be taken if a robust performance assessment and model is to be constructed.

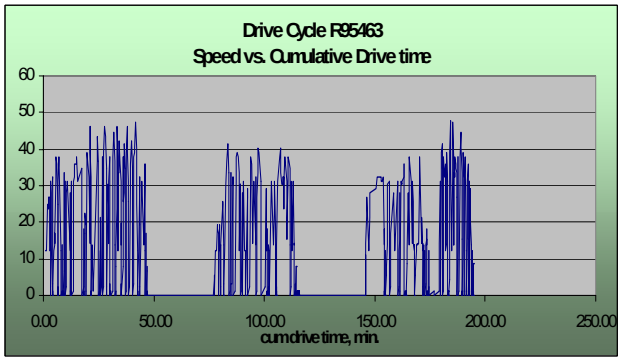
In order to obtain data that is representative of the existing operation, there are a couple of ways to design the test regime. One is to rotate the vehicles through a wide range of typical routes and replicate each as needed to get the needed data. This way, varied routes of short and long distance are used, highway versus urban drive cycles, many operators, etc. are included in the analysis, and an average taken across the full operation for expected efficiency and emissions reduction. Designing a test such as this would require upwards of six months of on-road testing and dedication of resources that this evaluation project will not support time- and budget-wise.

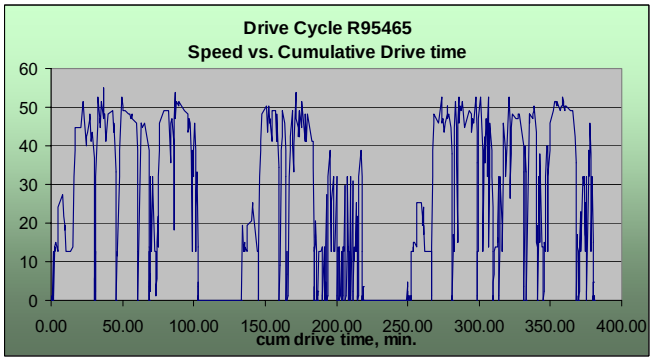
The other approach is to examine the existing operations and determine several routes that would provide representative or average results of the whole system as in the first approach. This method was used for the analysis here. Data from existing delivery trucks with GPS units was analyzed to determine the average and range of several key factors in selecting which routes to use for testing. The GPS units provide a position versus time trace that can be resolved into speed versus distance or speed versus time and analyzed for a number of metrics for comparison.

Below is an example of some of the speed/time trace data obtained from existing operations:









Statistical analysis was performed on the speed/time data to provide average drive distance per day, average speed, distance per day, and a breakdown of amount of time and distance

spend in several speed ranges. Speed ranged chosen were <10mph for "parking lot" operation, <30 mph for city/urban driving, 30-45 mph to represent suburban driving, and ?45 mph for highway driving. The <30 mph selection is inclusive of the <10 mph driving.

The following is an example of the data analyzed for one vehicle running a "DC Pre-Pick: type route over a 15 day period.

Drive Cycle Analysis	R99221 DC Pre-Pick			
	TIME, Min.		**DISTANCE, mi.**	
Parking Lot, <10mph	310.9	20.5%	9.8	1.2%
City, <30mph	537.93	35.5%	49.0	6.3%
Suburban, 30 - 45mph	570.37	37.7%	336.8	43.0%
Highway, >45 mph	405.38	26.8%	397.76	50.8%
Total Drive	1513.68	100.0%	783.6	100.0%
AVG SPEED:	31.06	mph		
AVG Distance per day:	52.24	miles		
Days in cycle	15	days		

The DC Pre-Pick route type is the majority of Frito-Lay's delivery routes in large metropolitan areas and the vast majority of overall routes in the delivery system. Since the DC Pre-Pick routes are also in the DFW, Houston, and other metro areas, the drive cycles for these routes will more stop-and-go, thus offering the potential gains found with the hybrid drive trains and regenerative braking. For these reasons, the DC Pre-Pick route type will be basis for drive cycle analysis and the on-road hybrid testing in Phase 2.

Compiling drive cycle data line that in the table above for a number of trucks, we can get an overall look at the metro delivery operation and begin to establish metrics by which routes for the Phase 2 testing will be selected.

Frito-Lay Drive Cycle Analysis Summary

			DC Pre-Pick			
			Min	Avg	Max	Std
	Speed	mph	13.4	21.1	34.6	6.6
	Daily Drive Distance	miles	8.3	26.8	52.6	15.4
	Drive Time per Day	min	37.3	72.2	122.0	25.0
TIME BASIS	Crawling (<10 mph)	%	19.8%	31.4%	38.5%	6.6%
	City (0-30 mph)	%	32.6%	53.3%	66.0%	11.4%
	Suburban (30-45 mph)	%	22.1%	35.8%	42.4%	5.4%
	Highway (>45 mph)	%	0.0%	12.7%	45.3%	13.9%
MILES BASIS	Parking Lot (<10 mph)	%	0.9%	4.8%	38.1%	11.1%
	City (0-30 mph)	%	4.7%	15.9%	45.6%	11.7%
	Suburban (30-45 mph)	%	20.0%	60.2%	78.2%	17.9%
	Highway (>45 mph)	%	0.0%	24.0%	75.3%	24.6%
	Total Route days		149			
	Total Miles		3994			
	# of trucks in sample		11			

Analysis of the data was insightful in a number of ways. First, the average speeds were much lower than would have been estimated without data; secondly a significant amount of drive time is spent at very low speed operation (<10 mph) negotiating loading docks, parking lots, etc.; and thirdly that the normal delivery operation yields very wide ranges in every parameter. A further variability analysis shows that the vast majority of variability is between individual routes:

					Source of Variance	
DC Pre-Pick, Miles based	Var(r-r)	Var(d-d)	Var(tot)	Std Dev Total	Route-Route % of Total	Day-Day % of Total
Avg Speed, mph, DC Pre-Pick	44.07	0.00	44.07	6.64	95.14%	4.86%
Distance, mi, DC Pre-Pick	238.24	0.00	238.24	15.44	94.29%	5.71%
<10 mph, DC Pre-Pick	1.22%	0.00%	0.01	0.11	67.37%	32.63%
<30 mph, DC Pre-Pick	1.38%	0.00%	0.01	0.12	76.56%	23.44%
30-45 mph, DC Pre-Pick	3.20%	0.00%	0.03	0.18	82.66%	17.34%
>45 mph, DC Pre-Pick	6.08%	0.00%	0.06	0.25	98.63%	1.37%

Randomly selecting routes would require that a large number of them be evaluated in the course of testing to ensure that results would on average represent the whole operation. Also, the variability analysis shows that route speed/time/distance traces are very

repeatable, thus reducing the number of replications required to arrive at statistical significance.

From this data, routes with speed and distance parameters close to the average can be selected for the testing in Phase 2. The process for identifying exactly which routes these are and establishing communication with the drivers and supervisors is currently underway. As an ongoing activity once the testing for immediate project is complete, the hybrid vehicles will be tested on other routes at the extremes of drive time/distance and speed.

Because of delays in the delivery of the hybrid test vehicles, the testing will be taken "offline" from the normal delivery operation. Since the end date of the project is fixed, the compressible portion of the schedule has been the on-road testing phase. The original schedule allowed for up to 24 weeks of on-road delivery testing; that window is now at 12 weeks. Given that a number of replications are required to achieve statistically valid data, an offline testing approach allows for a number of replicates (estimated up to 4) to be run each day, rather than just once, providing much more data on a daily basis. A dummy load of water or other material will be used to simulate the starting loaded weight of the trucks, and the ballast weight will be reduced during the course of the simulated route run. Every effort will be made in the course of test execution and design to closely simulate the normal daily delivery operations to ensure the data gathered is representative of actual delivery activities. Another benefit to the offline approach is that the test will have drivers dedicated to the testing only, so more data collection and attention to the test can be reasonably asked of them without interruption to the normal business activities of Frito-Lay.

The on-road test design is shown below. The design rotates both the baseline and the hybrid trucks through several routes, and provides for 15 replications per route. Initially, it was believed that 5-10 replications would provide sufficient data to arrive at statistical confidence, but based on NREL's input, this was increased to 15 replicates. In NREL's experience, emission testing using the portable testing equipment is somewhat noisy and difficult to achieve repeatability. Since the project budget allows for lease of only 2 PEMS, the monitoring equipment will have to be alternated between the baseline and the hybrid vehicles during on-road testing.

Frito-Lay Hybrid Vehicle Testing Schedule
15 Run Dallas / 5 Run Houston

It is anticipated that testing will occur over a four-month period with the allowance for a fifth month if additional data is required. The testing plan will involve collecting data for fifteen runs per vehicle on two different routes in Dallas and five runs per vehicle on two different routes in Houston using two emission-monitoring units. The data will be reviewed; the statistically acceptable runs for each vehicle and route will be used for analysis and write up.

Dallas	Route RA	Vehicle 1 (V1)	diesel - older	Test Equipment - CAT1
Dallas	Route RB	Vehicle 2 V2)	gas - hybrid	Test Equipment - CAT2
Houston	Route RC	Vehicle 3 (V3)	diesel - newer	Test Equipment - CAT1
Houston	Route RD	Vehicle 4 (V4)	diesel - hybrid	Test Equipment - CAT2

	Dallas		Houston	
	RA	RB	RC	RD
1	V1	V2		
2	V1	V2		
3	V1	V2		
4	V2	V1		
5	V2	V1		
6	V2	V1		
7	V3	V4		
8	V3	V4		
9	V3	V4		
10	V4	V3		
11	V4	V3		
12	V4	V3		
13			V1	V2
14			V2	V1
15			V3	V4
16			V4	V3
17	optional			
18	optional			
19	optional			
20	optional			

PHASE 3

Testing I Phase 3 will be identical to that in Phase 1 of the project. The intention of this "durability" testing is to evaluate the performance of the hybrid trucks after normal mileage has accumulated through the delivery operation, to identify if a degradation in performance has occurred over time. The same FTP UDDS driving schedule used in Phase 1 will be repeated for both the diesel-electric and the gas-electric hybrid trucks. The baseline trucks will not be tested since they will already have significant mileage, and performance is expected to be relatively stable at his point in their life cycle.

4) Data Collection and Analysis

Phase 1 and Phase 3 data will be collected by SwRI. Phase 2 road test data will be collected by the LGGROUP/Frito-Lay field team. Data from all three phases of testing will be evaluated and the results provided in a final written report.

a)On-Road Emission Data Collection

Phase 2 data will be collected in the following manner:

The drivers' log and questionnaire will be used when determining why various runs showed anomalous data. Driver's logs will also be used to understand driveability and other aspects of the hybrid vehicles that are not measured by the performance monitor, as well as log any problems encountered with the vehicles. An example of the Driver's Survey which will be used can be found in the Appendix.

GPS data will be collected simultaneously along with the emission data.
All the collected data will be stored in text format (GPS data will be in the .gps format, which can be used as text files.) On test vehicles that have an onboard powertrain control module (PCM), the vehicle speed and distance will be obtained from the PCM. For vehicles that do not have a PCM, GPS data will be used to obtain the vehicle speed and distance.

It is planned that after vehicle setup and equipment calibration, a trained individual will check each run daily. If possible, the test equipment will be connected to wireless communications equipment allowing remote monitoring and downloading of data. The automated wireless transmission method is preferred by the project team due to data accuracy and to minimize project execution logistics with gathering the road testing data in the field.

The following table contains a summary of data to be collected and the proposed method of collection.

Hybrid Delivery Truck Data Collection Summary - On-Road Testing

Parameter	Unit of Measure	Primary Method	Secondary Method	Notes
Distance driven	miles	GPS	ECM/ odometer	GPS most accurate
Fuel Consumed	gallons	fuel card	ECM	Cross check methods for accuracy; use most accurate
Drive Time	hrs:min	PEMS	GPS	Cross check methods for accuracy; use most accurate
Temperature	degF	weather data		On-line weather data source: NOAA website or equivalent
Humidity	%	weather data		On-line weather data source: NOAA website or equivalent
Idle time		ECM	--	Only for International/Eaton unit; Azure will feature engine-off operation with no idle except as needed for initial battery/ultracap charge at startup.
NOx	ppm	PEMS	--	calibrated against SWRI lab results
CO	%	PEMS	--	"
CO2	%	PEMS	--	"
PM	ppm	PEMS	--	"
HC	ppm	PEMS	--	"
MPG	miles per gallon			calculated value from fuel consumed & miles driven
Avg Speed	miles per hour			calculated value from miles driven & drive time

The data will be processed in Excel. Emissions for the test vehicles will be summarized based on different test conditions. The spatial and temporal distributions of both vehicle speed and emissions will be plotted, and the relationships between the fuel consumption and emissions and model variables (speed, acceleration, and engine RPM (may not be engine RPM, engine load might be a better independent variable – we can discuss)) will be drawn. The measured emissions will be compared with SWRI dynamometer results. Test conditions, emission factors, and vehicle types will be sorted and evaluated; significant differences will be noted. A user-friendly Excel based utility for the fast processing of collected data for both general purpose and for specific utilization will be developed.

b)Data Collection Equipment

The PEMS was selected based on features such as data type gathered, data accuracy level, equipment reliability, available training, ease of use and total cost for the testing cycle. The equipment manuals will be closely followed for installation on the vehicles. This chapter introduces the basic features of this equipment. With two systems available on the market for use in this type of testing, the project team evaluated each unit to provide the required data at the best overall value to the project, Frito-Lay and TCEQ.

Initially, the alternative of using SEMTECH-D equipment on a rental basis was looked at. The SEMTECH-D device developed by Sensors, Inc. is capable of measuring the second-by-second fuel consumption and emissions of NO, NO_2, THC, CO, and CO_2. It also can provide GPS information. An add-on device would be needed to track PM for diesel vehicles.

Clean Air Technologies of Buffalo, NY provides the Montana System. It is capable of measuring second-by-second fuel consumption and emissions of HC, CO, CO_2, NOx and PM readings for diesel and gasoline vehicles.

As a minimum, for road testing, the emission monitor has to monitor NOx concentrations along with monitoring vehicle speed, distance, and MPG as outlined in the original project proposal to TCEQ.

Cost proposals were received for both types of equipment. The decision was made to use the Montana system considering cost, equipment support and training, reliability and ease of use.

Detailed descriptions of the portable emissions units may be found in the Appendix.

c) Data Collection Training

Since the PEMS is a very sensitive scientific device, the research team will be trained by CATI. The training will be done in San Antonio at SwRI.

Training courses include:
(1) the theories of measuring vehicle exhausted flow;
(2) the operational mechanisms of PEMS;
(3) the maintenance of the equipment;
(4) the design of field test;
(5) the way to process collected data;
(6) the experiences on testing idling emissions;
(7) the coordination of GPS system; and
(8) the processing of some basic hardware problems when testing.

Both hybrid trucks will be have the Montana system mounted on them during Phase I dynamometer testing. The researchers will practice all steps on how to place the equipment in vehicle, how to connect all the cables, how to operate the system, and how to read and manage the on-screen data when testing.

After testing, the researchers will learn how to retrieve the generated second-by-second emission data and to process the data. During the first training session, the researchers will get to know the basic principles and how to manage the equipment.

The training techniques, during this session, include how to handle the problem when the engine information can not be uploaded; what countermeasures are needed if there was a warning saying "the system is overheated;" how to transfer the data if the system was shut down improperly; etc.

d)Analysis and Evaluations

This section deals with the analysis and evaluation of the collected emission data. The data processing procedures will be provided first. Then, measured emissions for trucks will be summarized based on different test conditions.

The temporal and spatial distributions of emissions will be analyzed. After that, the relations between emissions and model variables (speed, accelerations, RPM, etc.) will be presented.

A 95% confidence interval is desired – this will depend on the variability of the data, and may drive test length/duration and number of replications. The mean and standard deviation will be calculated by vehicle for fuel economy and emissions. The sample size will then be used together with the standard deviation to identify runs within the 95% confidence interval.

Only complete runs will be considered for data analysis. It is planned to have fifteen runs per vehicle and route combination in Dallas. Five runs per vehicle and route combination will subsequently be made in Houston. Obvious data problems will be discarded.

(i) Procedures on Data Analysis and Evaluations

On-board monitor data and driver's surveys collected from the test vehicles will be submitted to LGGROUP for review and compilation. Test data from each of the test vehicles will be reviewed and compared for percent emission reduction and fuel efficiency.

The generated emission data and GPS data will be second-by-second data. After the initial tests in the Fall of 2006, the procedures for data analysis and evaluations will be further improved for analyzing the collected data.

The following is the general description of the data processing procedure.

Step 1. Controlling data quality

Data quality control includes interpreting and eliminating errors and missing data. For example, for some reasons, the vehicle speed increased 200 mi/hr in one second, which is obviously impossible. This kind of speed would be smoothed by the speed before and after that particular temporal point.

Step 2. Summarizing data for each run

Summarized data analysis includes the summary of the total / average emissions for each run in terms of mileage and/or time spent. This will provide the comparable emissions for different tests and for different runs. The summarized results could also be used for the comparisons with other model estimates. This step will be repeated for each of the runs.

Step 3. Plotting speed diagrams

The temporal and spatial speed diagrams for each test are plotted. The temporal speed diagrams will come from either the emission data base or the GPS data base. However, the spatial speed diagram will employ the longitude and latitude coordinates from the GPS data base. If the speed data in the GPS file is of good quality, all the speed diagrams will be plotted by using GPS data.

Step 4. Plotting temporal and spatial distribution of emissions and fuel consumptions

Temporal distribution of emissions and fuel consumption will be conducted by analyzing the emission database in comparison to the vehicle PEMS data and to GPS system derived data. The PEMS provides second-by-second information on emissions, fuel consumptions, vehicle speed, engine RPM, engine temperature, and throttle position data that is measured directly using sensors. For engines with a supported Engine Control Module (ECM) and diagnostic port, engine and vehicle data will be acquired through this interface. The GPS data will provide exact time, speed, and position data independent of the vehicle drivetrain sensors.

Since emission data and GPS data came from two different sources, time is the only factor that can connect them together. However, due to the different settings, the time line on emission data base may not be matched with the GPS time. Time alignment is very important. After correctly synchronizing the time, the spatial analysis could be conducted. The emissions that will be taken into account in the data analysis are HC, CO, CO_2, NOx, and PM.

Step 5. Plotting the relationships between emissions / fuel and Model Variables (Speed and Time)

Since both the emissions and the model variables will be generated with time, it is natural to observe their relationships by plotting their temporal distributions in one figure. For example, if the relationships between NOx and speed are compared, the temporal distributions of both NOx and speed can appear in a single figure.

Step 6. Comparing the measured emissions with the calculated emissions.

Phase 1 and Phase 3 laboratory dynamometer emissions results will give input for what the calculated emissions should be. This will be compared graphically and mathematically to

the road emissions results by vehicle type and route. This will help verify the total emission and fuel reductions under various road conditions.

1. Phase 1 – Baseline FTP

The analysis in this phase will interpret the laboratory dynamometer test results. This will give the expected values for emissions parameters of CO, CO2, HC, NOx and PM. Fuel economy will also be obtained. A statistical check will be made to verify test results for each vehicle.

2. Phase 2 – Road Test

The analysis in this phase will interpret the road test results. This will give the values for emissions parameters of NOx and PM. Fuel economy will also be obtained. A statistical check will be made to verify test results for each vehicle. These results will be compared to the Phase 1 and Phase 3 laboratory results.

3. Phase 3 – Durability Test FTP

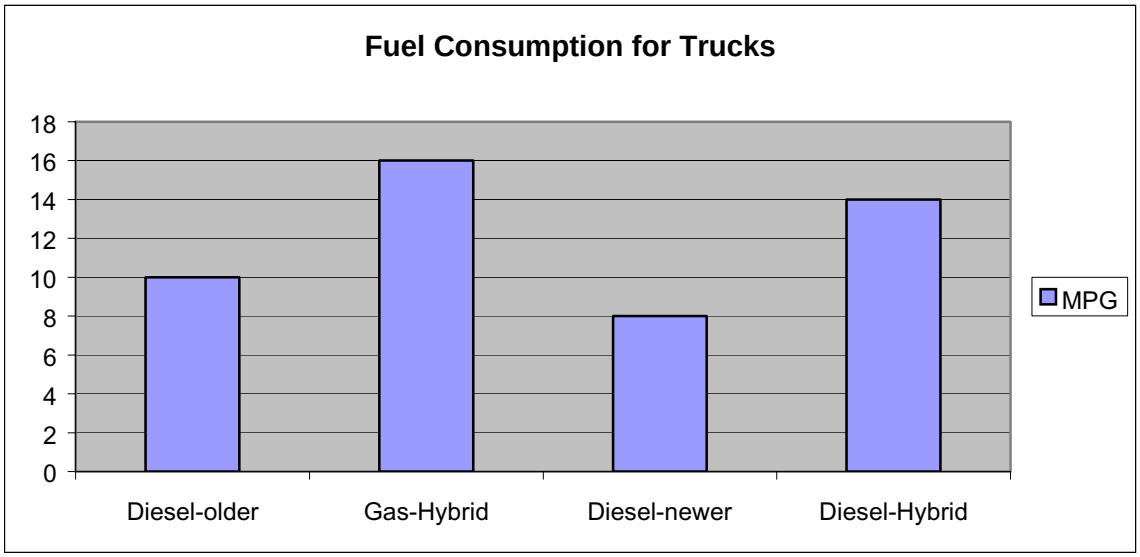
The analysis in this phase will interpret the laboratory dynamometer test results for durability. This will give the expected values for emissions parameters of CO, CO2, HC, NOx and PM. Fuel economy will also be obtained. A statistical check will be made to verify test results for each vehicle.

