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DRAFT FOR REVIEW

Emissions Implications of Plug-In Electric Vehicles

Prepared by the Texas A&M Transportation Institute
Prepared for the Texas Department of Transportation
August 2013

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By

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: INTRODUCTION

Mobile-source emissions from conventional gasoline and diesel powered motor vehicles are a major contributor to emissions of criteria pollutants (or their precursors) and greenhouse gases (GHG). In nonattainment and near nonattainment areas, the State Implementation Plan (SIP) and conformity requirements may necessitate reduction in criteria pollutant emissions and their precursors that are generated by conventionally powered vehicles. Plug-in electric vehicles (PEVs), which encompass both plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs), are widely thought to generate significantly less emissions, but the quantification of the magnitude of differences is uncertain.

The objective of this task is to provide the Texas Department of Transportation (TxDOT) with a better understanding of the emissions and performance of commercially available plug-in electric vehicles (PEVs), specifically plug-in hybrid electric vehicles (PHEVs), and the implications that increased market share of these vehicles can have on overall mobile-source emissions in Texas. This task memorandum is an updated version of the Task 2.7 Technical Memorandum prepared in FY2012. The work performed in FY2013 was undertaken to demonstrate the differences in emissions between PEVs and conventional vehicles by performing emissions measurement (for commercially available PHEVs) and comparing with conventional vehicles on the basis of the Environmental Protection Agency (EPA's) MOtor Vehicle Emission Simulator (MOVES) emissions rates.

Overview of PEVs and Emissions

As mentioned previously, the two main types of PEVs are PHEVs and BEVs. Several models of these vehicles are currently available in the US market, from many popular car manufacturers. In terms of vehicle characteristics, the main difference between a PHEV and a BEV is that PHEVs are powered by a rechargeable battery pack as well as an internal combustion engine (that generally operates once the battery is depleted), while a BEV is solely powered by a rechargeable battery pack (i.e. an all-electric vehicle). In both cases, the battery recharging occurs by plugging the vehicle in to electric vehicle supply equipment (EVSE). BEVs must be charged regularly in order to operate the vehicle, and charging PHEVs regularly will minimize the amount of gasoline or diesel they consume[1].

The emissions associated with PEVs' operations therefore consist of direct tailpipe emissions (for PHEVs) and indirect emissions associated with the electricity generation/consumption due to recharging their batteries (for both PHEVs and BEVs). Many studies have sought to determine if PEVs can reduce emissions compared to conventional vehicles, and the extent of the emissions reduction that can be achieved.

[1] DOE EERE. (2012) Plug-In Electric Vehicle Handbook – for Fleet Managers. 2011.DOE/GO-102012-3273.

From an overall emissions standpoint, the results seen in the literature are mixed and the results depended on various factors, including the sources of energy for electricity generation in the area where the vehicle is being charged[2]. Considering market penetration as well as the electricity generation mix, a report from the Electric Power Research Institute (EPRI) and Natural Resource Defense Council (NRDC) concluded that a PHEV would reduce GHG emissions by 40-65% or more compared to a conventional vehicle and 7-46% or more compared to a HEV in 2050 depending on PHEV battery capacity and electricity generation mix for recharging and if a large number of PHEVs enter the vehicle fleet from 2010 to 2050.[3] However, regarding to battery and generation mix, Thomas reported that BEVs with 300-mile range would have higher GHG emissions compared with even conventional vehicles if electricity generation is based on the current coal technology.[4]

Comparing Emissions of PEVs and Conventional Vehicles

BEVs are solely powered by electrical energy stored in a battery pack using an electric motor. Their operation is therefore only in Charge Depleting (CD) mode, where battery power is consumed. Because BEVs themselves do not produce tailpipe exhaust or emissions, EPA considers BEVs as zero-emission vehicles (ZEVs), and their contribution to mobile source emissions estimates would be zero.

The focus of this report is therefore more on PHEVs, where reasonable comparisons can be made between emissions of PHEVs operating in Charge Sustaining (CS) mode, i.e. with the internal combustion engine (ICE) running once the battery is depleted and conventional vehicles that also operate on ICEs. Comparisons can also be made for PHEVs' CS and CD mode operations.