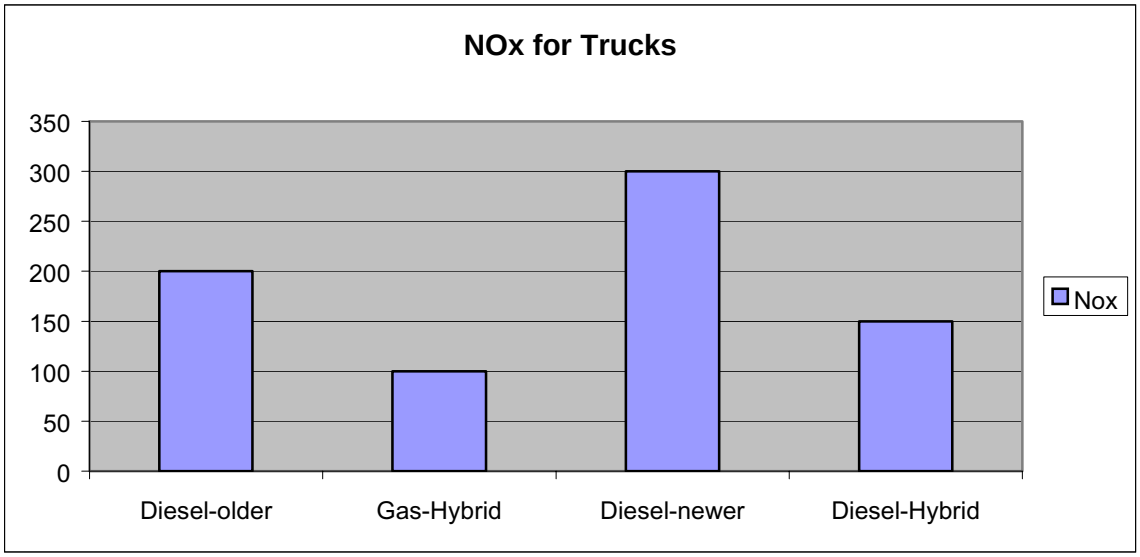
Expected Results (Emissions and Fuel Economy)

vehicle weight	improved fuel economy	decreased Nox	decreased HC	decreased CO	Decreased CO2
6500	25.90%	50.00%	14.70%	17.10%	20.10%
9900	35.20%	78.90%	37.80%	N/A	25.90%

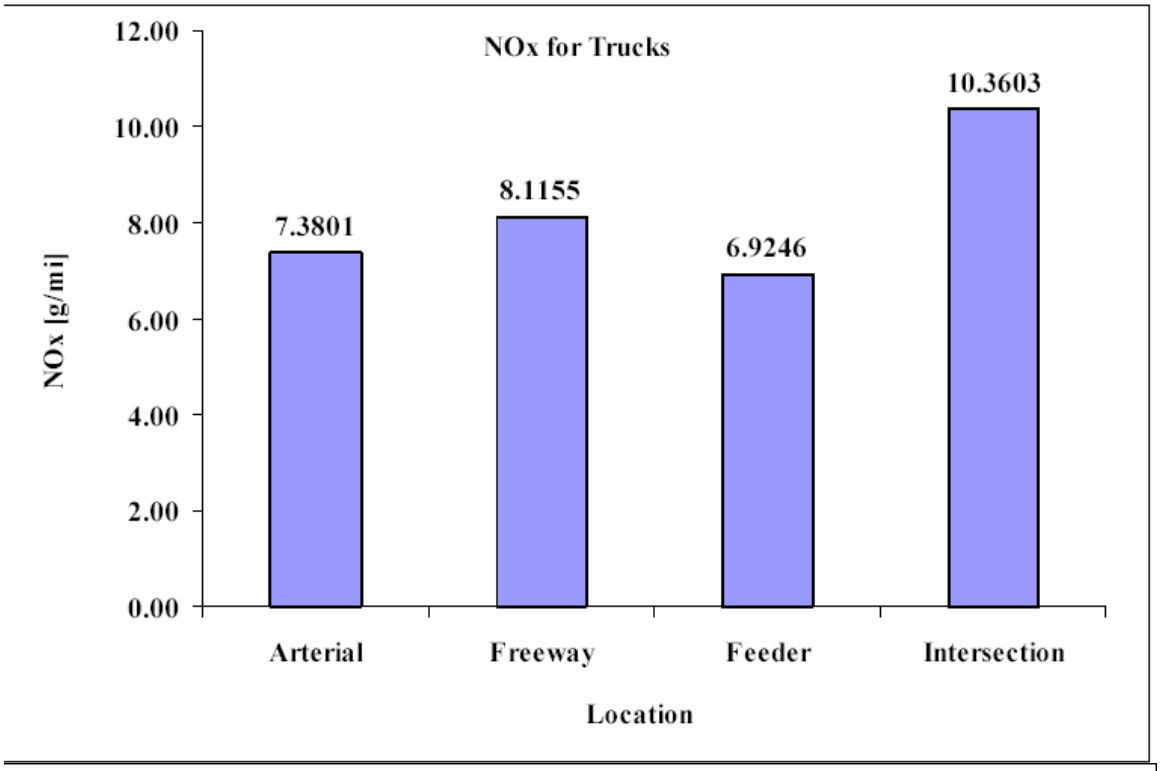
(b) Example charts & data report

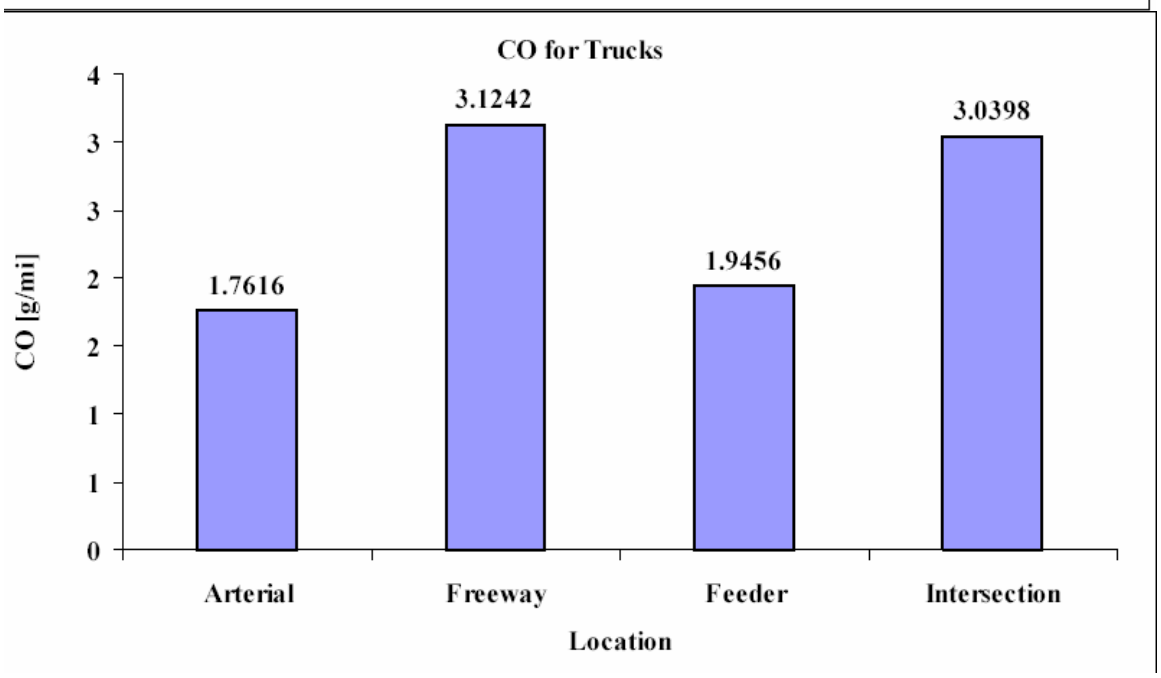
Example charts (There will be similar graphs for each drive cycle in Dallas and Houston):

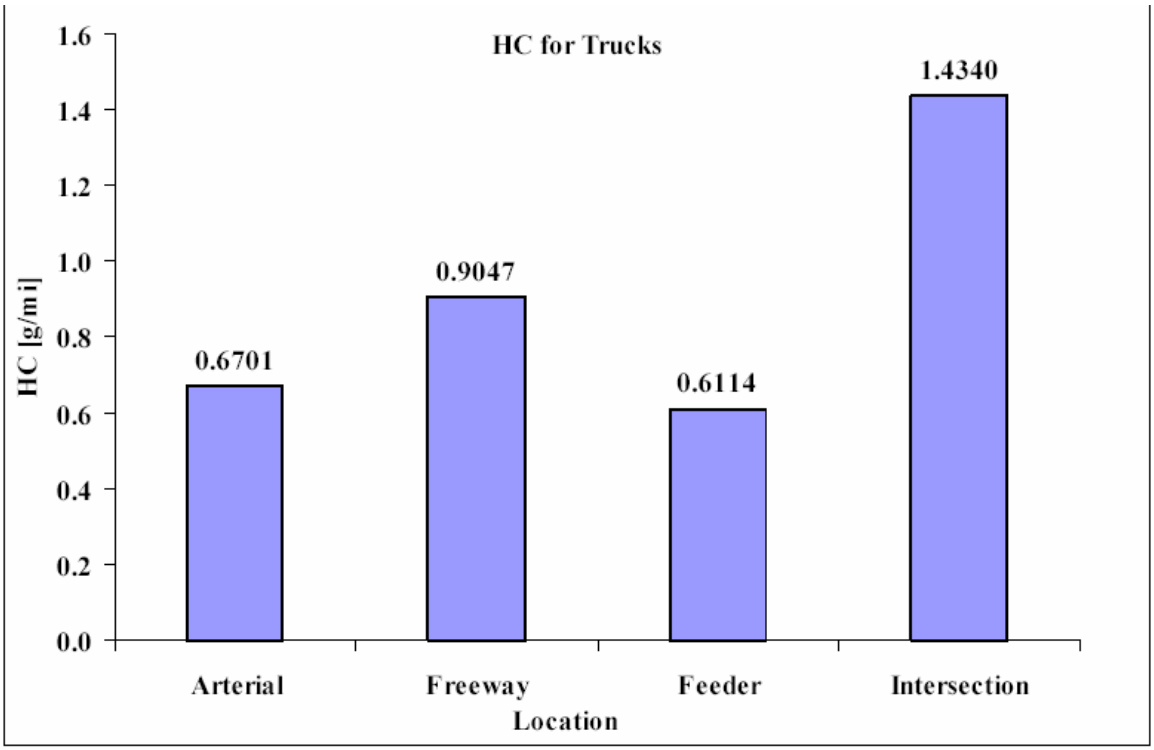


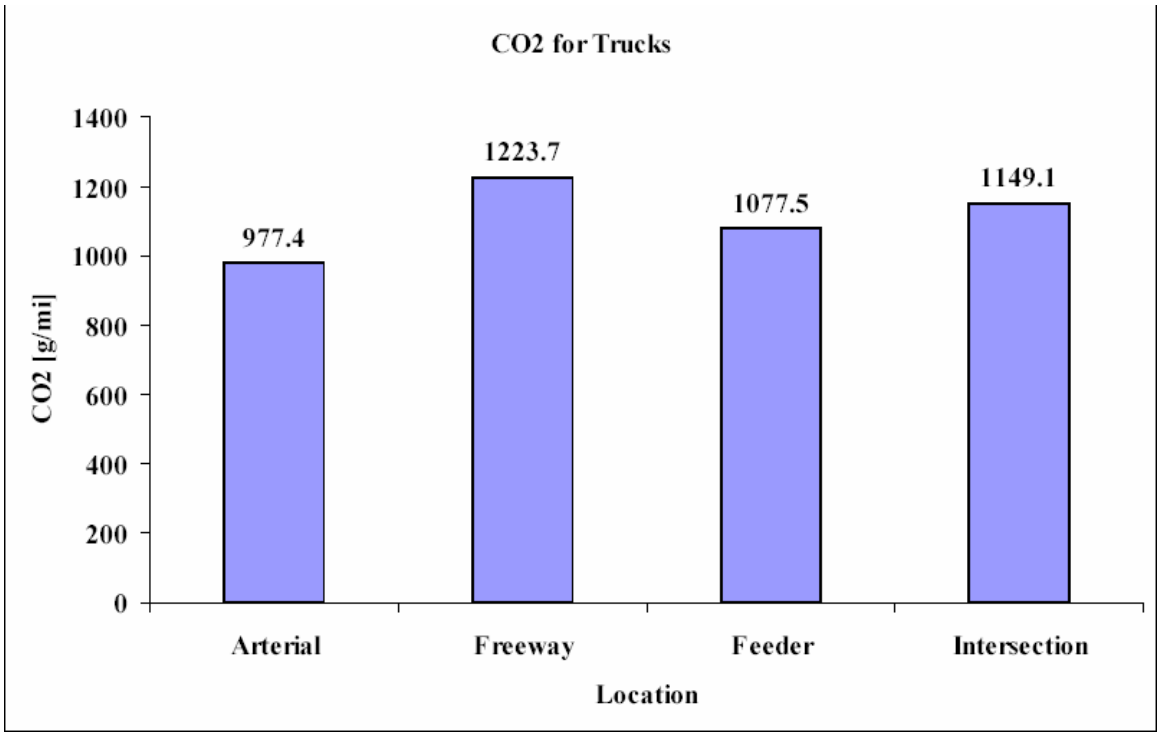


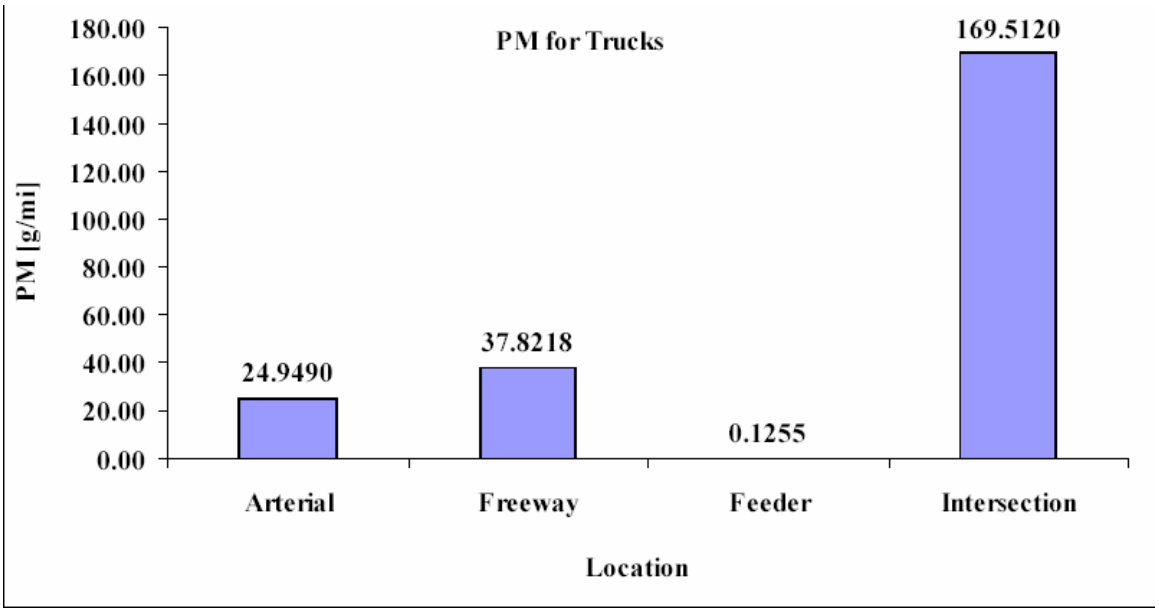
The following examples are from the HARC 2004 road test study. The bar graphs have categories for arterial, freeway, feeder and intersection vehicle emissions. It is planned to show similar data for both the base line diesel vehicles and hybrid versions of gas and diesel fuel vehicles. The Frito-Lay road test will have two routes for Dallas and two routes for Houston.

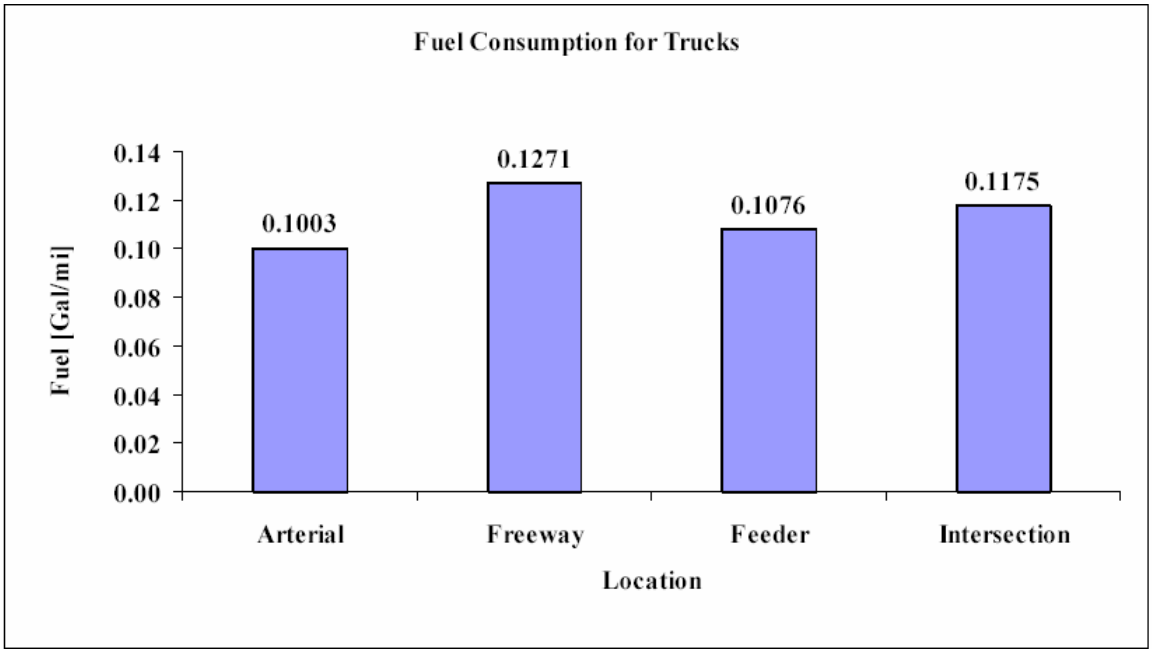

NOx for Trucks
NOx [g/mi]
12.00
10.00
8.00
6.00
4.00
2.00
0.00
7.3801
8.1155
6.9246
10.3603
Arterial
Freeway
Feeder
Intersection
Location


CO for Trucks
CO [g/mi]
4
3
3
2
2
1
1
0
1.7616
3.1242
1.9456
3.0398
Arterial
Freeway
Feeder
Intersection
Location


HC for Trucks
HC [g/mi]
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.6701
0.9047
0.6114
1.4340
Arterial
Freeway
Feeder
Intersection
Location


CO2 for Trucks
CO2 [g/mi]
1400
1200
1000
800
600
400
200
0
977.4
1223.7
1077.5
1149.1
Arterial
Freeway
Feeder
Intersection
Location


PM for Trucks
PM [g/mi]
180.00
160.00
140.00
120.00
100.00
80.00
60.00
40.00
20.00
0.00
24.9490
37.8218
0.1255
169.5120
Arterial
Freeway
Feeder
Intersection
Location


Fuel Consumption for Trucks
Fuel [Gal/mi]
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0.1003
0.1271
0.1076
0.1175
Arterial
Freeway
Feeder
Intersection
Location

APPENDIX

Driver's Survey

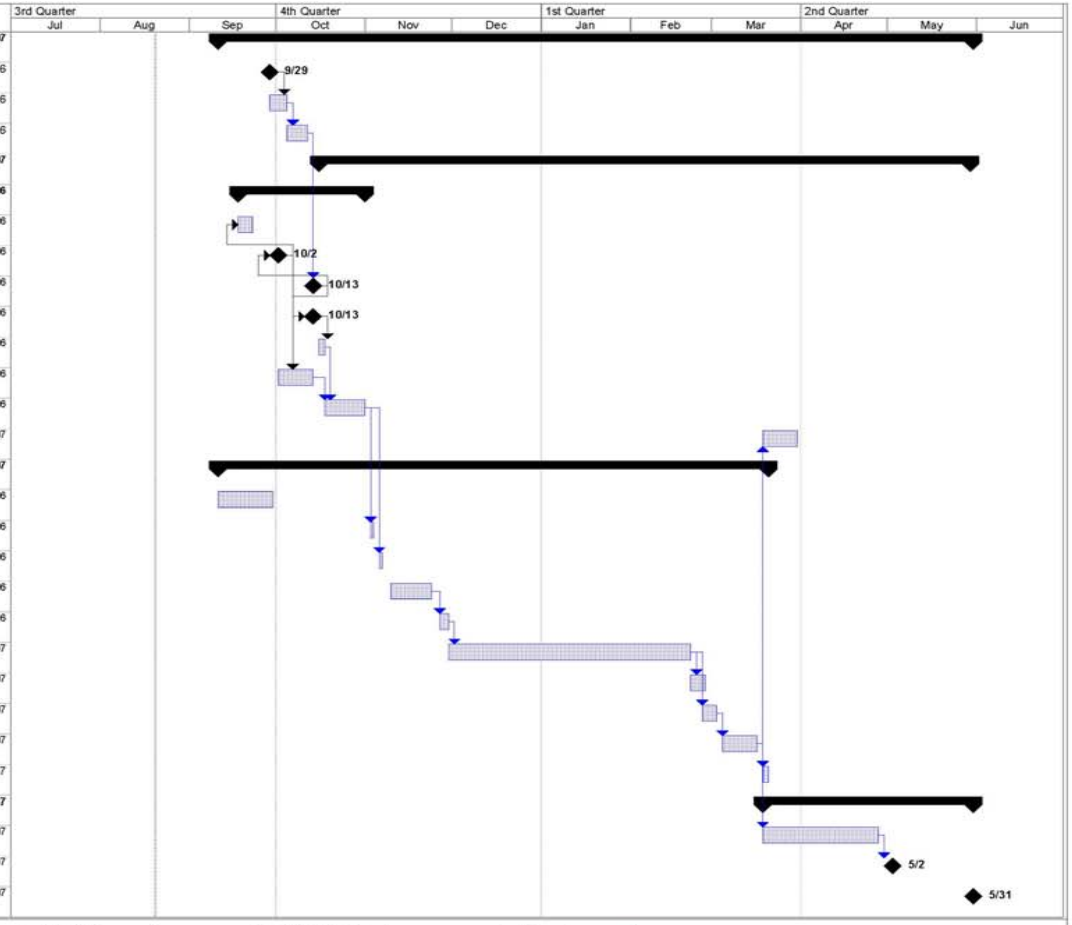
Truck # ________

Daily Data									Driver Rating 0=poor, 10=excellent					
Driver Name	Date	Route #	Route Type	Odometer	Fuel Purchased	Type of driving (hwy/suburban/ city, mix)	Weather (rain/dry/cloudy/humid/hot etc)			Noise	Power/ Acceleration	Braking		Overall Ease of Driving

NOTES OR COMMENTS:

Project Testing Schedule

ID	Task Name	Duration	Start	Finish
1	**VEHICLE TESTING**	**188 days**	**Mon 9/11/06**	**Thu 5/31/07**
2	HEVs ready to ship	0 days	Fri 9/29/06	Fri 9/29/06
3	HEVs ship to DFW	4 days	Fri 9/29/06	Wed 10/4/06
4	Display/Prep - HEVs at HQ	5 days	Thu 10/5/06	Wed 10/11/06
5	**Purchasing - SWRI**	**162 days**	**Mon 10/16/06**	**Tue 5/29/07**
13	**Lab Testing - SWRI**	**32 days**	**Mon 9/18/06**	**Tue 10/31/06**
14	Identify Baseline trucks, arrange shipment	1 wk	Mon 9/18/06	Fri 9/22/06
15	Baseline Trucks to SWRI	0 days	Mon 10/2/06	Mon 10/2/06
16	Ship/Deliver HEV Trucks to SWRI	0 days	Fri 10/13/06	Fri 10/13/06
17	Receive Hybrid Trucks - KEY DATE	0 days	Fri 10/13/06	Fri 10/13/06
18	Install Emissions Monitoring systems - CATI	2 days	Mon 10/16/06	Tue 10/17/06
19	FTP Dyno Testing - base line trucks/PEMS calibration	2 wks	Mon 10/2/06	Fri 10/13/06
20	FTP Dyno Testing HEVs	2 wks	Wed 10/18/06	Tue 10/31/06
21	Durability Testing (FTP Dyno) - Post-On Road Testing	2 wks	Mon 3/19/07	Fri 3/30/07
22	**On-Road Testing**	**137 days**	**Mon 9/11/06**	**Tue 3/20/07**
23	Identify & Arrange Key Local Participants - DFW/Houston	3 wks	Mon 9/11/06	Fri 9/29/06
24	Hybrid Trucks ship to DFW	1 day	Fri 11/3/06	Fri 11/3/06
25	Operations & Maintenance Training - DFW & Houston	1 day	Mon 11/6/06	Mon 11/6/06
26	PEMS in use S. Texas (CATI)	2 wks	Fri 11/10/06	Thu 11/23/06
27	Practice Run	3 days	Mon 11/27/06	Wed 11/29/06
28	Trucks on Test Routes - DFW area	12 wks	Thu 11/30/06	Wed 2/21/07
29	Move Vehicles to Houston	3 days	Thu 2/22/07	Mon 2/26/07
30	Practice Run	1 wk	Mon 2/26/07	Fri 3/2/07
31	Trucks on Test Route - Houston	2 wks	Mon 3/5/07	Fri 3/16/07
32	Deliver HEVs to SwRI for Durability Testing	2 days	Mon 3/19/07	Tue 3/20/07
33	**DATA/REPORT**	**53 days**	**Mon 3/19/07**	**Thu 5/31/07**
34	Data Analysis & Report Compilation	6 wks	Mon 3/19/07	Fri 4/27/07
35	Final Report-Out	0 days	Wed 5/2/07	Wed 5/2/07
36	PROJECT CLOSES - LAST DAY TO INCUR EXPENSES	0 days	Thu 5/31/07	Thu 5/31/07



Project: Hybrid Proj Schedule Testing
Date: Sun 8/20/06

Task | Split | Progress | Milestone | Summary | Project Summary | External Tasks | External Milestone | Deadline

Page 1

Basic Description of the PEMS

The PEMS is designed to measure vehicle mass exhaust emissions under actual on-road driving conditions using vehicle and engine operating data and concentrations of pollutants in exhaust gas sampled from the tailpipe. It typically is installed in the passenger seat or on the vehicle floor, and provides second-by-second information on emissions, fuel consumption, vehicle speed, engine RPM, temperature, throttle position and other engine parameter data can be measured directly using an array of analytical sensors. For vehicles with a supported engine computer diagnostic port, engine and vehicle data is acquired using this interface. For in-vehicle installation, exhaust sample lines can be routed through a window and secured to the exhaust system using hose clamps. The diagnostic port interface cable is routed to the unit from the port connector.

For sensor array installations, sensors are installed on the applicable engine systems and are then routed to the PEMS. Power is drawn from a cigarette lighter outlet or from a cable clamped directly onto the battery. The unit will be securely mounted in the vehicle for the duration of the on-road testing.

Undiluted exhaust gas is sampled from the tailpipe using repair-grade probes and 20-foot (7-meter) sample lines. The concentrations of NOx, in the exhaust gas are determined by a functional equivalent of a repair-grade gas analyzer subsystem. At the same time, vehicle speed, engine RPM, intake air mass flow, coolant temperature, and other engine operating parameters are collected using an on-board diagnostics connector or sensor array system. From the intake air mass flow, known composition of intake air, measured composition of exhaust, and user-supplied composition of fuel, a second by second exhaust mass flow is calculated. Multiplying the exhaust mass flow by the concentrations of different pollutants yields grams per second emission data.

Clean Air Technology PEMS Features

The Montana OEM-2100 has the following features:

- weight is less than 38 lbs.
- power requirements are 12-14 V DC (12 V nominal) and 4-6 amperes from the vehicle electrical system (110V AC adapter included).
- automatic battery backup.
- data capture rate is 1 Hz.

- sample flow is 6 liters/minute nominal for each gas analyzer, 3.8 – 4.0 l/min through PM detector.
- equipment outputs second by second data with 12-second delay.
- OBD data rate is 0.6 – 3.5 seconds/frame, depending on the vehicle.
- system computer is an industrial computer with the data interface of IDE compact flash memory, and the user interface is designed as the touch-screen or keyboard/keypad.
- All software are included in the computer.
- Real-time text information is displayed and the ASCII comma-delimited text file will be generated for the analysis.
- measured parameters include time, vehicle speed, acceleration, engine RPM, engine coolant temperature, engine load, throttle position, intake air mass flow, exhaust mass flow, fuel consumption, grams per second emissions of NOx and PM.
- operating temperature and humidity are 25-100 Degree F, 0-90% RH, non-condensing (for ambient conditions); and 40-95 Degree F, 0-90% RH, non-condensing (at instrument location).
- typical installation time is 10 to 20 minutes. The warm-up time of the equipment is limited by the gas analyzer warm-up time. The unit can be moved and installed while running.
- 15 minutes warming-up time are needed for gaseous emissions only and 30 minutes for PM measurements. However, 60 minutes are recommended for optimal accuracy.
- several optional equipment including the Global Positioning System (GPS), the pre-catalyst sampler (requires drilling a hole into exhaust), the heated-sample line, the heavy-duty engine scanner, and the universal sensor array.

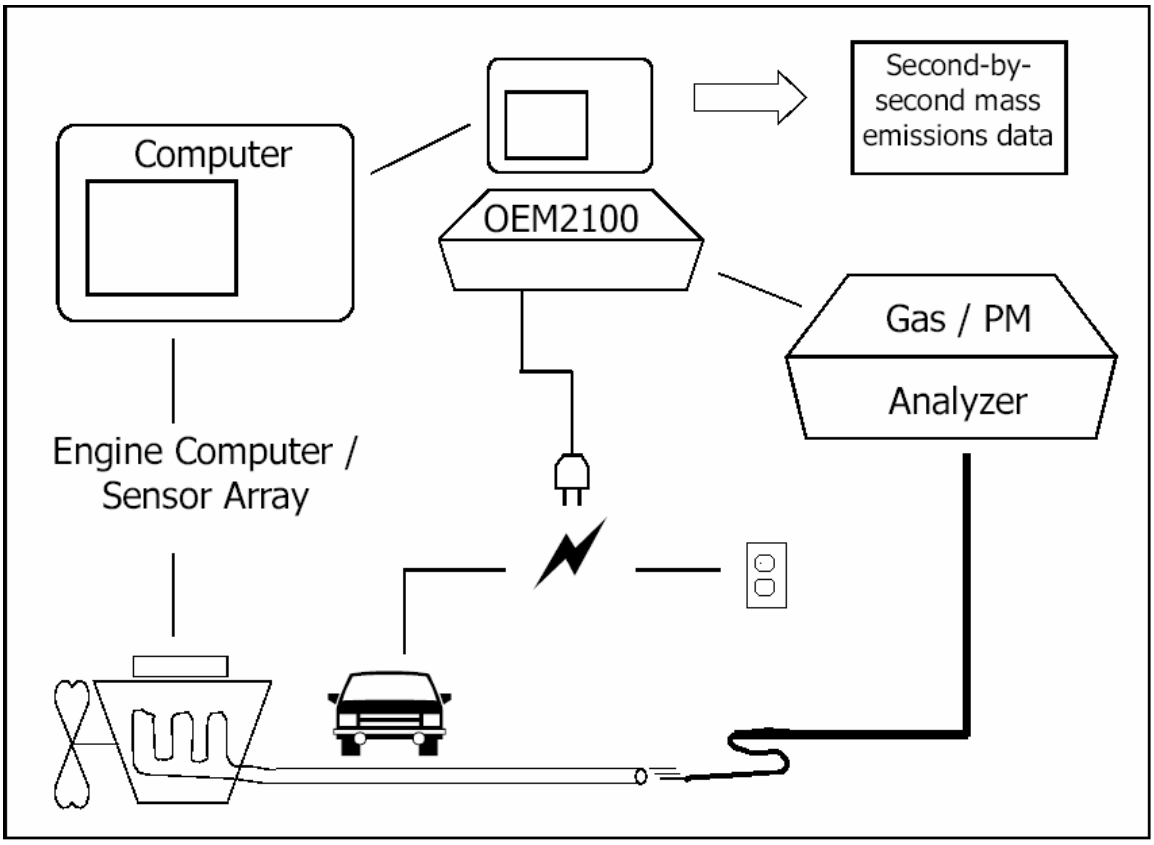
Montana System Specifications for analyzers, gas benches, and sample lines:

Gas	Measurement Range	Accuracy	Repeatability	Noise (rms)	Resolution
HC n-Hexane	0 - 2000 ppm 2001 - 1500 ppm 15001 - 30000 ppm	±4 ppm abs. or ±3% rel. ±5% rel. ±8% rel.	±3 ppm abs. or ±2% rel. ±3% rel. ±4% rel.	2 ppm abs. or 0.8% rel.	1 ppm
HC Propane	0 - 4000 ppm 4001 - 30000 ppm 30001 - 60000 ppm	±8 ppm abs. or ±3% rel. ±5% rel. ±8% rel.	±6 ppm abs. or ±2% rel. ±3% rel. ±4% rel.	4 ppm abs. or 0.8% rel.	1 ppm
CO	0.00 - 10.00% 10.01 - 15.00%	±0.02% abs. or ±3% rel. ±5% rel.	±0.02 abs. or ±2% rel. ±3% rel.	0.01% abs. or 0.8% rel.	0.001 vol. %

CO2	0.00 - 16.00% 16.01 - 20.00%	±0.3% abs. or ±3% rel. ±5% rel.	±0.1%abs. or ±2% rel. ±3% rel.	0.1% abs. or 0.8% rel.	0.01 vol. %
NOx	0-4000 ppm 4001-5000ppm	±25 ppm abs. or ±4% rel. ±5% rel.	±20 ppm abs. or ±3% rel. ±4% rel.	10 ppm abs. or 1% rel.	1 ppm
O2	0.00- 25.00%	±0.1% abs. or ±3% rel.	±0.1% abs. or ±3% rel.	0.1% abs. or 1.5% rel.	0.01 vol. %

The system is typically calibrated using a locally obtained “smog check” calibration gas mix (propane, CO, CO2, NO). Data from several laboratories using various vehicles and fuels shows that when the Montana System is operated simultaneously with the laboratory system, the difference is typically less than 10% for aggregate mass NOx and CO2 . The accuracy of HC and CO measurements depends on the fuel used and on the emission levels. The accuracy of PM measurement has not been quantified at this point. Data from the EPA Laboratory in Ann Arbor, Michigan also shows that the difference between the portable system and two laboratory systems (model and bag sampling) was comparable to the differences between the two laboratory systems.

The Montana system was used successfully for a Houston Advanced Research Center study ‘Collection and Evaluation of On-Road Vehicle Emission and Activity Data, April 2004’



(c) PEMS System Installation

Installation of PEMS included five typical steps.
(1) the warm up procedure
(2) safe and convenient placement of the system;
(3) establishing an appropriate source of power;
(4) routing exhaust sample lines for gas and particulate matter (PM) concentration measurements; and
(5) obtaining engine data for emissions flow calculation.

The PEMS equipment will be warmed up according to manufacturer's recommendations before vehicle is started. Data will be collected during entire vehicle run period. If necessary, an external battery booster power supply will be used to ensure sufficient power to start the vehicle.

The exhaust gas and particulate concentrations are reported by their respective analyzers. The exhaust flow is calculated by using the *instantaneous engine speed*, *intake air*

temperature, and *intake air pressure*, combined with known parameters of the engine such as *displacement*. This calculation is proprietary, but generally involves a mass balance equation, whereby the matter coming into the engine must equal that matter coming out of the engine. The system computer uses these engine parameters to calculate instantaneous emissions.

The PEMS has two basic ways of obtaining engine data for the flow calculation – either by obtaining the data from the *vehicle engine computer* or by *sensing the data* directly. When testing vehicles with an engine control unit (ECU) with an available diagnostic port, the system can be equipped with an ECU scanner that will communicate with the ECU and obtain any needed engine parameters. The two most common engine scanners that can be incorporated into the PEMS are a heavy duty engine scanner, and a light-duty engine scanner. Engine scanners supplied with the PEMS include software that allows them to communicate with most U.S vehicles.

The second method that the PEMS can obtain engine data is by sensing the engine parameters directly. This method involves attaching several analog sensors to the engine itself, and is termed a sensor array installation. This type of installation is slower than an ECU scanner installation, but it allows for installation on nearly any internal combustion engine, regardless of whether the vehicle is electronically controlled or mechanically controlled. A sensor array installation will only be used when the vehicle does not have an ECU.

The system will be installed in the cargo bay of the delivery truck, or in any other safe and convenient location in the vehicle.

(d) System Operation

To be obtained from the PEMS equipment manual.

(e) System Comparison

Capability	Semtech-D	Montana OEM-2100
Measure Nox	+/- 3% 0-500 PPM	+/- 4% 0-4000 PPM
Provide GPS data	Yes	Yes
Provde MPG, speed	Yes	Yes
Rental cost for two	$32,000 +/mo.	$25,000/mo
Ease of use	Difficult	Good
Ease of installation	Difficult	Good
Wireless capable	Yes	Yes
Training Support	Yes	Yes
Service Technician	Extra $$$$	Included as needed

(f) System Recommendation

It was recommended that the Montana OEM-2100 system be used for the road testing portion of this project. It will do the job and provides the best value. Input was received from NREL during a visit there on 3/27/06. It was subsequently decided to use the Montana OEM-2100 system. A contract agreement has been reached with Clean Air Technologies to rent the equipment and provide training and product support.

Appendix B

SwRI Testing Protocol

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ENGINE, EMISSIONS AND VEHICLE RESEARCH DIVISION
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ISO 9001 Certified
ISO 14001 Certified

December 6, 2005

Mr. Joe Gold
Rolling Frito-Lay Sales, LP
7701 Legacy Dr.
Plano, TX 75024

SUBJECT: SwRI Proposal No. 44847A, titled "Emissions Testing of Various Delivery Trucks"

Dear Mr. Gold:

This proposal was prepared in response to a request from Joe Gold from Rolling Frito-Lay Sales, LP to test two conventional delivery trucks (Truck 1 and 2) and two different hybrid-electric drive trucks (Truck 3 and 4). In Part I, all four trucks will be tested on the same heavy-duty chassis dynamometer and the trucks will be released for mileage accumulation. After completing mileage accumulation, the trucks will be tested again under Part 2. Exhaust emissions of PM, NO_x, HC, CO, and CO_2 will be measured and the emission levels of the hybrid trucks will be compared to those of the conventional trucks. Fuel economy will be calculated for each test using the carbon balance method. All emission measurements and calculations will be performed according to the EPA's Federal Code of Regulations, Part 86, Subpart N. Energy balance corrections will be performed for the hybrid vehicles per SAE Recommended Practice J2711 for heavy-duty, hybrid-drive vehicles.

1.0 STATEMENT OF WORK

The purpose of this work is to determine the effect of each type hybrid drive system on emissions in comparison to traditional trucks. SwRI will conduct five hot-start emission tests on each of four trucks over the same drive cycle, and the average value for each emission will be used to compare the relative emission levels of the trucks. The test plan for this work is outlined in Table 1. Rolling Frito-Lay Sales, LP will provide the test weights to be used by SwRI. It is recommended that to conduct a fair comparison, the test weight should be calculated using the sum of each truck's empty weight and one-half of the net cargo weight capacity. It is understood that Rolling Frito-Lay Sales, LP will either provide coastdown data to determine road load or SwRI will calculate the road load from the frontal area of the truck and the test weight, using EPA's recommended procedure for heavy-duty chassis testing.

TABLE 1. TEST PLAN FOR CHASSIS TESTING

Step	Description
1	Install baseline truck, Truck 1, and isolate fuel system, conduct coastdowns.
2	Conduct two prep runs.
3	Perform five hot-start tests for HC, CO, NO_x, PM, and CO_2.
4	Remove Truck 1 from dynamometer.
5	Install second baseline truck, Truck 2, and isolate fuel system, conduct coastdowns.
6	Conduct two prep runs.
7	Perform five hot-start tests for HC, CO, NO_x, PM, and CO_2.
8	Remove Truck 2 from dynamometer.
9	Install the first hybrid-electric drive truck, Truck 3, isolate fuel system, conduct coastdowns.
10	Set-up to record battery State of Charge (SOC) for SAE J2711 NEC correction.
11	Conduct two prep runs.
12	Perform five hot-start tests.
13	Remove Truck 3 from dynamometer.
14	Repeat Steps 9 through 13 for Truck 4.
15	After completing Part 1, release the trucks for durability operation and prepare a brief interim report.
16	After completing durability, repeat Step 1 through 14 for Part 2.
17	Assuming that test work is complete, release vehicles, finalize data, and prepare a final report.

The test cycle used for this work will be agreed upon by Rolling Frito-Lay Sales, LP and SwRI. Customer may substitute a drive cycle based on analysis of current typical delivery use. It is acknowledged that the substituted drive cycle should be representative of actual driving conditions seen in the Frito-Lay delivery system for this class and type of truck. It is assumed that the selected test cycle duration will not exceed 35 minutes.

It is assumed that the hybrid trucks will have a means to record the energy stored in the battery pack or hydraulic accumulator that is either displayed visually or can be measured with standard data acquisition equipment. If this is not the case, SwRI will work with Rolling Frito-Lay Sales, LP to determine a method to acquire this data according to the contingencies described below.

Prior to removing each truck from the dynamometer, the test results will be reviewed to ensure that the data acquired is complete and reasonable. Chassis test results will be reported in terms of g/mi for the truck over the selected test cycle.

After the initial round of emission testing is completed under Part 1, the trucks will be driven in the field by representatives of Rolling Frito-Lay Sales, LP to accumulate a specified amount of miles to examine the durability of each system. After mileage accumulation, all four trucks will be re-tested according to the test plan in Table 1, to quantify any deterioration in performance of each vehicle under Part 2.

2.0 REPORTING, SCHEDULING, AND PRICE

At the completion of this project, SwRI will provide a summary of the emissions and fuel economy results to the Rolling Frito-Lay Sales, LP.

An interim report will be provided after Part 1 of testing. SwRI will supply a test fuel, meeting EPA specifications for emission certification purposes.

3.0 CONTINGENCIES

Recognizing that problems may develop, the following prices are quoted for deviations from the proposed test plan caused by truck malfunctions or inability of the truck to perform the requested plan on a reasonable schedule. For chassis emissions operations, unscheduled downtime or waiting time for truck-related problems or client-initiated delays in excess of one working day is $880 per 8-hour operating day. Waiting time with no activity on the part of SwRI personnel can be maintained for no more than two working days per occurrence before reaching a decision on removing the truck from the test program or proceeding with diagnostic or maintenance activity. After the first two days of waiting, additional waiting time increases to $3,300 per day.

If problems require SwRI assistance in diagnosis or correction, such as performing electrical or mechanical checkout procedures, or emissions "prep" runs, such "developmental assistance" can be provided at the rate of $2,400 per 8-hour operating day. Developmental assistance with informal emissions measurements can be provided at a rate of $3,800 per 8-hour operating day. SwRI will accept direction for additional efforts from the client's on-site representative (if any), by e-mail, fax, or telephone with written follow-up. Such direction will form the basis for additional charges for the requested efforts.

No attempt is being made here to anticipate all possible situations, but the contingencies given should handle a number of possible problems. Situations not covered can be negotiated with the client's authorized representative. If additional test work, beyond that proposed herein, is to be added, SwRI will attempt to perform the additional test work as a continuation of the proposed work. However, if performance of the additional test work substantially increases the originally proposed time to complete the technical effort, SwRI reserves the right to reschedule the additional test work in cooperation with the client.

4.0 SUMMARY

We hope this proposal meets the needs of Rolling Frito-Lay Sales, LP in planning for this work. If you have any questions, please contact Joe Anthony at (210) 522-3191 regarding technical matters, or Barb Clark at (210) 522-6094 regarding contractual or financial matters. We appreciate the opportunity to prepare this preproposal and we look forward to meeting your research needs.

Prepared by:

Joseph W. Anthony
Senior Research Engineer
Department of Engine and Emissions Research

Reviewed by:

Jayant V. Sarlashkar
Manager
Department of Engine and Emissions Research

Approved by:

Daniel W. Stewart
Director of Research
Department of Engine and Emissions Research

Appendix C

TCEQ Grant (scope of work)

GRANT ACTIVITIES

Article 1. Objectives

1.1. The objective of this work is to:

1.1.1. Conduct emissions and fuel efficiency testing to determine the most cost effective solution to deliver a significant reduction in emissions on two (2) different hybrid drivetrains.

1.1.1.1. Hybrid Electric Gas drivetrain

1.1.1.2. Hybrid Electric Diesel drivetrain

1.1.2. Trucks will be tested on a fixed route as well as a variety of actual routes delivering products to market.

1.1.3. In addition to conventional and durability testing, data recorders will be placed on the vehicles to measure various emissions and fuel efficiency under these "real-time" scenarios.

Article 2. Scope of Work

Task 1: Development and Delivery of Hybrid Vehicles

2.1. Task Statement: This task involves the design and delivery of the prototype vehicles by each vendor.

2.1.1. The PERFORMING PARTY will contract with SOLECTRIA Corporation to partner with UCBC/Workhorse Custom Chassis to develop, build, and test a prototype hybrid electric Class-3 delivery vehicle.

2.1.2. The PERFORMING PARTY will contract with EATON Corporation to install the EATON MD Direct Drivetrain System into a Frito-Lay 2-ton delivery vehicle.

2.1.3. The PERFORMING PARTY will insure during the construction of the hybrid vehicles that vehicle performance monitors will be installed. These devices will be used to determine vehicle performance such as miles per gallon (MPG), vehicle speed, and distance.

2.1.4. The PERFORMING PARTY will deliver the Prototype Vehicles to SWRI Facility in San Antonio, Texas.

2.1.5. Schedule: The PERFORMING PARTY shall complete this task within 10 months of the signed Notice to Proceed Date as issued by TCEQ.

2.1.6. Deliverables: The PERFORMING PARTY shall submit a report on the prototype vehicles to TCEQ. This report will include but not limited to descriptions of the prototypes, any test data collected, and photos of the prototypes.

Task 2: Testing of Existing Fleet and Prototypes Vehicles

2.2. Task Statement: The prototype and standard vehicles will be tested in three phases.

2.2.1. The PERFORMING PARTY will perform conventional testing at the SWRI test facility in a laboratory environment using the heavy-duty chassis dynamometer.

2.2.1.1. The PERFORMING PARTY will perform conventional vehicle testing on two existing Frito-Lay vehicles (one new 2003-2005)diesel powered and one older(1985-1995)diesel powered vehicles) most representative of the vehicles to be replaced in the study area).If time, vehicle availability, and budgeting allow the PERFORMING PARTY will also perform conventional testing on a new gasoline powered vehicle.

2.2.1.2. The PERFORMING PARTY will perform conventional vehicle testing on the two different types of hybrid vehicles (hybrid electric/gas, hybrid electric/diesel).

2.2.2. The PERFORMING PARTY will perform "real time" emissions monitoring in the Dallas and Houston areas for various fixed delivery routes.

2.2.2.1. The PERFORMING PARTY will place the two prototypes into service once the conventional testing is completed.

2.2.2.2. The PERFORMING PARTY will work with LGGROUP to identify the routes that will be driven by the test vehicles.

2.2.2.3. The PERFORMING PARTY will collect on-road testing information for performance, reliability, emissions, and miles/gallon (MPG).

2.2.2.4. The PERFORMING PARTY will insure drivers will be trained by the vendors for operations and maintenance (O&M) issues and will also be trained by LGGROUP to collect daily on-board readings and complete driver surveys.

2.2.2.5. The PERFORMING PARTY will install testing, emission and performance monitors in the hybrid prototype vehicles and will provide real-time data acquisition.

2.2.2.6. The PERFORMING PARTY will perform real time testing on the two existing Frito Lay vehicles tested in 2.2.1.

2.2.3. The PERFORMING PARTY will perform durability testing at the SWRI.

2.2.3.1. The PERFORMING PARTY will test the vehicles on the same heavy-duty chassis dynamometer and exhaust emissions of nitrous oxides (NOx), particulate matter (PM), hydrocarbons (HC), carbon dioxide (CO2) and carbon monoxide (CO) will be measured.

2.2.3.2. The PERFORMING PARTY will measure emission levels of the hybrid trucks against the existing fleet trucks.

2.2.3.3. The PERFORMING PARTY will calculate fuel economy for each test using the carbon balance method.

2.2.3.4. The PERFORMING PARTY will perform all emission measurements and calculations according to the EPA's Federal Code of Regulations, Part 86, Subpart N. Energy balance corrections will be performed for the hybrid vehicles per SAE Recommended Practice J2711 for heavy-duty, hybrid-drive vehicles.

2.2.3.5. The PERFORMING PARTY will use the FTP heavy-duty urban dynamometer driving schedule and the average value for each emission will be used to compare the relative emissions levels of the trucks.

2.2.4. Schedule: The PERFORMING PARTY shall complete this task within 16 months of the signed Notice to Proceed Date as issued by TCEQ.

2.2.5. Deliverables: The PERFORMING PARTY shall submit a report on the conventional testing, "real time" emissions monitoring, and the durability testing to TCEQ. This report will include but not limited to any test data collected.

Task 3: Data Review and Analysis

2.3. Task Statement: LGGROUP will act as the repository for all testing data.

2.3.1. The PERFORMING PARTY will submit the conventional and durability testing data collected by SWRI to the LGGROUP for review.

2.3.2. The PERFORMING PARTY will submit the on-board monitor data and driver's surveys collected from the test to LGGROUP for review and compilation.

2.3.3. The PERFORMING PARTY will insure all test data from each of the test vehicles will be reviewed and compared for percent emission reduction and fuel efficiency.

2.3.4. Schedule: The PERFORMING PARTY shall complete this task within 20 months of the signed Notice to Proceed Date as issued by TCEQ.