A fully charged PHEV is first operated in the CD mode drawing the propulsion energy from the battery pack. Once the battery reaches its minimum state of charge (SOC), the vehicle switches to the CS mode, which is functionally equivalent to conventional operations of a hybrid electric vehicle. During this mode, the vehicle maintains the SOC within a limited operating envelope, using the ICE and restored battery energy by capturing regenerative braking energy to optimize the ICE operations. Depending on PHEV design some PHEVs are assisted by their ICEs even during the CD mode. More details of different types of CD/CS mode operations and ICE operations are reported in previous TTI reports and in the literature.[5]

In the case of a PHEV battery, the larger the battery, the greater the fraction of the energy usage can come from the battery. However, larger batteries weigh more and can be not efficient for

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[2] Passier, G., F.V. Conte, S. Smets, F. Badin, A. Brouwer, M. Alaküla, D. Santini, and M. Alexander (2007) *Status Overview of Hybrid and Electric Vehicle Technology*, MON-RPT-033-DTS-2007-02955, International Energy Agency.

[3] EPRI and NRDC (2007) *Environmental Assessment of Plug-In Hybrid Electric Vehicles, Volume I: Nationwide Greenhouse Gas Emissions*, EPRI Report # 1015325.

[4] Thomas, C. E. (2009) Cost-Benefit Analyses of Alternative Light-Duty Transportation Options for the 21st Century. *National Hydrogen Association Conference*, Columbia, SC, March 31.

[5] Elgowainy, A., J. Han, L. Poch, M. Wang, A. Vyas, M. Mahalik, and A. Rousseau (2010) Well-to-Wheels Energy Use and Greenhouse Gas Emissions Analysis of Plug-In Hybrid Electric Vehicles. ANL/ESD/10-1

short trips. Rousseau conducted a study on using real-world data to analyze PHEV battery requirements.[6] The study concluded that 12 kWh of energy would allow 50 percent of all drivers to complete their daily trips fully within the CD mode (i.e only using electric power). Battery size is often expressed as all-electric range (AER), the distance that could be traveled on just the battery if the car is operated in CD mode without using the engine.[7] For example, the term PHEV-10 and PHEV-40 refers to their AERs of 10 miles and 40 miles, respectively.

Estimating Emissions Associated with Battery Recharging

While not considered to be mobile source emissions, the electricity used to recharge PEV batteries are associated with emissions that need to be taken into consideration for a realistic picture of the emissions impact of these vehicles. When electricity supplied through the power grid is generated from power plants, the associated grid emissions vary depending on the resource mix used for electricity generation. The associated emissions data are currently available from EPA's Emissions and Generation Resource Integrated Database (eGRID). The eGRID is a comprehensive source of data on the environmental characteristics of almost all electric power generated in the United States.[8] Regional information (zip code) and electric distribution utility company information can be input by users through EPA's interactive website[9], the EPA's Power Profiler tool calculates the average emissions rates (lbs/MWh) in the geographical region for oxides of nitrogen (NOx), sulfur dioxide (SO_2), and Carbon Dixoide (CO_2) and provides the user with emissions information along with information of fuel mix (%) of sources ((non-hydro renewables, hydro, nuclear, oil, gas, and coal) used to generate electricity in the selected region. This tool was used in this report to estimate emissions associated with electricity generation.

MOVES Bin Approach to Compare CD and CS Modes

MOVES is the EPA's current mobile source emissions estimation model and provides tailpipe emissions rates for conventional vehicles. MOVES was used as the basis for the comparisons of emissions of PHEVs in CS and CD modes, as well as comparison with conventional vehicle emissions, as discussed later in the report. Although MOVES does not provide emissions rates for HEVs or PEVs yet, MOVES provides for the flexibility to accurately incorporate driving characteristics into emissions. Because the MOVES-based approach can provide instantaneous battery energy usage with respect to instantaneous CD mode driving characteristics, TTI used the MOVES-based rates to obtain battery energy usage rates more accurately. MOVES-based rates

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[6] Rousseau, A. (2008) PHEV Battery Requirements: Uncertainty Based on Real World Drive Cycles and Impact on Fuel Efficiency (ALBAA 2008)

[7] U.S. Department of Energy, http://www.eere.energy.gov , last accessed August 2013.