2.3.5. Deliverables: The PERFORMING PARTY shall submit a report on the all analysis performed by LGGROUP.

Task 4: Program management and reporting

2.4. Task statement: The PERFORMING PARTY will prepare and submit monthly detailed project reports and a comprehensive final report while ensuring compliance with all TCEQ program requirements.

2.4.1. The PERFORMING PARTY will coordinate all project resources to ensure compliance with NTRD program requirements while providing deliverables on-schedule and on-budget.

2.4.2. The PERFORMING PARTY will generate monthly progress reports and a final report summarizing all aspects of the project based on data from the monthly reports.

2.4.3. Schedule: The PERFORMING PARTY shall submit monthly reports to TCEQ by no later than 10 days after the end of each month. The PERFORMING PARTY shall submit the final report to complete this task within 20 months of the signed Notice to Proceed Date as issued by TCEQ.

2.4.4. Deliverables: The PERFORMING PARTY shall submit monthly progress reports with associated billing statements and a final project summary report to the TCEQ upon completion of this task.

Article 3. Glossary of Acronyms

The following terms have the meanings indicated.

CFR - Code of Federal Regulations

CARB - California Air Resources Board

CNG - compressed natural gas

CO - carbon monoxide

CO_2 - carbon dioxide

EPA - U.S. Environmental Protection Agency

FTP - Federal Test Procedures

gm/bhp-hr - grams per brake horsepower per hour
HLA - hydraulic launch assist

HP - horsepower

HC - hydrocarbons

LGGROUP - LOPEZGARCIA GROUP

N_2 - nitrogen

NO - Nitric oxide

NO_2 - nitrogen dioxide

NOx - oxides of nitrogen

NTRD - New Technology Research and Development Program

O_2 - oxygen

PM - particulate matter

SwRI - Southwest Research Institute

TCEQ - Texas Commission on Environmental Quality

THC - total hydrocarbons

VIN - vehicle identification number

VOC - volatile organic compound

— End of Grant Activities —

Appendix D

SwRI Phase I Test Report

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February 7, 2007

Mr. Joe Gold
Rolling Frito-Lay Sales, LP
7701 Legacy Dr.
Plano, TX 75024

SUBJECT: SwRI Interim Report for Project 12163, titled "Emissions Testing of Various Delivery Trucks"

This report describes the work completed for Part 1 of this project. Two conventional delivery trucks (Truck 1 and 2) and two different hybrid-electric drive trucks (Truck 3 and 4) were tested on the same heavy-duty chassis dynamometer. Table 1 is a summary of each truck's mechanical configuration and test weight. Exhaust emissions of PM, NO_x, HC, CO, and CO_2 were measured for each truck. The emissions levels of the hybrid trucks were compared to those of the conventional trucks. Fuel economy was calculated for each test using the carbon balance method. Energy balance corrections were performed for each hybrid truck per SAE Recommended Practice J2711 for heavy-duty, hybrid-drive vehicles.

TABLE 1. TRUCK CONFIGURATION SUMMARY

Truck	Engine	Drivetrain	Fuel	Test Wt, lb.
1	Cummins 3.9L In-line 4, direct-injection, turbocharged, intercooled	Automatic transmission	Diesel	9,160
2	General Motors, 6.5L V8, indirect-injection Naturally aspirated	Automatic transmission	Diesel	9,180
3	General Motors, 4.8L V8, port-injected Naturally aspirated	Series Hybrid Electric, NiMH battery pack	Gasoline	10,730
4	International, 4.5L V6, direct-injection, turbocharged, intercooled	Parallel Hybrid Electric, NiMH battery pack, Automated manual transmission	Diesel	10,530

Hybrid electric vehicles are typically equipped with energy storage devices. It was recognized that the net energy change (NEC) in the storage device will likely affect the measured emissions and fuel economy data. SAE J2711 was developed to provide a method to correct emissions and fuel economy data if the energy storage device's NEC varied by more than 1 percent of the total fuel energy consumed during the test. SAE J2711 does not recommend correcting data if the NEC is less than 1 percent. Fortunately, the NEC for each hybrid truck test was less 1 percent, so no correction was required. The NEC values for each truck are included in this report.

1.0 Vehicle Testing

The purpose of this work was to determine the effect of each type of hybrid drive system on emissions in comparison to conventional trucks. SwRI conducted five hot-start emission tests on each of four trucks over the same drive cycle, and the average value for each emission was used to compare the relative emission levels of the trucks. Rolling Frito-Lay Sales, LP (Frito-Lay) chose to test the trucks over the light-duty FTP UDDS (LD UDDS) drive cycle, Figure 1. The test plan for this work is given in Table 2. Frito-Lay provided the test weights used by SwRI using the sum of each truck's dry empty weight, fuel weight, driver, and half of the remaining cargo weight capacity. SwRI used this test weight and measured frontal area to calculate the road load using EPA's recommended procedure for heavy-duty chassis testing. The diesel trucks were fueled with ultra-low sulfur diesel with a density of 7.2 lb/gal. The gasoline truck used commercially-available gasoline with a density of 6.2 lb/gal.

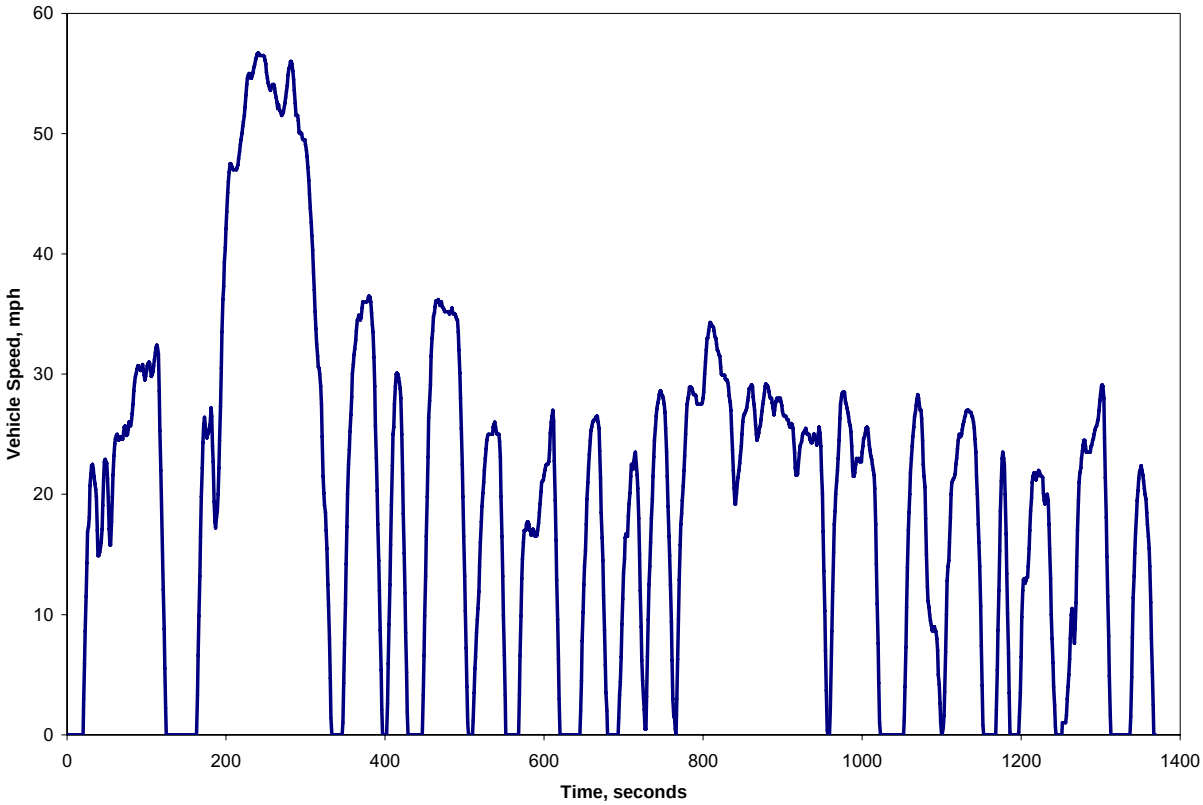

FIGURE 1. LIGHT-DUTY FTP UDDS (LD UDDS) DRIVE CYCLE

TABLE 2. TEST PLAN FOR CHASSIS TESTING

Step	Description
1	Install baseline truck, Truck 1, and isolate fuel system, conduct coastdowns.
2	Conduct two prep runs.
3	Perform five hot-start tests for HC, CO, NO_x, PM, and CO_2.
4	Remove Truck 1 from dynamometer.
5	Install second baseline truck, Truck 2, and isolate fuel system, conduct coastdowns.
6	Conduct two prep runs.
7	Perform five hot-start tests for HC, CO, NO_x, PM, and CO_2.
8	Remove Truck 2 from dynamometer.
9	Install the first hybrid-electric drive truck, Truck 3, isolate fuel system, conduct coastdowns.
10	Set-up to record battery State of Charge (SOC) for SAE J2711 NEC correction.
11	Conduct two prep runs.
12	Perform five hot-start tests.
13	Remove Truck 3 from dynamometer.
14	Repeat Steps 9 through 13 for Truck 4.
15	After completing Part 1, release the trucks for durability operation and prepare the report for Part 1 testing.

2.0 TEST RESULTS

The following sections describe each vehicle's installation, coastdown, and emissions results. In the case of the hybrid trucks, a table with the NEC value for each test is included in the corresponding sections.

2.1 Truck 1 - Test Results

Truck 1, VIN 5B4HP42P553404763, was powered by a 2005 3.9L Cummins, turbocharged, intercooled, direct injected diesel engine and was equipped with an automatic transmission. The truck was installed on the chassis dynamometer, as shown in Figure 2 and tested at 9,160 lb. Coastdowns for this truck are shown in Figure 3. The truck was then driven over the drive cycle once to condition the vehicle for the hot-start testing. The five hot-start tests were conducted with a 20-minute soak in between each test to change emission sample bags and PM filters. The test results for Truck 1 are summarized in Table 3.

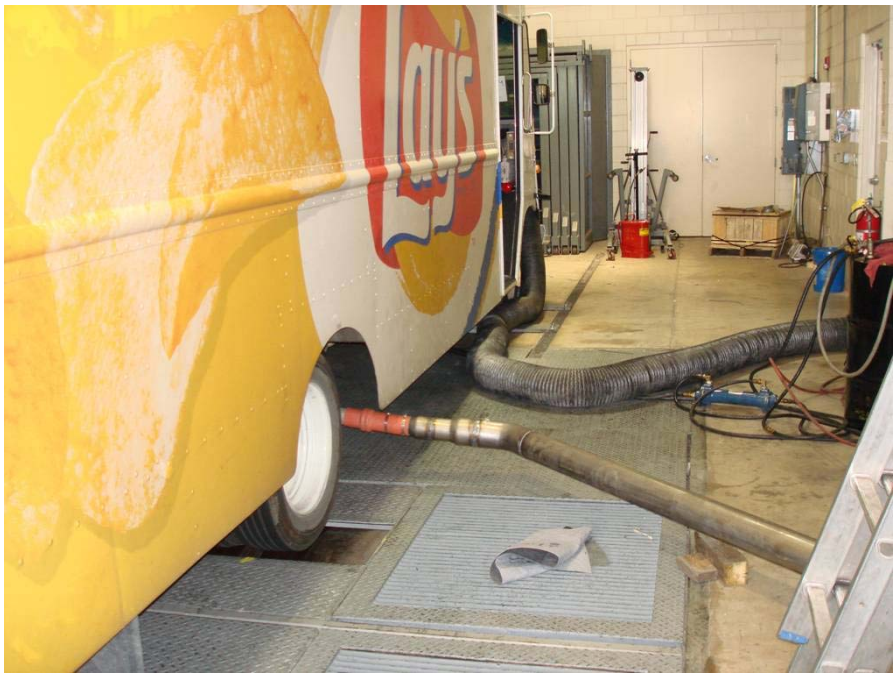

FIGURE 2. TRUCK 1 INSTALLED ON THE HEAVY-DUTY CHASSIS DYNAMOMETER

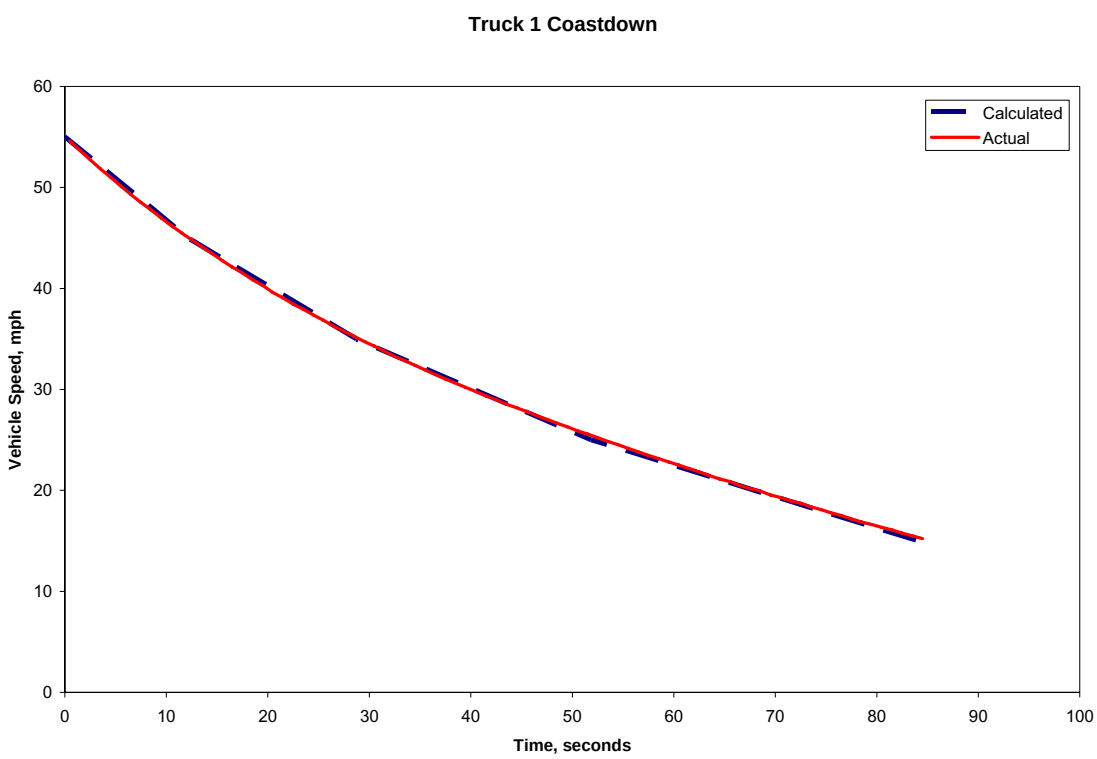

FIGURE 3. TRUCK 1 COASTDOWN RESULTS COMPARED TO CALCULATED COASTDOWN VALUES

TABLE 3. EMISSION RESULTS FOR TRUCK 1 OVER LD FTP UDDS DRIVE CYCLE

Test Code	HC g/mi	CO g/mi	NO_x g/mi	PM mg/mi	CO_2 g/mi	MPG	Fuel kg	Miles
4763-H1	0.15	2.23	6.27	78	715	14.4	1.71	7.5
4763-H2	0.14	2.37	6.30	78	707	14.6	1.70	7.6
4763-H3	0.14	2.32	6.20	74	707	14.6	1.69	7.5
4763-H4	0.16	2.28	6.21	73	701	14.7	1.69	7.6
4763-H5	0.13	2.32	6.07	75	696	14.8	1.68	7.6
Average =	**0.14**	**2.30**	**6.21**	**75**	**705**	**14.6**	**1.69**	**7.6**
c.o.v.	6%	2%	1%	3%	1%	1%	1%	0%

2.2 Truck 2 - Test Results

Truck 2, VIN 1GBHP32Y8W3304305, was powered by a 1997 6.5L GM naturally-aspirated, in-direct injected diesel engine and was equipped with an automatic transmission. The truck was installed on the chassis dynamometer, as shown in Figure 4, and tested at 9,180 lb. Coastdowns for this truck are shown in Figure 5. The truck was also fitted with a calibrated mass air flow sensor to record engine air flow to compare with Clean Air Technologies' air flow estimation. This data is not included in the report, as it was for reference only. The truck was then driven over the drive cycle once to condition the vehicle for the hot-start testing. After five hot-start tests were conducted, the first test appeared to be an outlier and a sixth test was performed while the truck was still on the dynamometer. However, after using ASTM-E178 criteria, the first test was not an outlier, so it was decided to use all six tests for the average and c.o.v. calculations. The test results for Truck 2 are summarized in Table 4.

FIGURE 4. TRUCK 2 INSTALLED ON THE HEAVY-DUTY CHASSIS DYNAMOMETER

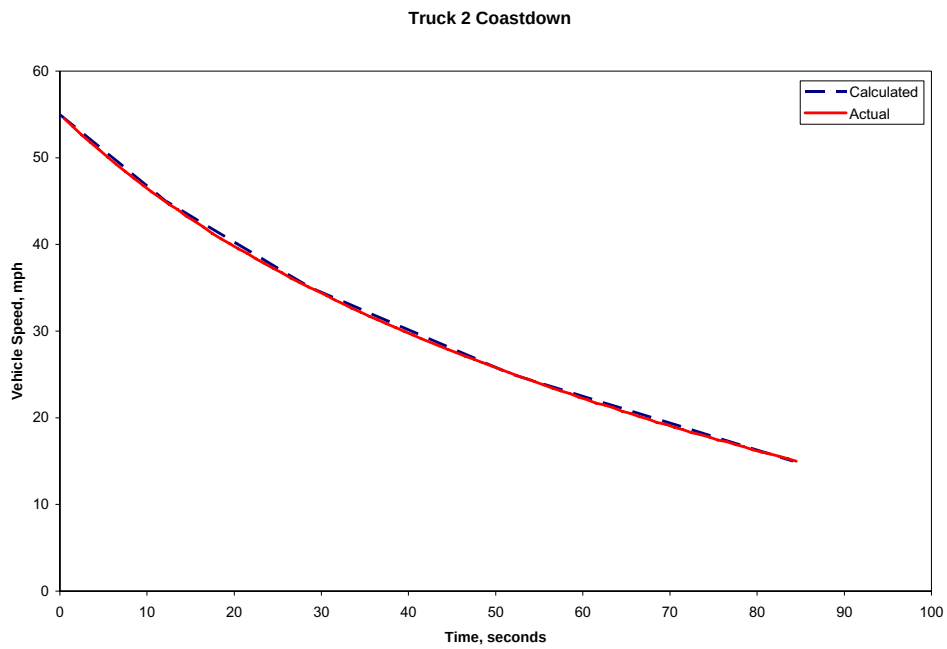

FIGURE 5. TRUCK 2 COASTDOWN RESULTS COMPARED TO CALCULATED COASTDOWN VALUES

TABLE 4. EMISSION RESULTS FOR TRUCK 2 OVER LD FTP UDDS DRIVE CYCLE

Test Code	HC g/mi	CO g/mi	NO_x g/mi	PM mg/mi	CO2 g/mi	MPG	Fuel kg	Miles
4305-H1*	0.35	1.59	2.98	218	852	12.1	2.04	7.6
4305-H2	0.30	1.44	3.11	144	847	12.2	2.03	7.6
4305-H3	0.30	1.44	3.68	133	839	12.3	2.00	7.5
4305-H4	0.30	1.48	3.63	158	838	12.3	2.01	7.6
4305-H5	0.31	1.47	3.74	136	840	12.3	2.02	7.6
4305-H6	0.30	1.41	3.64	126	837	12.3	2.00	7.5
Average =	**0.31**	**1.47**	**3.46**	**152**	**842**	**12.2**	**2.02**	**7.6**
c.o.v.	6%	4%	9%	22%	1%	1%	1%	0%

* This test was initially thought to be an outlier during testing, but it was not, using ASTM-E178. This test was used in the average and c.o.v. calculations.

2.3 Truck 3 - Test Results

Truck 3, VIN 584KP02V063416051, was powered by a 2005 4.8L GM Vortec, port injected gasoline engine and was equipped with series hybrid drivetrain using two electric motors and a nickel metal hydride (NiMH) battery pack. The truck was installed on the chassis dynamometer, as shown in Figure 6, and tested at 10,730 lb. Coastdowns for this truck are shown in Figure 7. The truck was then driven over the drive cycle once to condition the vehicle for the hot-start testing. As in the previous truck, after five hot-start tests were conducted, the first test appeared to be an outlier and sixth test was conducted. Using ASTM-E178, the NOx result from the first test was an outlier, so the sixth test was used in place of the first test for the average and c.o.v. calculations. The emission test results for Truck 3 are summarized in Table 5 and the NEC values are summarized in Table 6. As described in the introduction, the percent NEC for this truck were less than 1 for all of the tests, so no data correction was necessary.

FIGURE 6. TRUCK 3 INSTALLED ON THE HEAVY-DUTY CHASSIS DYNAMOMETER

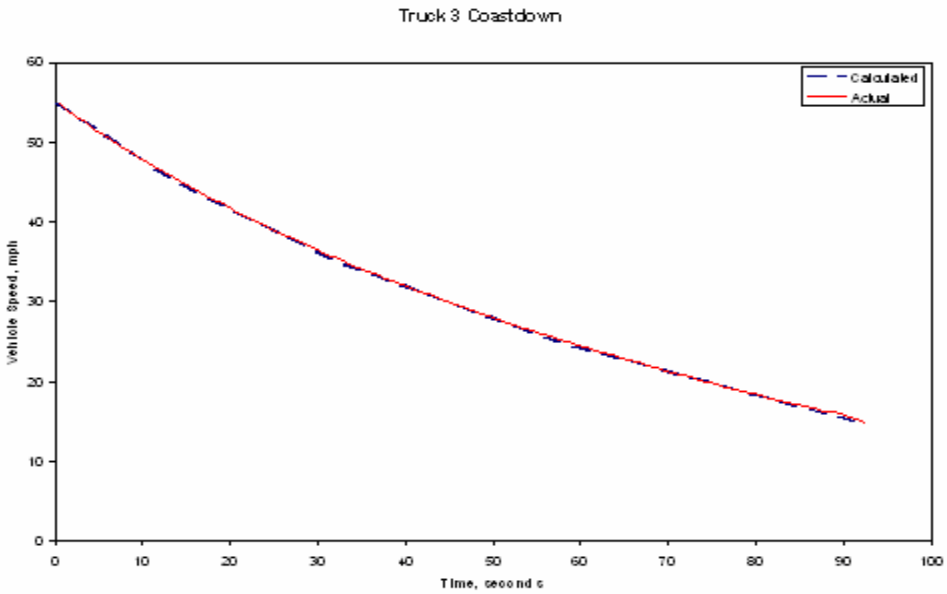

FIGURE 7. TRUCK 3 COASTDOWN RESULTS COMPARED TO CALCULATED COASTDOWN VALUES

TABLE 5. EMISSION RESULTS FOR TRUCK 3 OVER LD FTP UDDS DRIVE CYCLE

Test Code	HC g/mi	CO g/mi	NO_x g/mi	PM mg/mi	CO2 g/mi	MPG	Fuel kg	Miles
F6051-H1	0.15	1.41	1.04	7	765	11.7	1.84	7.6
F6051-H2	0.12	2.21	0.37	10	739	12.0	1.77	7.6
F6051-H3	0.18	2.89	0.23	6	739	12.0	1.78	7.6
F6051-H4	0.15	2.51	0.28	5	748	11.9	1.80	7.6
F6051-H5	0.12	2.59	0.13	6	737	12.1	1.77	7.6
F6051-H6	0.17	2.35	0.28	8	742	12.0	1.79	7.6
Average =	**0.15**	**2.51**	**0.26**	**7**	**741**	**12.0**	**1.78**	**7.6**
c.o.v.	19%	10%	34%	27%	1%	1%	1%	0%

* This test was an outlier based on the NO_X value using ASTM-E178. This test was not used in the average and c.o.v. calculations.

TABLE 6. NEC RESULTS FOR TRUCK 3 OVER LD FTP UDDS DRIVE CYCLE

Test Code	SOC, %		NEC, MJ	Fuel Energy, MJ	NEC, %
	Start	End			
F6051-H1	61.0	58.5	-0.28	77.2	0.0
F6051-H2	58.5	58.0	-0.06	74.5	0.0
F6051-H3	58.0	56.5	-0.17	74.8	0.0
F6051-H4	56.5	58.0	0.17	75.7	0.0
F6051-H5	58.0	57.5	-0.06	74.5	0.0
F6051-H6	57.5	61.0	0.39	75.1	0.0

2.4 Truck 4 – Test Results

Truck 4, VIN 5B4HPD25363412537, was powered by a 2006 4.5L direct-injected turbocharged diesel engine and was equipped with parallel hybrid drivetrain using an electric motor between the engine and transmission. The transmission was an Eaton automated manual. The battery pack was nickel metal hydride (NiMH). Truck 4's hybrid system was not completely refined and the engine's ECU was not using production software and calibrations, so the results of this truck may not be representative of the final product. The truck was installed on the chassis dynamometer, as shown in Figure 8, and tested at 10,530 lb. Coastdowns for this truck are shown in Figure 9. The truck was driven over the drive cycle twice to condition the vehicle for the hot-start testing. The emission test results for Truck 4 are summarized in Table 7 and the NEC values are summarized in Table 8. As described in the introduction, the NEC for all of the tests for this truck were less than 1 percent, so no data correction was necessary.

FIGURE 8. TRUCK 4 INSTALLED ON THE HEAVY-DUTY

CHASSIS DYNAMOMETER

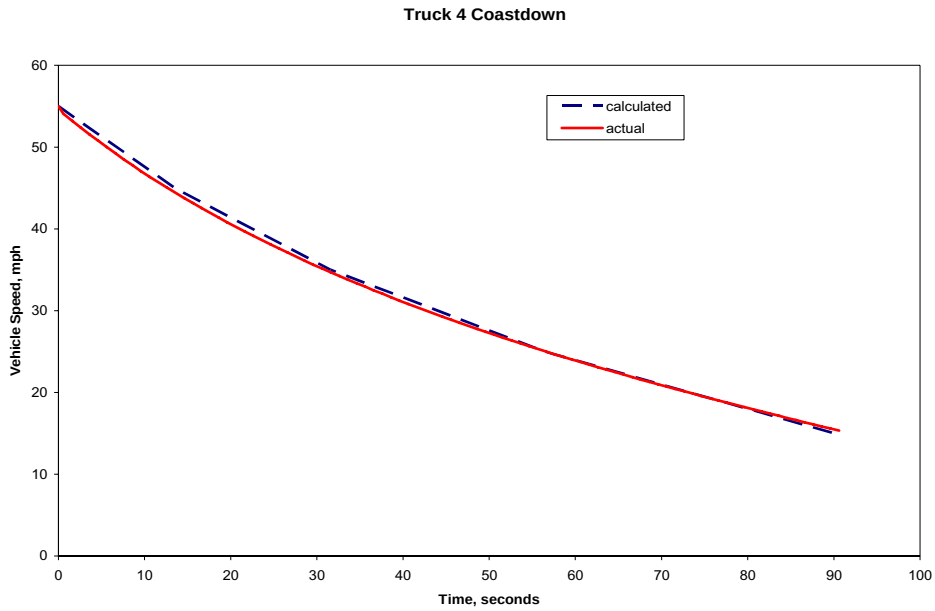

FIGURE 9. TRUCK 4 COASTDOWN RESULTS COMPARED TO CALCULATED COASTDOWN VALUES

TABLE 7. EMISSION RESULTS FOR TRUCK 4 OVER LD FTP UDDS DRIVE CYCLE

Test Code	HC g/mi	NO_x g/mi	PM mg/mi	CO g/mi	CO2 g/mi	Fuel kg	MPG	Miles
F2537-H1	0.56	5.04	181	2.14	679	1.62	15.1	7.5
F2537-H2	0.57	5.00	158	1.94	677	1.63	15.2	7.6
F2537-H3	0.53	5.05	148	2.05	671	1.62	15.3	7.6
F2537-H4	0.49	4.94	139	2.03	654	1.57	15.7	7.6
F2537-H5	0.50	4.86	154	2.38	654	1.57	15.7	7.5
Average =	**0.53**	**4.98**	**156**	**2.11**	**667**	**1.60**	**15.4**	**7.5**
c.o.v.	7%	2%	10%	8%	2%	2%	2%	0%

TABLE 8. NEC RESULTS FOR TRUCK 4 OVER LD UDDS DRIVE CYCLE

Test Code	SOC		NEC MJ	Fuel Energy, MJ	NEC %
	Start	End			
F2537-H1	51.5	53.0	0.10	71.3	0.0
F2537-H2	53.0	53.0	0.00	71.5	0.0
F2537-H3	53.0	53.0	0.00	71.2	0.0
F2537-H4	53.0	51.5	-0.10	69.2	0.0
F2537-H5	51.5	53.0	0.10	69.0	0.0

3.0 SUMMARY

Four trucks with different engine and drivetrain combinations were tested over at least five runs of the same drive cycle. The emissions and fuel economy results were very different. Table 9 shows the average emissions values for each truck. Figure 10 ranks the trucks by emission from lowest to highest.

TABLE 9. AVERAGE EMISSION RESULTS FOR TRUCK 4 OVER LD FTP UDDS DRIVE CYCLE

Test Code	HC g/mi	CO g/mi	NO_x g/mi	PM mg/mi	CO2 g/mi	MPG	Fuel kg	Miles
Truck 1	0.14	2.30	6.21	75	705	14.6	1.69	7.6
Truck 2	0.31	1.47	3.46	152	842	12.2	2.02	7.6
Truck 3	0.15	2.51	0.26	7	741	12.0	1.78	7.6
Truck 4	0.53	2.11	4.98	156	667	15.4	1.60	7.5

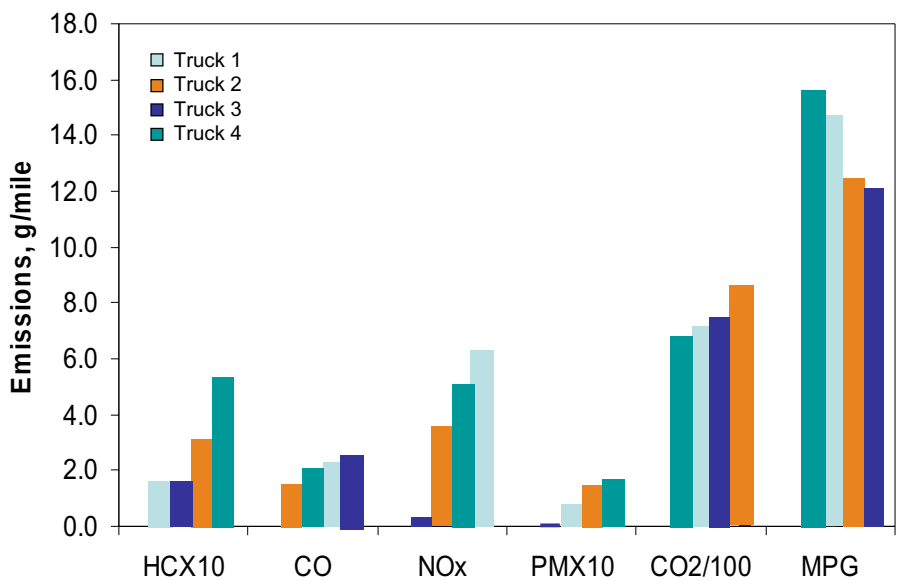

FIGURE 10. RANKING OF TRUCKS BY EMISSION LEVEL

Truck 1 was equipped with a direct-injection, turbocharged diesel engine with an automatic transmission. The engine was the smallest displacement of the trucks tested. This type of engine configuration and displacement is very fuel efficient compared to the other engine configurations tested, and Truck 1 produced the second lowest CO2 emissions and second highest fuel economy of the four trucks, only the parallel hybrid diesel truck was better. The PM emission for Truck 1 was the lowest of the diesel powered trucks, only the gasoline powered Truck 3 had a lower level. Truck 1 CO emissions were the third highest, which was somewhat unexpected, since the HC emissions were so low, however, the small displacement may have moved the engine into operating into a region where the air-fuel ratio was richer than at lighter load conditions. Another consequence of the engine's small displacement and high load conditions was high NO_x emissions. Truck 1 had the highest NO_x emissions of the trucks tested, which was expected.

Truck 2 was equipped with indirect-injection (IDI), naturally-aspirated diesel engine with an automatic transmission. The engine had the largest displacement at 6.5L and was the oldest in terms of model year and technology. The truck had the third highest HC emissions and the highest of the three diesel powered trucks. This was likely due to the low-pressure fuel injection system and high cylinder crevice volume, typical of IDI engines. The truck produced the lowest CO and second lowest NO_x emissions. Naturally-aspirated engines typically have lower peak cylinder pressures compared to turbocharged engines and, therefore, the in-cylinder peak temperatures, which cause NO_x to form, are lower. Lower NO_x often corresponds to higher PM, as was the case for this truck. Truck 2 produced the third highest PM emissions. The truck produced the most CO2 emissions and the third lowest volumetric fuel economy. The reason the CO2 emissions were the highest, but the fuel economy in miles/gallon (MPG) was the third lowest is that density of diesel fuel is greater than gasoline fuel. Diesel weighs 7.2 lb/gal and gasoline weighs 6.2 lb/gal. Diesel fuel also contains more energy on a mass basis, 20 MJ/lb for diesel compared to 19.2 MJ/lb for gasoline.

Truck 3 produced the lowest emissions except for CO and CO2. Truck 3 was equipped with a gasoline engine with 3-way catalysts and a series hybrid drivetrain. The 3-way catalysts typically reduce engine-out emissions by approximately 95 percent and the series hybrid system decouples engine operation from the drive wheels, which allows the engine to operate closer to steady-state conditions than a conventional vehicle or parallel hybrid vehicle. Transient operation typically increases emissions, so as the engine is operated closer to steady-state, the emissions should be lower. Gasoline engines also produce almost no PM, even without aftertreatment, so the low PM number was expected. Truck 3 produced the highest CO emissions, which is likely due to the high engine-out CO typical of gasoline engines any time the air-fuel ratio becomes fuel rich. Finally, Truck 3 produced the second highest CO2 emissions and the worst fuel economy. In general, gasoline engines are less fuel efficient than diesel engines, especially at light load conditions, so it was not surprising that even with a hybrid drivetrain, the CO2 emissions were higher than all but the naturally-aspirated diesel truck, Truck 2.

As noted previously for Truck 4, the hybrid system was not completely refined and the engine's ECU was not using production software and calibrations, so the results of this truck may not be representative of the final product. Despite these limitations, the truck produced the lowest CO2 and highest fuel economy of the trucks tested. Truck 4 was equipped with a direct-injection, turbocharged diesel engine with parallel hybrid drivetrain. The truck produced the highest HC and PM emissions. This is likely due to the engine calibration and the extremely transient behavior of this engine over the drive cycle. This was the only engine coupled to a manual-style transmission, which requires direct response to the drive wheels. The series hybrid completely de-couples the engine from the drive wheels and the conventional trucks tested had automatic transmissions with torque converters which shift smoother and have a torque converter to dampen some of the dynamic transients between the transmissions and the engine. Truck 4 did have an electric motor in place of a traditional clutch, but the hybrid system was not completely refined. The truck produced the highest CO and the third highest NO_x emissions. It is difficult to say if these are representative of the final product, as better controls may reduce the observed emission levels.

All trucks were successfully tested and there were no mechanical failures. After emission testing was completed under Part 1, the trucks were released for use in the field by representatives of Rolling Frito-Lay Sales, LP to examine the durability of each system. After sufficient mileage accumulation, all four trucks will return under Part 2 for re-testing to quantify any deterioration in performance of each vehicle.

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Results and discussion given in this report relate only to the test items described in this report.

/mab

Appendix E

Daily Vehicle and Run Checklist

Frito-Lay Hybrid Vehicle Evaluation
Daily Vehicle and Run Checklist

OLD ~~NEW~~ DIESEL SOUTH

Date: 16 Feb 07	02-16-07
Vehicle No.:	R70226
Driver Name:	Ray/Jim
Insurance Papers Present	
Vehicle Registration Present	
Temperature F	0 C
Weather (Rainy, Cloudy, Sunny)	
PRE-RUN INSPECTIONS AND START-UP	
Truck Inspection	
Tire Pressure:	
Front Left (Green - Red Corrected) 75 psi	
Front Right (Green - Red Corrected) 75 psi	
Rear Left	
Inner (Green - Red Corrected) 75 psi	
Outer (Green - Red Corrected) 75 psi	
Rear Right	
Inner (Green - Red Corrected) 75 psi	
Outer (Green - Red Corrected) 75 psi	
Fuel Type	Diesel
Fuel Gauge Reading Before	15.05
Analyzer Inspection Start-up	
Last System Calibration (date)	
Analyser Filter Cleaned (date)	
Battery Charge B-1	13.89V
Analyser Turned on for Warm Up (time)	0817

	Run 1	Run 2	Run 3
File Number	B70216B	B70216C	B70216D
Bag Number	~~B70216A~~	1	1
Start Mileage	236153.5	236182.5	236209.9
Route	B-2	B-2	B-2
Run start time	09:04:12	10:41:46	12:36:00
Stop 1 key off	09:25:50	10:61:00	12:57:48
Mileage	236165.3	236192.8	236220.3
Stop 1 key on	09:28:50	11:04:00	13:00:00
Stop 2 key off	09 29:30	11:05:25	13:01:30
Mileage	236165.7	236193.2	236220.7
Stop 2 key on	09:32:36	11:08:25	13:04:30
Stop 3 key off	09 35:32	11:11:35	13:07:17
Mileage	236166.5	236194.0	236221.5
Stop 3 key on	09:38:32	11:14:35	13:10:17
Stop 4 key off	09:40:30	11:16:26	13:12:13
Mileage	236167.2	236194.7	236222.2
Stop 4 key on	09:43:30	11:19:26	13:15:18
Stop 5 key off	09 46:03	11 21:48	13:17:15
Mileage	236167.9	236195.4	236222.8
Stop 5 key on	09:49:03	11 24:45	13:20:15
Stop 6 key off	09:50:25	11 24:48	13:21:40
Mileage	236168.8	236196.3	236223.8
Stop 6 key on	09:53:25	11:27:45	13:27:40
Stop 7 key off	09:55:40	11:32:40	13:30:00
Mileage	236169.5	236197.4	236224.5
Stop 7 key on	09:58:40	11:35:40	13:33:00
Stop 8 key off	10:01:40	11 37:58	13:36:10
Mileage	236170.2	236197.7	236225.1
Stop 8 key on	10:04:40	11:40:58	13:39:10
Stop 9 key off	10:06:30	11:43:28	13:41:15
Mileage	236170.8	236198.3	236225.8
Stop 9 key on	10:09:30	11:46:28	13:44:15
Stop 10 key off	10:28:46	12:07:45	14:07:37
Mileage	236182.4	236209.8	236237.3
Stop 10 key on			
End Time	10:28:46	12:07:45	14:07:32
End Mileage	236182.4	236209.8	236237.3
Total Mileage	28.9	27.3	27.4

Analyser Start Up

1. Connect power cable to battery
2. Turn on all 6 switches
3. Follow prompts on screen
4. Do not edit any information click 'Y","Y" and enter
5. This should have you at the data screen
6. Allow the sysytem to warm up for 45 minutes
7. Complete the rest of the check list items.

236182.4
236153.5
28.9

236209.8
236182.5
27.3

Troubleshooting tips

Verify RPM is reading. If not push "P" key on diesel truck
Verify RPM is reading. If not push "S" key on gas hybrid truck
Verify temperature reading

236237.3
236209.9
27.4

Starting Runs

1. After system warm up:
2. Connect exhuast sampling hose to filters on analysers
3. Start diesel truck and let run for 5 minutes
4. Start Hybrid truck and make three laps in the parking lot with
5. Press <ESC> This creates file number
6. As you pull through the gate push "+" to create bag number
7. Record time and mileage at each stop using the time from the analyzer

Ending Runs

1. Stop at gate push "-" to stop bag

Notes:

Driver Time Keeping

Start Time
Lunch Start
Lunch Stop
Finish Time

Syst Froze up Couldn't get a new Bag Reset Syst At 09:04:10 Worked ok ~~Then Else Worked~~
Froze up 11:22:10 Reset ~~Bag~~ File Num D System ok

Ending day

1. Press <ESC> to write file
2. Disconnect exhaust sampling hose
3. Let sampler run 5 minutes and turn unit off
4. Exchange batteries or hook up charger.

Page 1 of ~~[illegible]~~

Frito-Lay Hybrid Vehicle Evaluation
Daily Vehicle and Run Checklist

SOUTH

Date: 8 Feb 07	
Vehicle No.: RU 8796	
Driver Name: Willis	
Insurance Papers Present	
Vehicle Registration Present	
Temperature F 24C	
Weather (Rainy, Cloudy, Sunny)	
PRE-RUN INSPECTIONS AND START-UP	
Truck Inspection	
Tire Pressure:	
Front Left (Green - Red Corrected) 75 psi	
Front Right (Green - Red Corrected) 75 psi	
Rear Left	
Inner (Green - Red Corrected) 75 psi	
Outer (Green - Red Corrected) 75 psi	
Rear Right	
Inner (Green - Red Corrected) 75 psi	
Outer (Green - Red Corrected) 75 psi	
Fuel Type DIESEL	
Fuel Gauge Reading Full	
6 of 5	6-9
Analyzer Inspection Start-up	
Last System Calibration (date)	
Analyser Filter Cleaned (date)	
Battery Charge 13.8461 (1246) Stat	13.8461
Analyser Turned on for Warm Up (time)	0717

B-2 Bat 13.76 Start
B2 " 12:56 Stop

Analyser Start Up

1. Connect power cable to battery
2. Turn on all 6 switches
3. Follow prompts on screen
4. Do not edit any information click 'Y','Y' and enter
5. This should have you at the data screen
6. Allow the sysytem to warm up for 45 minutes
7. Complete the rest of the check list items.

Troubleshooting tips

Verify RPM is reading. If not push "P" key on diesel truck
Verify RPM is reading. If not push "S" key on gas hybrid truck
Verify temperature reading

Starting Runs

. After system warm up:
. Connect exhuast sampling hose to filters on analysers
. Start diesel truck and let run for 5 minutes
. Start Hybrid truck and make three laps in the parking lot with
. Press <ESC> This creates file number
. As you pull through the gate push "+" to create bag number
. Record time and mileage at each stop using the time from the
nalyzer

System Flow up At 09:03:2

nding Runs

Stop at gate push "-" to stop bag Restarted

otes:

Gas Analyzer Flow up At 3675.6 10:30:09
~~Had~~ RPM was working OK

	Run 1 B	Run 2	Run 3
File Number	K70208A	K70208D	K70208E
Bag Number	1	1	1
Start Mileage	36728.5	36755.6	36782.8
Route	B1	B-1	B-1
Run start time	08:41:52	10:36:00	12:32:08
Stop 1 key off	09:09:44	10:50:00	12:51:08
Mileage	36738.7	36765.9	36792.9
Stop 1 key on	09:10:11	10:53:00	12:54:18
Stop 2 key off	09:11:48	10:54:40	12:55:47
Mileage	36739.0	36766.2	36793.4
Stop 2 key on	09:14:48	10:57:40	12:58:47
Stop 3 key off	09:18:05	10:59:55	13:02:19
Mileage	36739.9	36767.2	36794.2
Stop 3 key on	09:21:05	11:02:55	13:05:19
Stop 4 key off	09:27:05	11:05:06	13:06:40
Mileage	36740.5	36767.8	36794.8
Stop 4 key on	09:36:05	11:08:06	13:09:40
Stop 5 key off	09:28:10	11:10:50	13:12:36
Mileage	36741.4	36768.4	36795.5
Stop 5 key on	09:31:10	11:13:50	13:15:36
Stop 6 key off	09:34:48	11:16:42	13:18:50
Mileage	36742.1	36769.9	36796.5
Stop 6 key on	09:37:48	11:19:42	13:21:50
Stop 7 key off	09:39:40	11:21:48	13:24:0
Mileage	36742.9	36770.1	36797.1
Stop 7 key on	09:42:40	11:24:48	13:27:0
Stop 8 key off	09:45:12	11:27:15	13:29:18
Mileage	36743.6	36770.7	36797.7
Stop 8 key on	09:48:12	11:30:15	13:32:18
Stop 9 key off	09:50:38	11:33:02	13:35:35
Mileage	36744.2	36771.3	36798.3
Stop 9 key on	09:53:35	11:36:02	13:38:35
Stop 10 key off	10:15:06	11:56:46	13:58:33
Mileage	36755.5	36782.7	36809.0
Stop 10 key on			
End Time	10:15:06	11:56:46	13:58:33
End Mileage	36755.5	36782.7	36809.0
Total Mileage	27.0	27.1	27.1

Driver Time Keeping

Start Time
Lunch Start
Finish Time
Lunch Stop

36809.0
36792.9
6'

36755.5
36728.5
27.0

36782.7
36755.6
27.1

Ending day

1. Press <ESC> to write file
2. Disconnect exhaust sampling hose
3. Let sampler run 5 minutes and turn unit off
4. Exchange batteries or hook up charger.

Frito-Lay Hybrid Vehicle Evaluation
Daily Vehicle and Run Checklist

FORD NORTH

Date:	03/30/07
Vehicle No.:	207000
Driver Name:	Jim
Insurance Papers Present	
Vehicle Registration Present	
Temperature F	22°
Weather (Rainy, Cloudy, Sunny)	
GPS	4-6-9-10-11
PRE-RUN INSPECTIONS AND START-UP	
Truck Inspection	
Tire Pressure:	
Front Left (Green - Red Corrected) 75 psi ✓	
Front Right (Green - Red Corrected) 75 psi ✓	
Rear Left	
Inner (Green - Red Corrected) 75 psi ✓	
Outer (Green - Red Corrected) 75 psi ✓	
Rear Right	
Inner (Green - Red Corrected) 75 psi ✓	
Outer (Green - Red Corrected) 75 psi ✓	
Fuel Type	GAS
Fuel Gauge Reading	1/2 TANK
Analyzer Inspection Start-up	
Last System Calibration (date)	
Analyser Filter Cleaned (date)	
Battery Charge 13-13	13.62
Analyser Turned on for Warm Up (time)	05:45

	Run 1 B	Run 2	Run 3
File Number	B70330A	B70330C	B70330D
Bag Number	1	1	1
Start Mileage	2259.1	2280.1	2306.3
Route	A-1	A-1	A-1
Run start time	06:14:37	08:13:56	09:55:10
Stop 1 key off	06:52:27	08:24:54	10:06:48
Mileage	2263.8	2284.9	2306.1
Stop 1 key on	06:55:27	08:27:54	10:09:48
Stop 2 key off	06:58:33	08:30:30	10:12:07
Mileage	2264.21	2285.5	2306.7
Stop 2 key on	07:01:33	08:33:30	10:15:07
Stop 3 key off	07:04:54	08:37:16	10:18:44
Mileage	2265.7	2286.7	2307.9
Stop 3 key on	07:07:54	08:40:16	10:21:44
Stop 4 key off	07:12:05	08:47:31	10:24:40
Mileage	2266.8	2288.0	2309.0
Stop 4 key on	07:15:05	08:51:31	10:27:40
Stop 5 key off	07:25:17	09:02:52	10:38:50
Mileage	2270.9	2292.0	2313.1
Stop 5 key on	07:28:17	09:05:52	10:41:50
Stop 6 key off	07:30:25	09:09:21	10:43:42
Mileage	2271.5	2292.6	2313.7
Stop 6 key on	07:33:25	09:11:21	10:46:42
Stop 7 key off	07:43:17	09:19:49	10:53:48
Mileage	2273.9	2295.1	2316.1
Stop 7 key on	07:46:17	09:22:19	10:56:48
Stop 8 key off	07:52:36	09:27:49	11:03:33
Mileage	2276.2	2297.3	2318.4
Stop 8 key on	07:55:36	09:30:49	11:06:33
Stop 9 key off	08:05:38	09:39:25	11:24:37
Mileage	2279.9	2301.1	2323.6
Stop 9 key on			
Stop 10 key off			
Mileage			
Stop 10 key on			
End Time	08:05:38	09:39:25	11:24:37
End Mileage	2279.9	2301.1	2323.6
Total Mileage	20.8	21.0	22.3

Analyser Start Up
1. Connect power cable to battery
2. Turn on all 6 switches
3. Follow prompts on screen
4. Do not edit any information click 'Y","Y" and enter
5. This should have you at the data screen
6. Allow the sysytem to warm up for 45 minutes
7. Complete the rest of the check list items.

79.9
59.1
20.8

File # B Standard

301.1
280.1
21.0

Troubleshooting tips
Verify RPM is reading. If not push "P" key on diesel truck
Verify RPM is reading. If not push "S" key on gas hybrid truck
Verify temperature reading

23.6
01.3
22.3

Starting Runs
1. After system warm up:
2. Connect exhuast sampling hose to filters on analysers
3. Start diesel truck and let run for 5 minutes
4. Start Hybrid truck and make three laps in the parking lot with
5. Press <ESC> This creates file number
6. As you pull through the gate push "+" to create bag number
7. Record time and mileage at each stop using the time from the analyzer

Ending Runs
1. Stop at gate push "-" to stop bag

Notes:

Driver Time Keeping
Start Time
Lunch Start
Lunch Stop
Finish Time

System FAILAT 07:53:05 Time only
Restart A 07:56:20 Sys OK

Ending day
1. Press <ESC> to write file
2. Disconnect exhaust sampling hose
3. Let sampler run 5 minutes and turn unit off
4. Exchange batteries or hook up charger.

Frito-Lay Hybrid Vehicle Evaluation
Daily Vehicle and Run Checklist

Date:	07-28-07
Vehicle No.:	Diesel Hybrid
Driver Name:	RAY/JIM
Insurance Papers Present	
Vehicle Registration Present	
Temperature F	74C
Weather (Rainy, Cloudy, Sunny)	
GPS	9
PRE-RUN INSPECTIONS AND START-UP	
Truck Inspection	
Tire Pressure:	
Front Left (Green - Red Corrected) 75 psi	
Front Right (Green - Red Corrected) 75 psi	
Rear Left	
Inner (Green - Red Corrected) 75 psi	
Outer (Green - Red Corrected) 75 psi	
Rear Right	
Inner (Green - Red Corrected) 75 psi	
Outer (Green - Red Corrected) 75 psi	
Fuel Type	
Fuel Gauge Reading	5/8 3/4
Analyzer Inspection Start-up	
Last System Calibration (date)	27 Feb 07
Analyser Filter Cleaned (date)	
Battery Charge B-1	13.4
Analyser Turned on for Warm Up (time)	710

	Run 1	Run 2 D	Run 3
File Number	B70228A	B702228B	B702228C
Bag Number	1	1	1
Start Mileage	1853.1	1875.3	1897.5
Route	A-1	A-1	A-1
Run start time	08:11:00	09:26:20	11:21:24
Stop 1 key off	08:21:20	09:54:35	11:31:20
Mileage	1858.0	1880.6	1902.4
Stop 1 key on	08:24:20	09:57:35	11:34:20
Stop 2 key off	08:26:45	10:01:45	11:37:20
Mileage	1858.7	1880.9	1903.0
Stop 2 key on	08:29:45	10:04:45	11:40:20
Stop 3 key off	08:33:25	10:09:45	11:44:40
Mileage	1859.5	1882.1	1904.2
Stop 3 key on	08:36:25	10:12:45	11:47:40
Stop 4 key off	08:39:15	10:15:20	11:50:30
Mileage	1861.0	1883.2	1905.3
Stop 4 key on	08:42:15	10:18:20	1153.30
Stop 5 key off	08 54:30	10:29:15	12:03:50
Mileage	1865.1	1887.2	1909.4
Stop 5 key on	08:57:30	10:32:15	12:06:50
Stop 6 key off	09:00:15	10:35:10	12:09:00
Mileage	1865.7	1887.9	1909.9
Stop 6 key on	09:03:15	10:38:10	12:12:00
Stop 7 key off	09:15:00	10:45:40	12:18:20
Mileage	1868.3	1890.5	1912.5
Stop 7 key on	09:18:00	10:48:40	12:21:20
Stop 8 key off	09:20:35	10:58:30	12:27:50
Mileage	1870.8	1893.0	1914.9
Stop 8 key on	09:23:35	11:01:00	12:30:50
Stop 9 key off	09:33:35	11:10:20	12:37:37
Mileage	1875.2	1897.4	1918.7
Stop 9 key on			
Stop 10 key off			
Mileage			
Stop 10 key on			
End Time	09:33:35	11:10:20	12:37:37
End Mileage	1875.2	1897.4	1918.7
Total Mileage	22.1	22.1	21.1

B-1 BATTERY
FROZE UP AT 09:57:35
RESTART AT 09:55:35 OK

Analyser Start Up

1. Connect power cable to battery
2. Turn on all 6 switches
3. Follow prompts on screen
4. Do not edit any information click 'Y","Y" and enter
5. This should have you at the data screen
6. Allow the sysytem to warm up for 45 minutes
7. Complete the rest of the check list items.

1875.2
53.1
22.1

97.4
75.3
22.1

95
97
21

1918.7
1897.5

Troubleshooting tips

Verify RPM is reading. If not push "P" key on diesel truck
Verify RPM is reading. If not push "S" key on gas hybrid truck
Verify temperature reading

Starting Runs

1. After system warm up:
2. Connect exhuast sampling hose to filters on analysers
3. Start diesel truck and let run for 5 minutes
4. Start Hybrid truck and make three laps in the parking lot with
5. Press <ESC> This creates file number
6. As you pull through the gate push "+" to create bag number
7. Record time and mileage at each stop using the time from the analyzer

Ending Runs

1. Stop at gate push "-" to stop bag

Notes:

Driver Time Keeping

Start Time
Lunch Start
Lunch Stop
Finish Time

FROZE UP AT 10:04:10
RESTART AT 10:05:00

Ending day

1. Press <ESC> to write file
2. Disconnect exhaust sampling hose
3. Let sampler run 5 minutes and turn unit off
4. Exchange batteries or hook up charger.

Frito-Lay Hybrid Vehicle Evaluation
Daily Vehicle and Run Checklist

SOUTH

Date: 08/02/2	
Vehicle No.:	14HBRed
Driver Name: Schwinglou / Willis	
Insurance Papers Present	
Vehicle Registration Present	
Temperature F 100-180	
Weather (Rainy, Cloudy, Sunny)	
PRE-RUN INSPECTIONS AND START-UP	
Truck Inspection	
Tire Pressure:	
Front Left (Green - Red Corrected) 75 psi	
Front Right (Green - Red Corrected) 75 psi	
Rear Left	
Inner (Green - Red Corrected) 75 psi	
Outer (Green - Red Corrected) 75 psi	
Rear Right	
Inner (Green - Red Corrected) 75 psi	
Outer (Green - Red Corrected) 75 psi	
Fuel Type GAS	
Fuel Gauge Reading Full	
GPS	6-8-11
Analyzer Inspection Start-up	
Last System Calibration (date)	
Analyser Filter Cleaned (date)	
Battery Charge B1 start 13.52 stop 14.47	13.524
Analyser Turned on for Warm Up (time)	07:45

B2 St-13.7 St-

Analyser Start Up
1. Connect power cable to battery
2. Turn on all 6 switches
3. Follow prompts on screen
4. Do not edit any information click 'Y","Y" and enter
5. This should have you at the data screen
6. Allow the sysytem to warm up for 45 minutes
7. Complete the rest of the check list items.

FROZ UP 1030.06 RESTART 1034:00 OIL

Troubleshooting tips
Verify RPM is reading. If not push "P" key on diesel truck
Verify RPM is reading. If not push "S" key on gas hybrid truck
Verify temperature reading

~~1 Stop~~ 10.6
1453.5
1442.7
10.8

Starting Runs
1. After system warm up:
2. Connect exhuast sampling hose to filters on analysers
3. Start diesel truck and let run for 5 minutes
4. Start Hybrid truck and make three laps in the parking lot with
5. Press <ESC> This creates file number
6. As you pull through the gate push "+" to create bag number
7. Record time and mileage at each stop using the time from the analyzer

Ending Runs
1. Stop at gate push "-" to stop bag

MILAGE FREZ 1060.4 TIME 1030.6 RESTART 1034:0 Wont 1 B70202-B

Notes: 1472.5 1054.0

Started with Shutting Down GAS Wouldn't START AFTER WE LOST Elect Power shut down TRUCK FOR 3 minutes STARTED BACK UP AT 1057: GAS ONG STARTED

CHG ONG Light Went Out AT 11:08
" " " ON AT 11:10

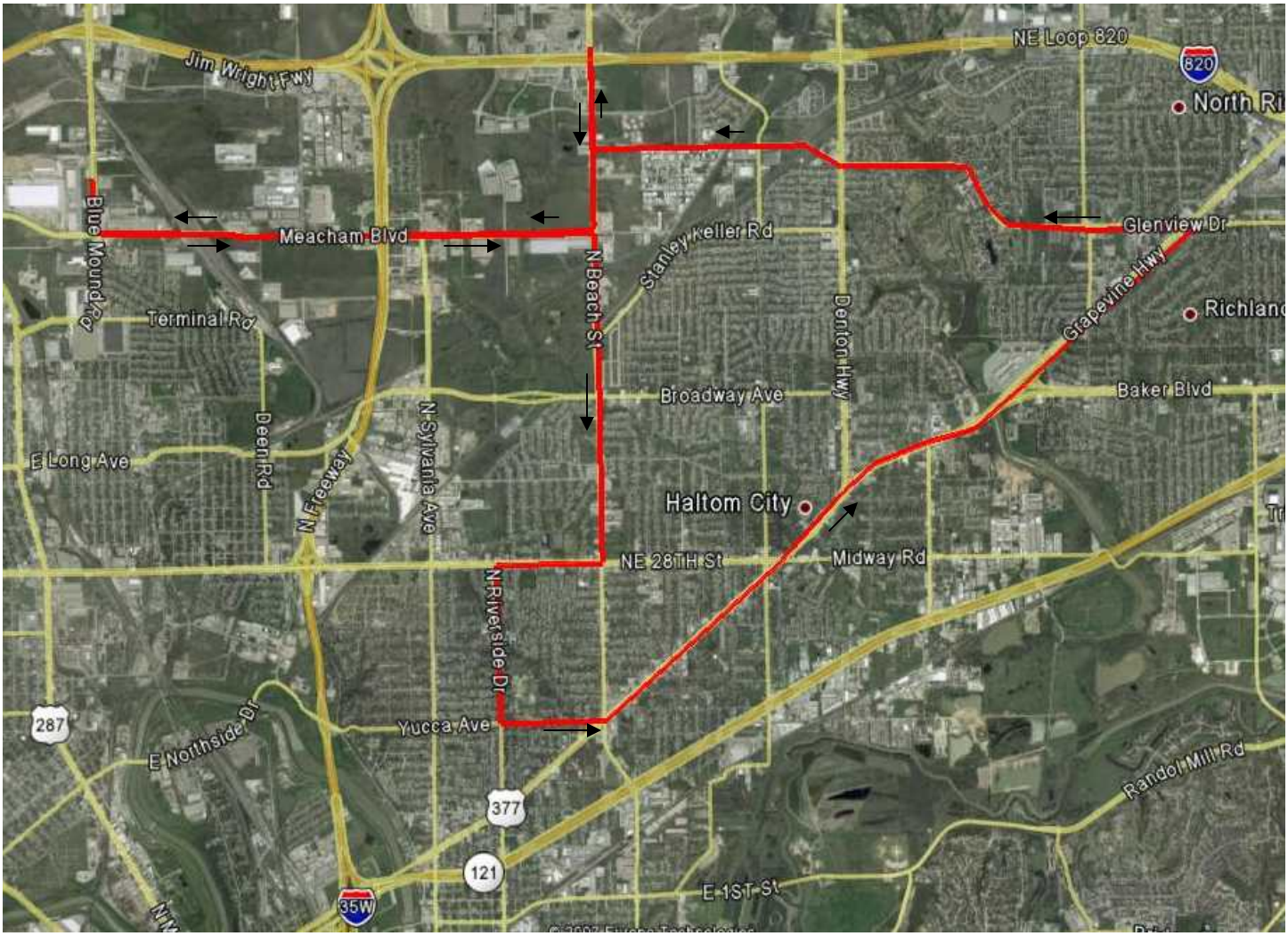
	Run 1	Run 2	Run 3
File Number	B70202A	B-70202C	B70202D
Bag Number	1	1	1
Start Mileage	1442.7	1471.4	1500.3
Route	B-1	B-1	B-1
Run start time	09:13:30	10:51:50	13:12:00
Stop 1 key off	09:33:30	11:15:30	13:38:20
Mileage	1453.5	1482.3	1510.9
Stop 1 key on	09:36:30	11:18:30	13:41:20
Stop 2 key off	09:38:35	11:20:22	13:43:50
Mileage	1454.0	1482.7	1511.3
Stop 2 key on	09:41:35	11:23:22	13:46:30
Stop 3 key off	09:45:01	11:27:30	13:49:45
Mileage	1454.9	1483.7	1512.1
Stop 3 key on	09:48.0	11:30:30	13:52:45
Stop 4 key off	09:49:45	11:32:45	13:54:50
Mileage	1455.6	1484.4	1512.9
Stop 4 key on	09:52:45	11:35:45	13:57:50
Stop 5 key off	09:55:40	11:39:05	13:59:50
Mileage	1456.3	1485.1	1513.6
Stop 5 key on	09:58:40	11:42:05	14:02:50
Stop 6 key off	10:01:40	11:46:10	14:06:10
Mileage	1457.3	1486.1	1514.6
Stop 6 key on	10:04:40	11:49:10	14:09:10
Stop 7 key off	10:07:10	11:53:25	14:12:20
Mileage	1458.1	1486.9	1515.3
Stop 7 key on	10:10:10	11:56:25	14:15:20
Stop 8 key off	10:12:30	11:58:55	14:17:38
Mileage	1458.7	1487.5	1516.0
Stop 8 key on	10:15:50	12:02:55	14:20:28
Stop 9 key off	10:17:50	12:04:10	1422:18
Mileage	1459.4	1488.2	1516.7
Stop 9 key on	10:20:50	12:07:10	14:25:18
Stop 10 key off	FIE	12:45:55	15:10
Mileage	B70202B	1500.2	1533.5
Stop 10 key on			
End Time	10:40:0	12:45:55	1510.6
End Mileage	1471.4	1500.2	1533.5
Total Mileage	28.7	28.8	33.2

Driver Time Keeping

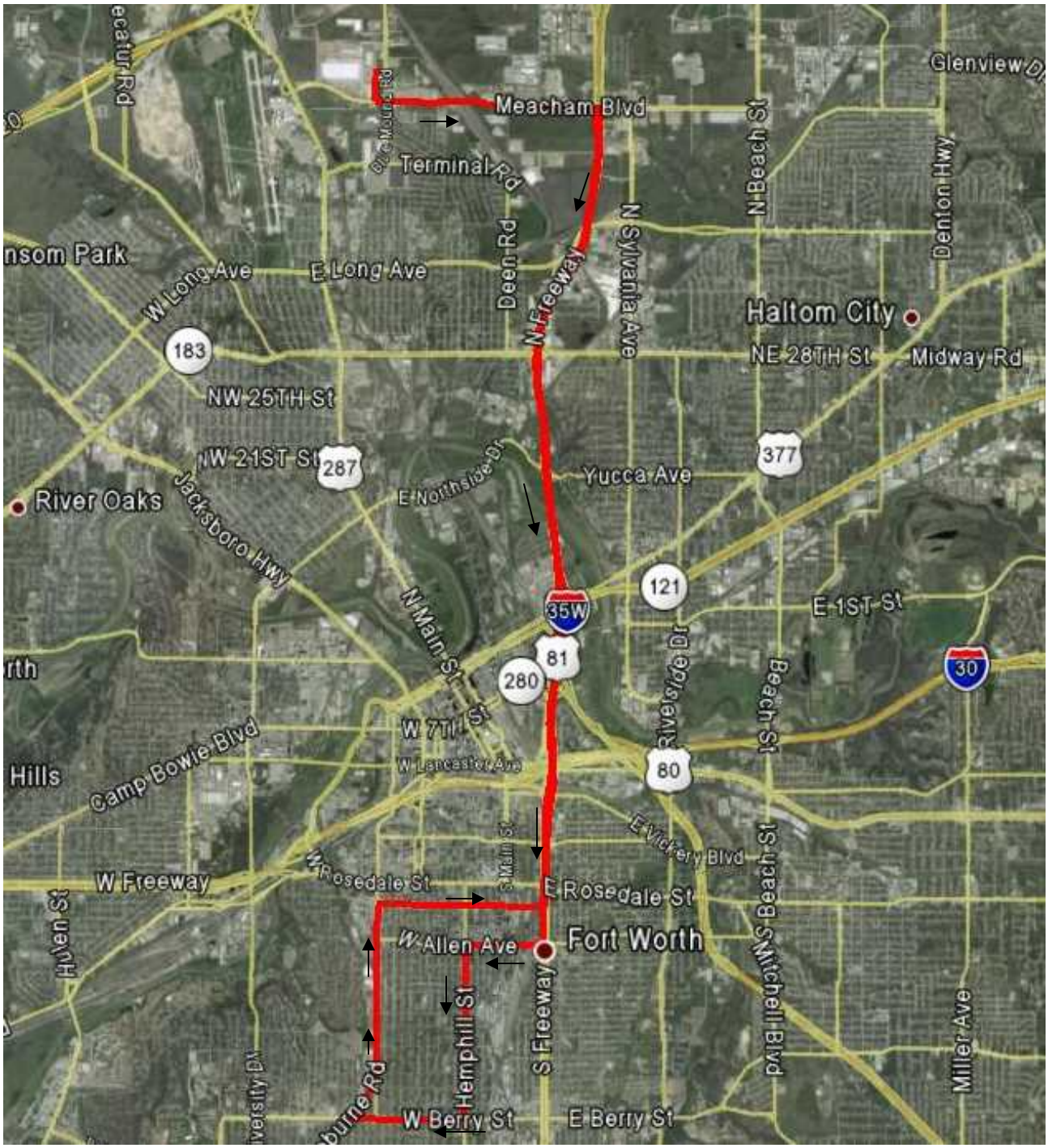
Start Time	1471.4	1500.2 / 1471.4 / 28.8	1533.5
Lunch Start	1442.7	Lunch Stop	1500.3
Finish Time	28.7		33.2

Ending day
1. Press <ESC> to write file
2. Disconnect exhaust sampling hose
3. Let sampler run 5 minutes and turn unit off
4. Exchange batteries or hook up charger.

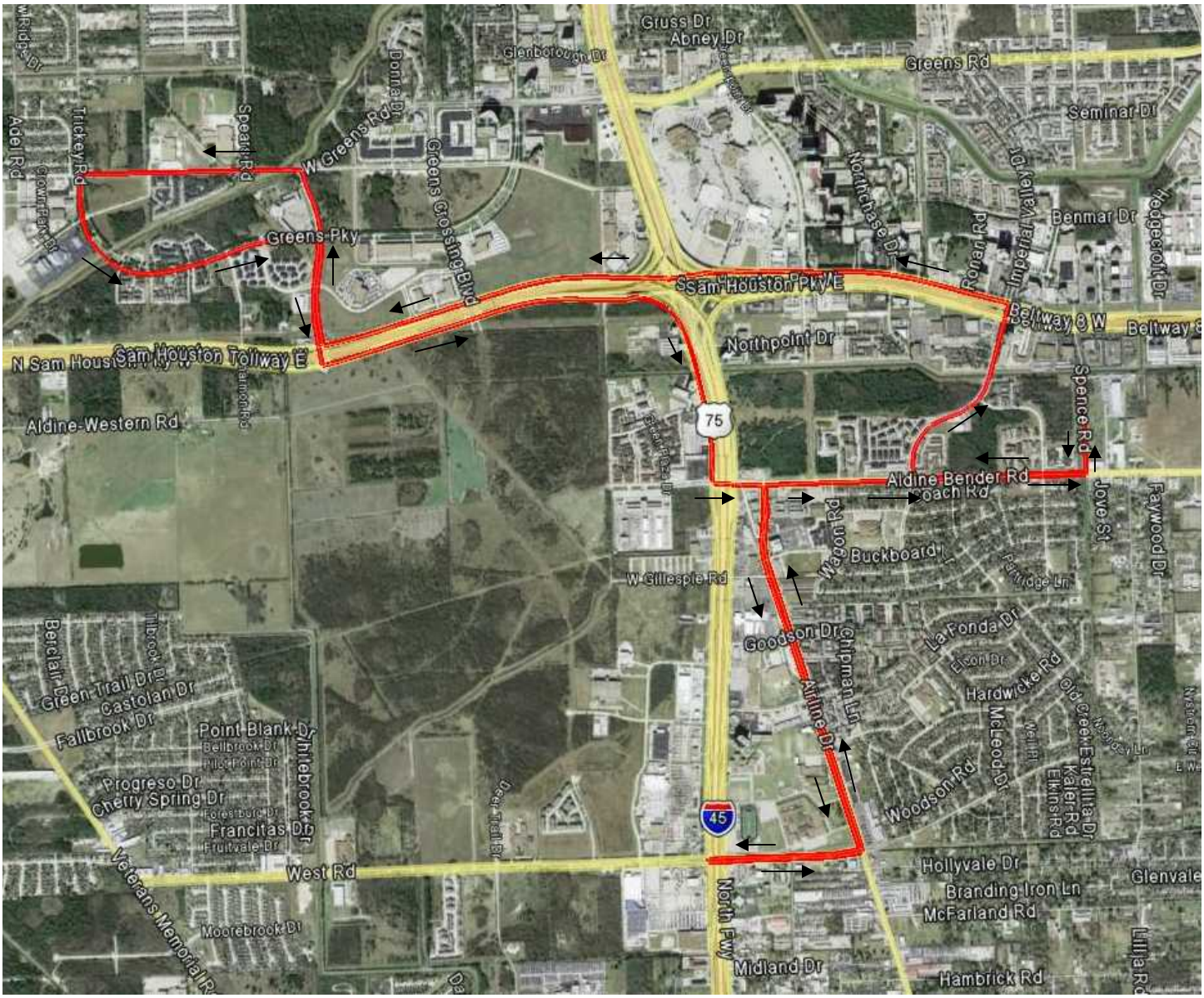
DFW North Route



DFW South Route



Houston Route



Appendix F

SwRI Phase 3 Test Report

SOUTHWEST RESEARCH INSTITUTE®

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ISO 9001 Certified
ISO 14001 Certified

May 15, 2007

Mr. Joe Gold
Rolling Frito-Lay Sales, LP
7701 Legacy Dr.
Plano, TX 75024

SUBJECT: SwRI Letter Final Report titled, "Emissions Testing of Various Delivery Trucks," Project 03-12163.

Dear Mr. Gold:

This report describes the work completed for Parts 1 and 2 of the chassis dynamometer testing for this project. Two conventional delivery trucks (Truck 1 and 2) and two different hybrid-electric drive trucks (Truck 3 and 4) were tested in December 2006 and January 2007 for Part 1 of this project on the same heavy-duty chassis dynamometer at SwRI.

1.0 INTRODUCTION

The trucks left SwRI and were operated in the field by Frito-Lay from January 2007 through March 2007. The four trucks returned for heavy-duty chassis testing near the end of March 2007. During that time, Truck 4 received updates for the hybrid system and engine control to provide better performance and driveablility. Frito-Lay also requested that SwRI increase the scope of work to test Truck 4 with the hybrid system disabled and test another truck, Truck 5, which is representative of a conventional, gasoline-powered configuration to compare to Truck 3. Table 1 is a summary of each truck's mechanical configuration and test weight. Exhaust emissions of PM, NO_x, HC, CO, and CO_2 were measured for each truck. The emissions levels of the hybrid trucks were compared to those of the conventional trucks. Fuel economy was calculated for each test using the carbon balance method. Energy balance corrections were performed for each hybrid truck per SAE Recommended Practice J2711 for heavy-duty, hybrid-drive vehicles.

Hybrid electric vehicles are typically equipped with energy storage devices. It was recognized that the net energy change (NEC) in the storage device will likely affect the measured emissions and fuel economy data. SAE J2711 provides a method to correct emissions and fuel economy data if the energy storage device's NEC varied by more than 1 percent of the total fuel energy consumed during the test. SAE J2711 does not recommend correcting data if the NEC is less than 1 percent. Fortunately, the NEC for each hybrid truck test was less 1 percent, so no correction was required. The NEC values for each truck are included in this report.

TABLE 1. TRUCK CONFIGURATION SUMMARY

Truck	Engine	Drivetrain	Fuel	Test Wt, lb.
1	Cummins 3.9L In-line 4, direct-injection, turbocharged, intercooled	Automatic transmission	Diesel	9,160
2	General Motors, 6.5L V8, indirect-injection Naturally aspirated	Automatic transmission	Diesel	9,180
3	General Motors, 4.8L V8, port-injected Naturally aspirated	Series Hybrid Electric, NiMH battery pack	Gasoline	10,730
4	International, 4.5L V6, direct-injection, turbocharged, intercooled	Parallel Hybrid Electric, NiMH battery pack, Automated manual transmission	Diesel	10,530
5	Ford 5.4L, V8 port-injection, Naturally aspirated	Automatic transmission	Gasoline	9,010

2.0 Vehicle Testing

The purpose of this work was to determine the effect of each type of hybrid drive system on emissions in comparison to conventional trucks. SwRI conducted five hot-start emission tests on each of five trucks over the same drive cycle, and the average value for each emission was used to compare the relative emission levels of the trucks. Rolling Frito-Lay Sales, LP (Frito-Lay) chose to test the trucks over the light-duty FTP UDDS (LD UDDS) drive cycle, Figure 1. The test plans for Parts 1 and 2 are given in Tables 2 and 3, respectively . Frito-Lay provided the test weights used by SwRI using the sum of each truck's dry empty weight, fuel weight, driver, and half of the remaining cargo weight capacity. SwRI used this test weight and measured frontal area to calculate the road load using EPA's recommended procedure for heavy-duty chassis testing. The diesel trucks were fueled with ultra-low sulfur diesel with a density of 7.2 lb/gal. The gasoline truck used commercially-available gasoline with a density of 6.2 lb/gal.

3.0 TEST RESULTS

The following sections describe each vehicle's installation, coastdown, and emissions results. In the case of the hybrid trucks, a table with the NEC value for each test is included in the corresponding sections.

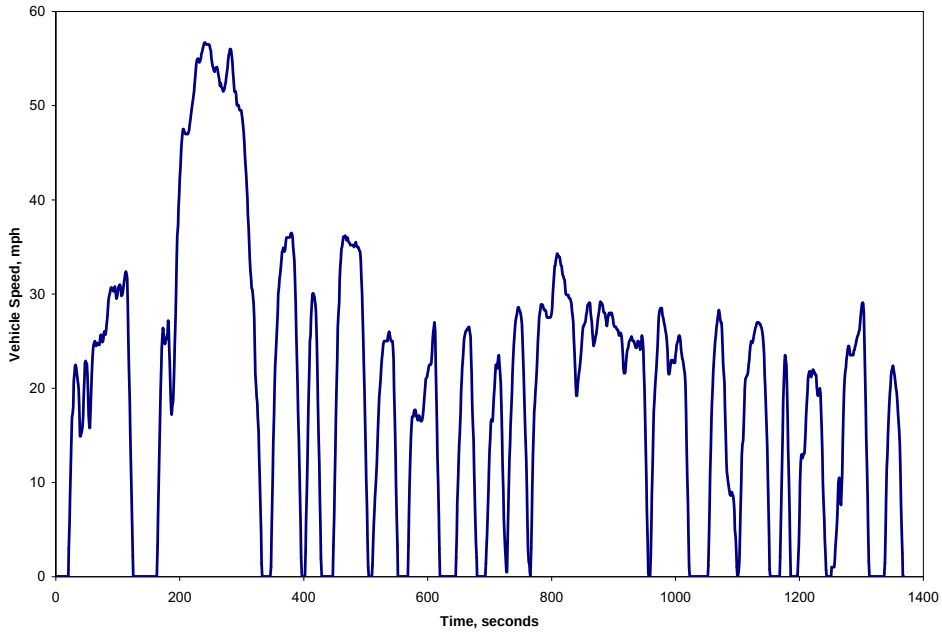

FIGURE 1. LIGHT-DUTY FTP UDDS (LD UDDS) DRIVE CYCLE

TABLE 2. PART 1 TEST PLAN FOR CHASSIS TESTING

Step	Description
1	Install baseline truck, Truck 1, and isolate fuel system, conduct coastdowns.
2	Conduct two prep runs.
3	Perform five hot-start tests for HC, CO, NO_x, PM, and CO_2.
4	Remove Truck 1 from dynamometer.
5	Install second baseline truck, Truck 2, and isolate fuel system, conduct coastdowns.
6	Conduct two prep runs.
7	Perform five hot-start tests for HC, CO, NO_x, PM, and CO_2.
8	Remove Truck 2 from dynamometer.
9	Install the first hybrid-electric drive truck, Truck 3, isolate fuel system, conduct coastdowns.
10	Set-up to record battery State of Charge (SOC) for SAE J2711 NEC correction.
11	Conduct two prep runs.
12	Perform five hot-start tests.
13	Remove Truck 3 from dynamometer.
14	Repeat Steps 9 through 13 for Truck 4.
15	After completing Part 1, release the trucks for durability operation and prepare the report for Part 1 testing.

TABLE 3. PART 2 TEST PLAN FOR CHASSIS TESTING

Step	Description
1	Install Truck 1, isolate fuel system, conduct coastdowns.
2	Conduct two prep runs.
3	Perform five hot-start tests for HC, CO, NO_x, PM, and CO_2.
4	Remove Truck 1 from dynamometer.
5	Repeat Steps 1 through 4 for Truck 2.
6	Install Truck 3 with test fuel in on-board fuel tank, conduct coastdowns.
7	Set-up to record battery State of Charge (SOC) for SAE J2711 NEC correction.
8	Conduct two prep runs.
9	Perform five hot-start tests for HC, CO, NO_x, PM, and CO_2.
10	Remove Truck 3 from dynamometer.
11	Install baseline truck, Truck 4, and isolate fuel system, conduct coastdowns.
12	Set-up to record battery State of Charge (SOC) for SAE J2711 NEC correction.
13	Conduct two prep runs.
14	Perform five hot-start tests for HC, CO, NO_x, PM, and CO_2.
15	Disable hybrid drive system on Truck 4
16	Repeat Steps 13 and 14.
17	Remove Truck 4 from dynamometer.
18	Install Truck 5 with test fuel in on-board fuel tank, conduct coastdowns.
19	Repeat Steps 13 and 14 for Truck 5.
20	Prepare final report.

3.1 Truck 1 - Test Results

Truck 1, VIN 5B4HP42P553404763, was powered by a 2005 3.9L Cummins, turbocharged, intercooled, direct injected diesel engine and was equipped with an automatic transmission. The truck was installed on the chassis dynamometer, as shown in Figure 2 and tested at 9,160 lb. Coastdowns for this truck are shown in Figure 3. The truck was then driven over the drive cycle twice to condition the vehicle for the hot-start testing. The five hot-start tests were conducted with a 20-minute soak in between each test to change emission sample bags and PM filters. The test results for Truck 1 in Parts 1 and 2 are summarized in Tables 4 and 5, respectively.

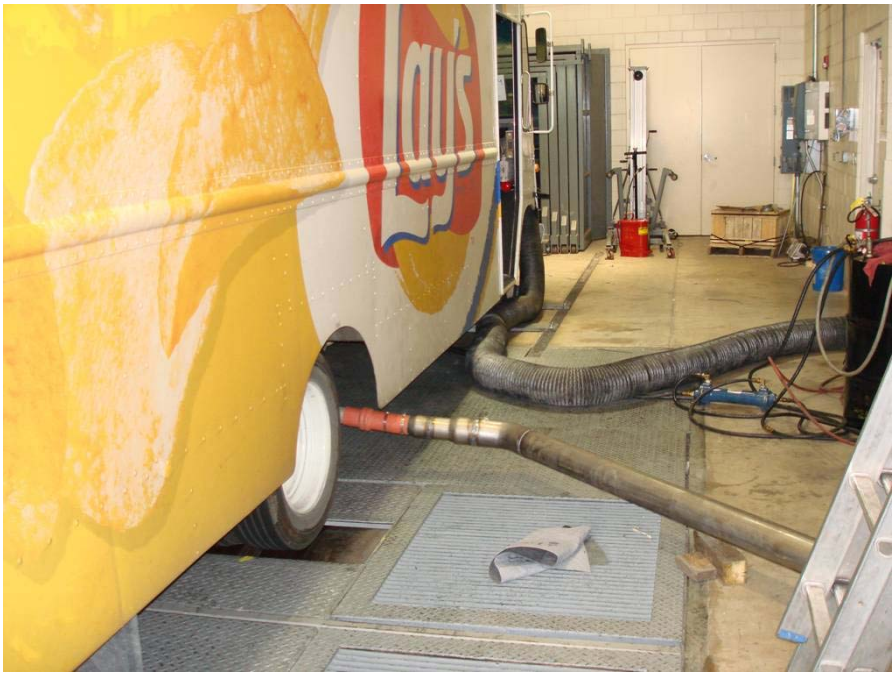

FIGURE 2. TRUCK 1 INSTALLED ON THE HEAVY-DUTY CHASSIS DYNAMOMETER

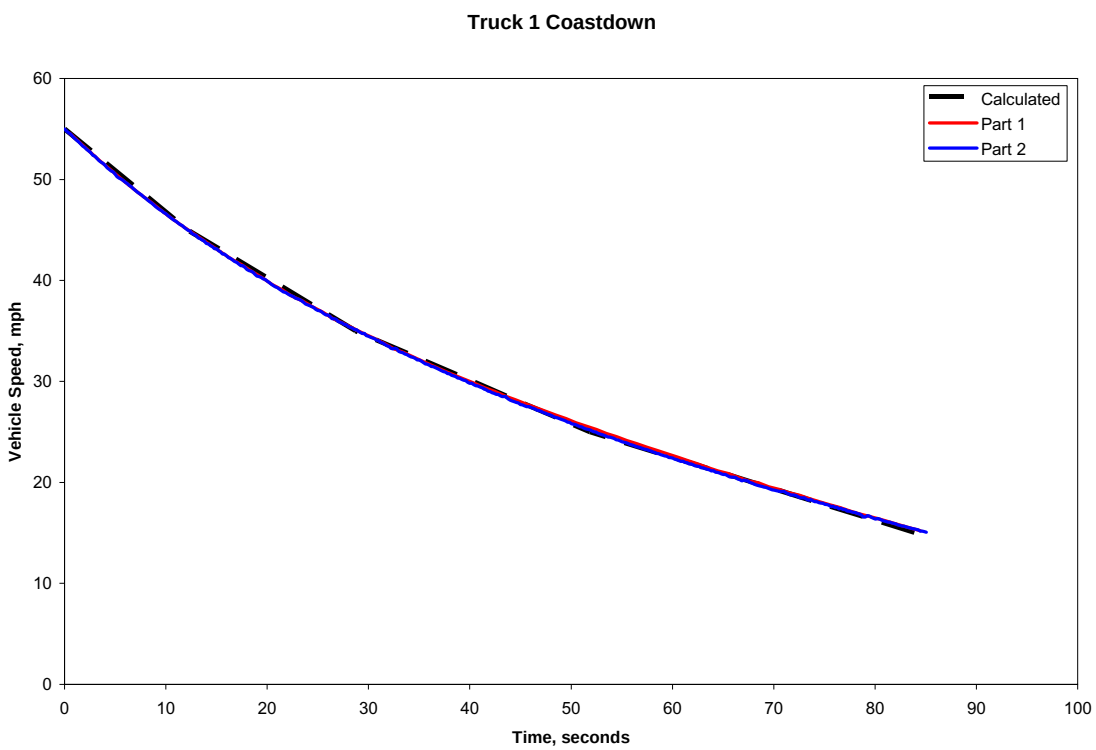

FIGURE 3. TRUCK 1 COASTDOWN RESULTS COMPARED TO CALCULATED COASTDOWN VALUES

TABLE 4. EMISSION RESULTS FOR TRUCK 1 OVER LD FTP UDDS DRIVE CYCLE DURING PART 1

Test Code	HC, g/mi	CO, g/mi	NO_x, g/mi	PM, mg/mi	CO_2, g/mi	MPG	Fuel, kg	Miles
4763-H1	0.15	2.23	6.27	78	715	14.4	1.71	7.53
4763-H2	0.14	2.37	6.30	78	707	14.6	1.70	7.55
4763-H3	0.14	2.32	6.20	74	707	14.6	1.69	7.53
4763-H4	0.16	2.28	6.21	73	701	14.7	1.69	7.59
4763-H5	0.13	2.32	6.07	75	696	14.8	1.68	7.58
Average =	**0.14**	**2.30**	**6.21**	**75**	**705**	**14.6**	**1.69**	**7.56**
c.o.v.	6%	2%	1%	3%	1%	1%	1%	0%

TABLE 5. EMISSION RESULTS FOR TRUCK 1 OVER LD FTP UDDS DRIVE CYCLE DURING PART 2

Test Code	HC, g/mi	CO, g/mi	NO_x, g/mi	PM, mg/mi	CO_2, g/mi	MPG	Fuel, kg	Miles
4763B-H1	0.13	2.25	6.14	89	724	14.2	1.73	7.54
4763B-H2	0.12	2.30	6.17	82	727	14.2	1.74	7.54
4763B-H3	0.11	2.26	6.14	86	723	14.3	1.73	7.55
4763B-H4	0.14	2.22	6.19	82	722	14.3	1.73	7.55
4763B-H5	0.12	2.23	6.12	83	722	14.2	1.73	7.54
Average =	**0.12**	**2.25**	**6.15**	**84**	**724**	**14.2**	**1.73**	**7.54**
c.o.v.	9%	1%	3%	4%	1%	1%	1%	0%

3.2 Truck 2 - Test Results

Truck 2, VIN 1GBHP32Y8W3304305, was powered by a 1997 6.5L GM naturally-aspirated, indirect injected diesel engine and was equipped with an automatic transmission. The truck was installed on the chassis dynamometer, as shown in Figure 4, and tested at 9,180 lb. Coastdowns for this truck in each Part are shown in Figure 5. During Part 1, the truck was fitted with a calibrated mass air flow sensor to record engine air flow to compare with the mobile emissions measurement device's air flow estimation. This data is not included in the report, as it was for reference only. The truck was then driven over the drive cycle twice to condition the vehicle for the hot-start testing. After five hot-start tests were conducted, the first test appeared to be an outlier and a sixth test was performed while the truck was still on the dynamometer. However, after using ASTM-E178 criteria, the first test was not an outlier, so it was decided to use all six tests for the average and c.o.v. calculations. Part 1 test results for Truck 2 are summarized in Table 6.

For Part 2, the mass air flow meter data was not recorded, since the mobile emissions measurement device was not present during Part 2 testing. The truck was only tested five times in Part 2 and the results for this testing are summarized in Table 7.

FIGURE 4. TRUCK 2 INSTALLED ON THE HEAVY-DUTY CHASSIS DYNAMOMETER

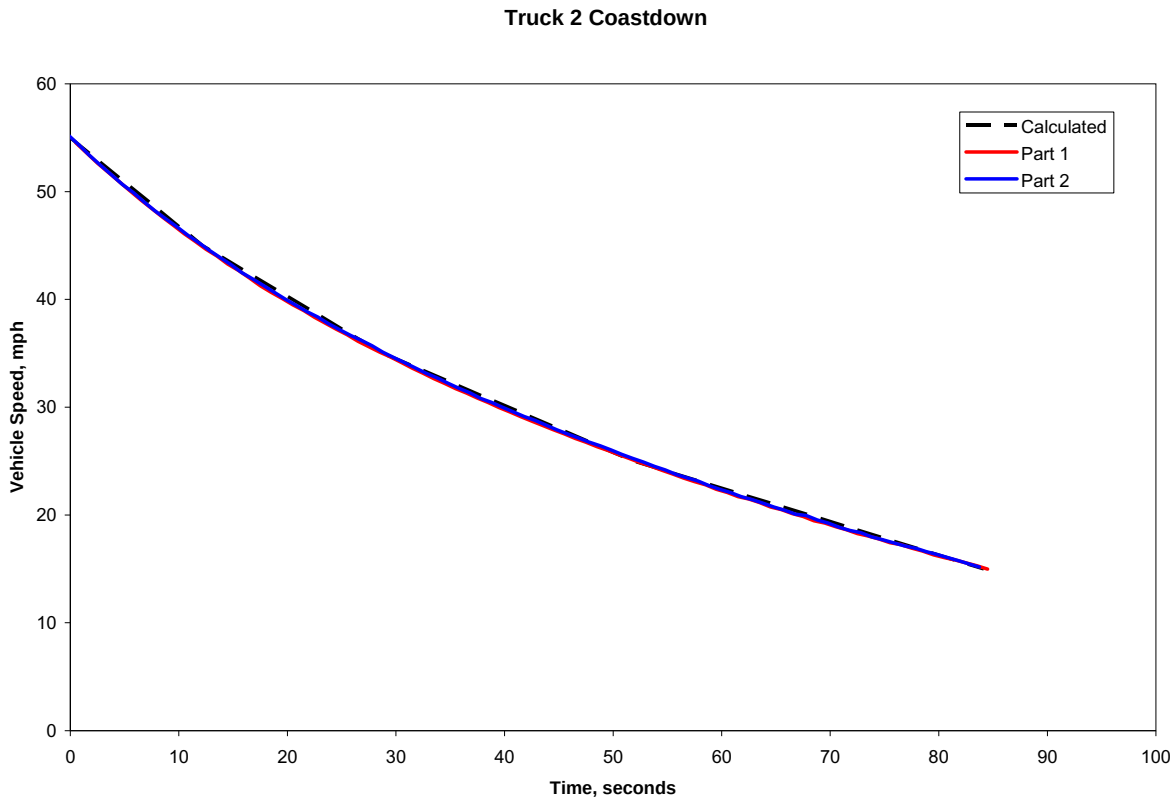

FIGURE 5. TRUCK 2 COASTDOWN RESULTS COMPARED TO CALCULATED COASTDOWN VALUES

TABLE 6. EMISSION RESULTS FOR TRUCK 2 OVER LD FTP UDDS DRIVE CYCLE DURING PART 1

Test Code	HC, g/mi	CO, g/mi	NO_x, g/mi	PM, mg/mi	CO_2, g/mi	MPG	Fuel, kg	Miles
4305-H1*	0.35	1.59	2.98	218	852	12.1	2.04	7.57
4305-H2	0.30	1.44	3.11	144	847	12.2	2.03	7.55
4305-H3	0.30	1.44	3.68	133	839	12.3	2.00	7.54
4305-H4	0.30	1.48	3.63	158	838	12.3	2.01	7.56
4305-H5	0.31	1.47	3.74	136	840	12.3	2.02	7.60
4305-H6	0.30	1.41	3.64	126	837	12.3	2.00	7.53
Average =	**0.31**	**1.47**	**3.46**	**152**	**842**	**12.2**	**2.02**	**7.56**
c.o.v.	6%	4%	9%	22%	1%	1%	1%	0%

* This test was initially thought to be an outlier during testing, but it was not, using ASTM-E178. This test was used in the average and c.o.v. calculations.

TABLE 7. EMISSION RESULTS FOR TRUCK 2 OVER LD FTP UDDS DRIVE CYCLE DURING PART 2

Test Code	HC, g/mi	CO, g/mi	NO_x, g/mi	PM, mg/mi	CO_2, g/mi	MPG	Fuel, kg	Miles
4305B-H1	0.37	1.70	3.52	147	834	12.4	1.99	7.53
4305B-H2	0.33	1.58	3.55	126	830	12.4	1.99	7.55
4305B-H3	0.35	1.68	3.49	135	836	12.3	2.06	7.77
4305B-H4	0.33	1.67	3.50	143	840	12.3	2.03	7.61
4305B-H5	0.33	1.61	3.52	137	835	12.3	1.99	7.52
Average =	**0.34**	**1.65**	**3.52**	**137**	**835**	**12.3**	**2.01**	**7.60**
c.o.v.	5%	3%	1%	6%	0%	0%	2%	1%

3.3 Truck 3 - Test Results

Truck 3, VIN 584KP02V063416051, was powered by a 2005 4.8L GM Vortec, port injected gasoline engine and was equipped with series hybrid drivetrain using two electric motors and a nickel metal hydride (NiMH) battery pack. The truck was installed on the chassis dynamometer, as shown in Figure 6, and tested at 10,730 lb. Coastdowns for this truck are shown in Figure 7 for both Parts of testing. For Part 1, the truck was driven over the drive cycle twice to condition the vehicle for the hot-start testing. As with the previous truck, after five hot-start tests were conducted, the first test appeared to be an outlier and sixth test was conducted. Using ASTM-E178, the NO_X result from the first test was considered an outlier, so the sixth test was used in place of the first test for the average and c.o.v. calculations. The emission test results and NEC values for Truck 3 are summarized in Tables 8 and 9 for Part 1.

For Part 2, Test 3 was determined to be an outlier based on the NO_X values using the ASTM-E178 method. However, the truck was only tested five times, as stated in the test plan. The emission test results and NEC values for this truck during Pat 2 testing are shown in Tables 10 and 11. As described in the introduction, the percent NEC for this truck were less than 1 for all of the tests, so no data correction was necessary.

FIGURE 6. TRUCK 3 INSTALLED ON THE HEAVY-DUTY CHASSIS DYNAMOMETER

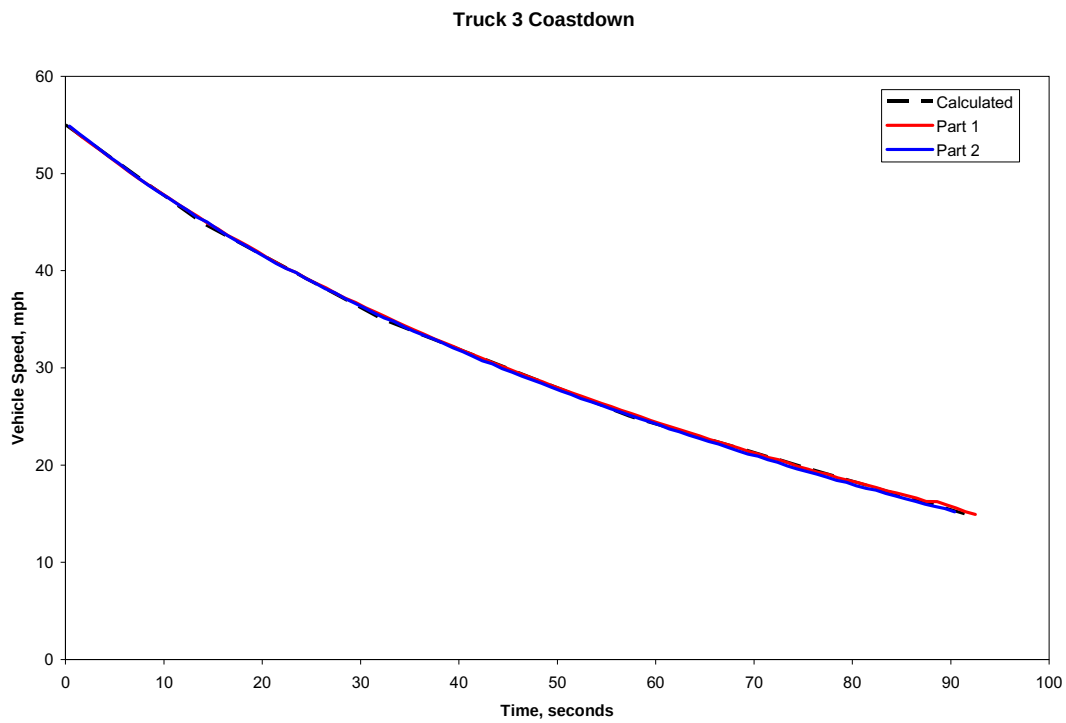

FIGURE 7. TRUCK 3 COASTDOWN RESULTS COMPARED TO CALCULATED COASTDOWN VALUES

TABLE 8. EMISSION RESULTS FOR TRUCK 3 OVER LD FTP UDDS DRIVE CYCLE DURING PART 1

Test Code	HC, g/mi	CO, g/mi	NO_x, g/mi	PM, mg/mi	CO_2, g/mi	MPG	Fuel, kg	Miles
F6051-H1	0.15	1.41	1.04	7	765	11.7	1.84	7.59
F6051-H2	0.12	2.21	0.37	10	739	12.0	1.77	7.56
F6051-H3	0.18	2.89	0.23	6	739	12.0	1.78	7.58
F6051-H4	0.15	2.51	0.28	5	748	11.9	1.80	7.59
F6051-H5	0.12	2.59	0.13	6	737	12.1	1.77	7.58
F6051-H6	0.17	2.35	0.28	8	742	12.0	1.79	7.58
Average =	**0.15**	**2.51**	**0.26**	**7**	**741**	**12.0**	**1.78**	**7.58**
c.o.v.	19%	10%	34%	27%	1%	1%	1%	0%

* This test was an outlier based on the NO_X value using ASTM-E178. This test was not used in the average and c.o.v. calculations.

TABLE 9. NEC RESULTS FOR TRUCK 3 OVER LD FTP UDDS DRIVE CYCLE DURING PART 1

Test Code	SOC, %		NEC, MJ	Fuel Energy, MJ	NEC, %
	Start	End			
F6051-H1	61.0	58.5	-0.28	77.2	0.0
F6051-H2	58.5	58.0	-0.06	74.5	0.0
F6051-H3	58.0	56.5	-0.17	74.8	0.0
F6051-H4	56.5	58.0	0.17	75.7	0.0
F6051-H5	58.0	57.5	-0.06	74.5	0.0
F6051-H6	57.5	61.0	0.39	75.1	0.0

TABLE 10. EMISSION RESULTS FOR TRUCK 3 OVER LD FTP UDDS DRIVE CYCLE DURING PART 2

Test Code	HC, g/mi	CO, g/mi	NO_x, g/mi	PM, mg/mi	CO_2, g/mi	MPG	Fuel, kg	Miles
F6051B-H1	0.19	3.93	0.18	10	755	11.7	1.82	7.56
F6051B-H2	0.14	2.44	0.25	10	756	11.8	1.81	7.54
F6051B-H3*	0.12	1.67	0.95	4	738	12.1	1.77	7.55
F6051B-H4	0.15	2.48	0.25	9	743	12.0	1.78	7.56
F6051B-H5	0.21	3.92	0.21	8	751	11.8	1.81	7.55
Average =	**0.17**	**3.19**	**0.22**	**9**	**751**	**11.8**	**1.80**	**7.55**
c.o.v.	18%	26%	15%	13%	1%	1%	1%	0%

* This test was an outlier based on the NO_X value using ASTM-E178. This test was not used in the average and c.o.v. calculations.

TABLE 11. NEC RESULTS FOR TRUCK 3 OVER LD FTP UDDS DRIVE CYCLE DURING PART 2

Test Code	SOC, %		NEC, MJ	Fuel Energy, MJ	NEC, %
	Start	End			
F6051B-H1	57.0	56.5	-0.06	79.9	0.0
F6051B-H2	56.5	58.0	0.17	79.6	0.0
F6051B-H3	58.0	57.5	-0.06	77.7	0.0
F6051B-H4	57.5	56.5	-0.11	78.5	0.0
F6051B-H5	56.5	58.0	0.17	79.4	0.0

3.4 Truck 4 – Test Results

Truck 4, VIN 5B4HPD25363412537, was powered by a 2006 4.5L direct-injected turbocharged diesel engine and was equipped with parallel hybrid drivetrain using an electric motor between the engine and transmission. The transmission was an Eaton automated manual. The battery pack was nickel metal hydride (NiMH). For Part 1, Truck 4's hybrid system was not completely refined and the engine's ECU was not using production software and calibrations, so the results of this truck may not be representative of the final product. The truck was installed on the chassis dynamometer, as shown in Figure 8, and tested at 10,530 lb. Coastdowns for this truck are shown in Figure 9. The truck was driven over the drive cycle twice to condition the vehicle for the hot-start testing. The emission test results and NEC values for Part 1 are summarized in Tables 12 and 13, respectively.

Truck 4 was the only truck modified before returning for Part 2 testing. It was noted that in Part 1 the truck's hybrid system control software was not fully developed and that the engine's ECU did not correctly receive torque commands from the hybrid controller. Both of those issues were addressed while the truck was operated in the field. The emission test results and NEC values for Part 1 are summarized in Tables 14 and 15, respectively. As described in the introduction, the NEC for all of the tests for this truck were less than 1 percent, so no data correction was necessary. During Part 2, emissions of HC, NOx and PM were reduced by 23, 18, and 2 percent, respectively. Emissions of CO increased by 15 percent. Fuel economy improved by 5 percent compared to the previous testing in Part 1.

At Frito-Lay's request, the truck was also tested with the hybrid system disabled. Although it was recognized that the vehicle would be lighter and the driveline inertia would be less without a hybrid system, no attempt was made to compensate or correct for the differences. The hybrid system was disabled by disconnecting the high-voltage battery cable from the pack at the connector. The testing in this configuration was conducted using the same procedure used in hybrid mode. The results of this testing is summarized in Table 16. With the hybrid system disabled, the emissions of HC were nearly identical, however, CO emissions nearly doubled, NOx increased 20 percent, and PM increased by 38 percent, compared to the hybrid configuration. Fuel economy was nearly 10 percent worse with the hybrid system disabled.

FIGURE 8. TRUCK 4 INSTALLED ON THE HEAVY-DUTY CHASSIS DYNAMOMETER

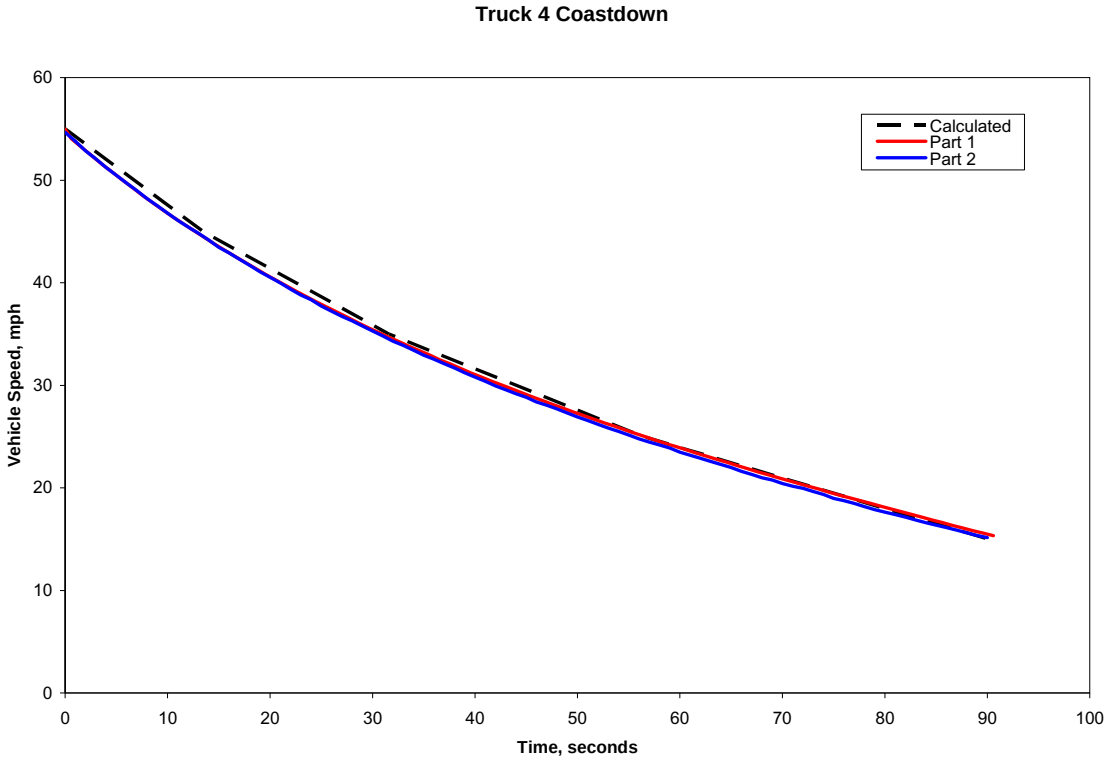

FIGURE 9. TRUCK 4 COASTDOWN RESULTS COMPARED TO CALCULATED COASTDOWN VALUES

TABLE 12. EMISSION RESULTS FOR TRUCK 4 OVER LD FTP UDDS DRIVE CYCLE DURING PART 1

Test Code	HC, g/mi	CO, g/mi	NO_x, g/mi	PM, mg/mi	CO_2, g/mi	MPG	Fuel, kg	Miles
F2537-H1	0.56	2.14	5.04	181	679	15.1	1.62	7.50
F2537-H2	0.57	1.94	5.00	158	677	15.2	1.63	7.55
F2537-H3	0.53	2.05	5.05	148	671	15.3	1.62	7.58
F2537-H4	0.49	2.03	4.94	139	654	15.7	1.57	7.56
F2537-H5	0.50	2.38	4.86	154	654	15.7	1.57	7.53
Average =	**0.53**	**2.11**	**4.98**	**156**	**667**	**15.4**	**1.60**	**7.54**
c.o.v.	7%	8%	2%	10%	2%	2%	2%	0%

TABLE 13. NEC RESULTS FOR TRUCK 4 OVER LD UDDS DRIVE CYCLE DURING PART 1

Test Code	SOC		NEC MJ	Fuel Energy, MJ	NEC %
	Start	End			
F2537-H1	51.5	53.0	0.10	71.3	0.0
F2537-H2	53.0	53.0	0.00	71.5	0.0
F2537-H3	53.0	53.0	0.00	71.2	0.0
F2537-H4	53.0	51.5	-0.10	69.2	0.0
F2537-H5	51.5	53.0	0.10	69.0	0.0

TABLE 14. EMISSION RESULTS FOR TRUCK 4 OVER LD FTP UDDS DRIVE CYCLE DURING PART 2

Test Code	HC, g/mi	CO, g/mi	NO_x, g/mi	PM, mg/mi	CO_2, g/mi	MPG	Fuel, kg	Miles
F2537B-H1	0.42	2.37	4.87	126	632	16.2	1.53	7.60
F2537B-H2	0.41	2.32	4.76	124	634	16.2	1.53	7.58
F2537B-H3	0.41	2.49	4.78	123	627	16.4	1.51	7.57
F2537B-H4	0.41	2.49	4.82	135	635	16.2	1.53	7.55
F2537B-H5	0.40	2.48	5.04	132	634	16.2	1.53	7.60
Average =	**0.41**	**2.43**	**4.86**	**128**	**632**	**16.2**	**1.53**	**7.58**
c.o.v.	2%	3%	2%	4%	0%	0%	1%	0%

TABLE 15. NEC RESULTS FOR TRUCK 4 OVER LD UDDS DRIVE CYCLE DURING PART 2

Test Code	SOC		NEC MJ	Fuel Energy, MJ	NEC %
	Start	End			
F2537B-H1	54.0	52.0	-0.13	67.2	-0.2
F2537B-H2	52.0	54.0	0.13	67.2	0.2
F2537B-H3	57.0	53.0	-0.26	66.5	-0.4
F2537B-H4	53.0	54.0	0.06	67.1	0.1
F2537B-H5	54.0	52.0	-0.13	67.5	-0.2

TABLE 16. EMISSION RESULTS FOR TRUCK 4 WITH HYBRID SYSTEM DISABLED OVER LD FTP UDDS DRIVE CYCLE

Test Code	HC, g/mi	CO, g/mi	NO_x, g/mi	PM, g/mi	CO_2, g/mi	MPG	Fuel, kg	Miles
F2537C-H1	0.42	5.02	5.74	190	704	14.5	1.68	7.45
F2537C-H2	0.40	4.64	5.80	169	698	14.7	1.67	7.50
F2537C-H3	0.40	4.78	5.78	174	691	14.8	1.66	7.50
F2537C-H4	0.40	4.75	5.90	181	698	14.7	1.67	7.47
F2537C-H5	0.40	4.57	5.86	173	693	14.7	1.66	7.48
Average =	**0.40**	**4.75**	**5.81**	**177**	**697**	**14.7**	**1.67**	**7.48**
c.o.v.	2%	4%	1%	5%	1%	1%	1%	0%

3.5 Truck 5 – Test Results

Truck 5, VIN 1FCJE39L46HB04103, was powered by a 2005 5.4L Ford, port injected gasoline engine and was equipped with an automatic transmission. The truck was installed on the chassis dynamometer, as shown in Figure 10 and tested at 9,010 lb. Coastdowns for this truck are shown in Figure 11. The truck was then driven over the drive cycle twice to condition the vehicle for the hot-start testing. The five hot-start tests were conducted with a 20-minute soak in between each test to change emission sample bags and PM filters. The test results for Truck 5 in are summarized in Table 17.

FIGURE 10. TRUCK 5 INSTALLED ON THE HEAVY-DUTY CHASSIS DYNAMOMETER

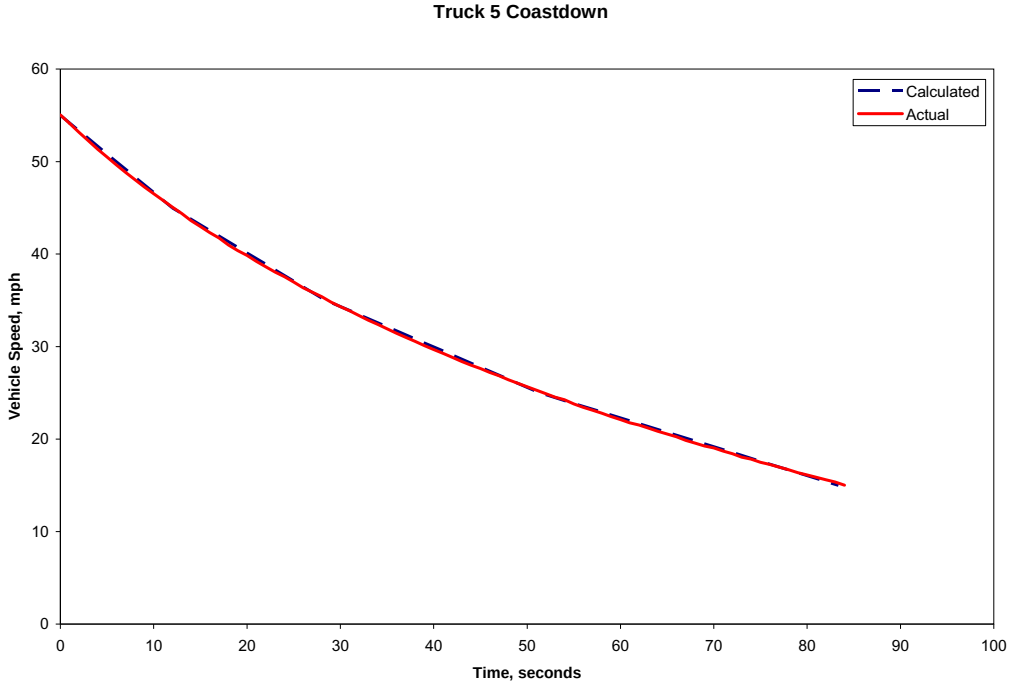

FIGURE 11. TRUCK 5 COASTDOWN RESULTS COMPARED TO CALCULATED COASTDOWN VALUES

TABLE 17. EMISSION RESULTS FOR TRUCK 5 OVER LD FTP UDDS DRIVE CYCLE

Test Code	HC, g/mi	CO, g/mi	NO_x, g/mi	PM, mg/mi	CO_2, g/mi	MPG	Fuel, kg	Miles
F4103-H1	0.00	1.17	0.21	5	804	11.1	1.91	7.52
F4103-H2	0.05	1.35	0.19	4	798	11.2	1.90	7.51
F4103-H3	0.01	1.86	0.17	3	805	11.1	1.91	7.49
F4103-H4	0.03	1.59	0.16	3	802	11.1	1.91	7.52
F4103-H5	0.04	1.47	0.08	3	797	11.2	1.89	7.50
Average =	**0.03**	**1.49**	**0.16**	**4**	**801**	**11.1**	**1.90**	**7.51**
c.o.v.	67%	17%	30%	23%	0%	0%	1%	0%

4.0 SUMMARY

Parts 1 and 2 of this project were successfully completed. For Part 1, four trucks with different engine and drivetrain combinations were tested over at least five runs of the same drive cycle. The emissions and fuel economy results were very different. Table 18 shows the Part 1 average emissions values for each truck. Figure 12 shows the trucks ranked by emission from lowest to highest. For Part 2, six different truck configurations were tested. Trucks 1, 2, and 3 were tested as they were configured during Part 1. Truck 4, a hybrid, was re-calibrated between Parts 1 and 2 and was tested as both a hybrid and a conventional truck. Truck 5 was also added for Part 2. Truck 5 was added to provide a baseline comparison to the gasoline hybrid, Truck 3. Table 19 shows the Part 2 average emissions values for each truck, and Figure 13 shows the trucks ranked by emission from lowest to highest.

TABLE 18. PART 1 AVERAGE EMISSION RESULTS FOR EACH TRUCK OVER LD FTP UDDS DRIVE CYCLE

Truck	HC, g/mi	CO, g/mi	NO_x, g/mi	PM, mg/mi	CO_2, g/mi	MPG	Fuel, kg	Miles
1	0.14	2.30	6.21	75	705	14.6	1.69	7.56
2	0.31	1.47	3.46	152	842	12.2	2.02	7.56
3	0.15	2.51	0.26	7	741	12.0	1.78	7.58
4	0.53	2.11	4.98	156	667	15.4	1.60	7.54

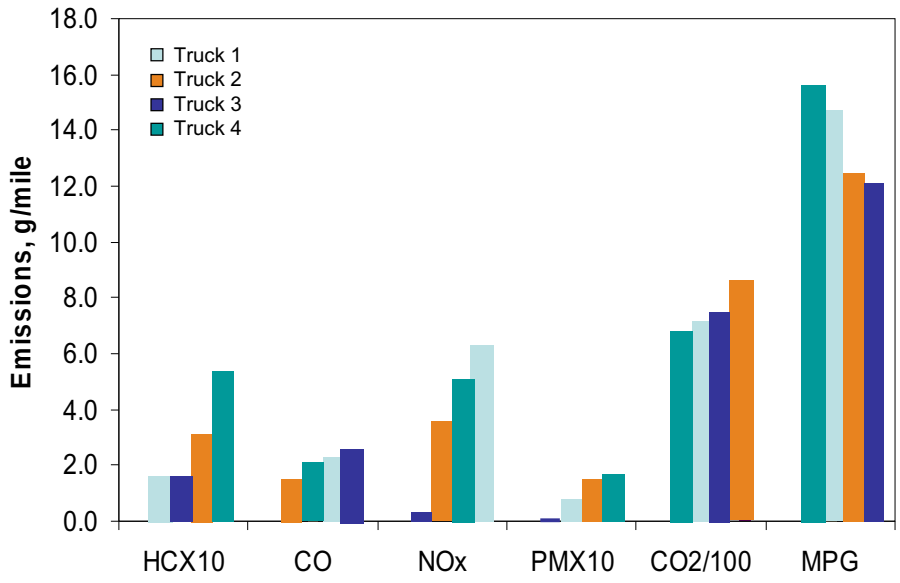

FIGURE 12. PART 1 RANKING OF TRUCKS BY EMISSION LEVEL

TABLE 19. PART 2 AVERAGE EMISSION RESULTS FOR EACH TRUCK OVER LD FTP UDDS DRIVE CYCLE

Truck	HC, g/mi	CO, g/mi	NO_x, g/mi	PM, mg/mi	CO_2, g/mi	MPG	Fuel, kg	Miles
1B	0.12	2.25	6.15	84	724	14.2	1.73	7.54
2B	0.34	1.65	3.52	137	835	12.3	2.01	7.60
3B	0.16	2.89	0.37	8	748	11.9	1.80	7.55
4B	0.41	2.43	4.86	128	632	16.2	1.53	7.58
4C	0.40	4.75	5.81	177	697	14.7	1.67	7.48
5	0.03	1.49	0.16	4	801	11.1	1.90	7.51

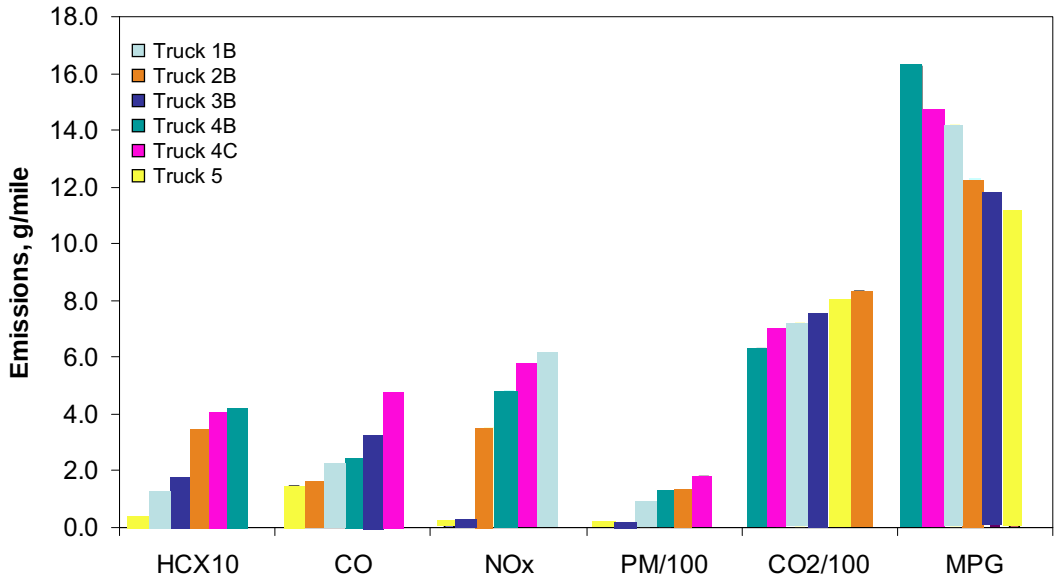

FIGURE 13. PART 2 RANKING OF TRUCKS BY EMISSION LEVEL

The trucks were tested before and after field evaluations to demonstrate each truck's durability. The emissions and fuel economy differences between Part 1 and Part 2 were insignificant. Truck 4 received software modifications to the hybrid system and engine control system, which explains its improved performance. Therefore the discussion of each truck will be limited to its performance in Part 2.

All of the trucks produced low HC and CO emissions, which are typically not issues for diesel engines and gasoline engines with catalyst systems. The gasoline trucks were equipped with three-way catalyst systems; and therefore, produced very low NOx emissions. However, the gasoline trucks also produced the worst fuel economy. The diesel trucks produced the highest NOx emissions and best fuel economy. Of the diesel trucks, Truck 1 produced the most NOx, followed by Truck 4, Truck 4C (Truck 4 with the hybrid system disabled), and Truck 2.

The gasoline engines also produced almost no PM, which is typical of gasoline engine operation, even without aftertreatment. Of the diesels, Truck 4C produced the most PM, followed by Truck 2, Truck 4, and Truck 1.

The hybrid systems improved fuel economy between 7 and 10 percent compared to similar configurations. The NOx emissions of the diesel hybrid was nearly 1 g/mile less, a 16 percent reduction, compare to the diesel baseline. The gasoline hybrid produced 0.21 g/mile more NOx, a two fold increase than the gasoline baseline.

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