[8] EPA. Clean Energy: eGRID, http://www.epa.gov/cleanenergy/energy-resources/egrid/index.html, last accessed in August 2012.

[9] EPA. Clean Energy: How Clean is the Electricity I use? – Power Profiler. http://www.epa.gov/cleanenergy/energy-and-you/how-clean.html, last accessed in August 2012.

can be also used to compare emissions of different types of vehicles based on predetermined schedules for official vehicle fuel economy and emissions testing for certification.

For the MOVES-based battery usage rates using driving characteristics data, the fine-scale disaggregate driving characteristic measure, vehicle specific power (VSP), will be identified. The VSP is a combined measure of instantaneous speed, acceleration, road grade, and road load. MOVES operating mode bins are then determined from VSP and instantaneous speeds. While the driving characteristics data are collected, battery usage rate data (in battery SOC) were also collected and incorporated into corresponding operating bins to get the MOVES-based instantaneous battery usage rates. In real world traffic conditions, a PEV operating over a test trip spends different times in different bins, depending on the operation. Using the MOVES-based rates associated with the driving characteristics bin data, emissions related to the recharging of batteries can be estimated for the trip in real traffic conditions or any predetermined drive schedules such as the Urban Dynamometer Drive Schedule (UDDS), US06, SC03, and highway fuel economy test (HWFET) schedules typically used for emissions and fuel economy verification.

This Report

The following chapters of this report describe the emissions testing conducted by TTI on two PHEVs and the results obtained, including the estimation of emissions associated with electricity consumption and comparisons using the MOVES bin approach outlined in this introductory chapter. These results include both direct emissions measured from the tailpipe as well as energy use translated to emissions attributable to the power generation required for battery recharging. As commercially-available electrified vehicles become more mainstream in Texas and the United States, the implications with regard to mobile source emissions become of great relevance. A summary of findings with regard to this issue are discussed in the final chapter.

CHAPTER 2: PHEV EMISSIONS TESTING

The main focus of this report is on the emissions testing conducted on two commercially-available PHEVs (Chevy Volts). The in-use real world testing was conducted while vehicles operated in real traffic conditions in a predetermined route around the Bryan/College Station area. The test route was created to ensure that both highway and city driving were included. Additionally, battery charging/depletion testing and cold start and idling testing was conducted inside the temperature controlled chamber at TTI's Environmental and Emissions Research Facility (EERF) located at Texas A&M University's Riverside Campus in Bryan, TX. The testing equipment included portable emissions measurement systems (PEMS), GPS units, as well as on-board diagnostics (OBD) data loggers. These instruments were used to collect tailpipe emissions data, driving characteristics data, and battery energy usage data, respectively. All the equipment and facilities used for the testing are summarized in Appendix A.

Testing Protocol

The protocol developed as part of this project was done to ensure that all potential operations were covered during the testing phase of the project. The protocol focused on three types of operations: driving, idling, and battery depletion/charging. Each operation had its own protocol that was followed during each test. This section describes the protocol that was followed for each type of operation.

Driving Protocol

The driving protocol was developed in order to ensure that the test vehicles were put through a test route that would replicate different types of driving, including both city and highway modes. As described in the previous chapter the MOVES bin approach was used for the driving comparison of emissions from the vehicles. The test route used was constructed in order to ensure that the vehicle was operated in the proper MOVES operation bins to have a valid comparison with the different drive cycles used. The test route started at the EERF facility and then headed to College Station via U.S. Highway 47. From there the test route passed through the center of the city and then back to the EERF. Figure 1 below outlines the test route that was followed for each test. The total distance for each test was approximately 31 miles.

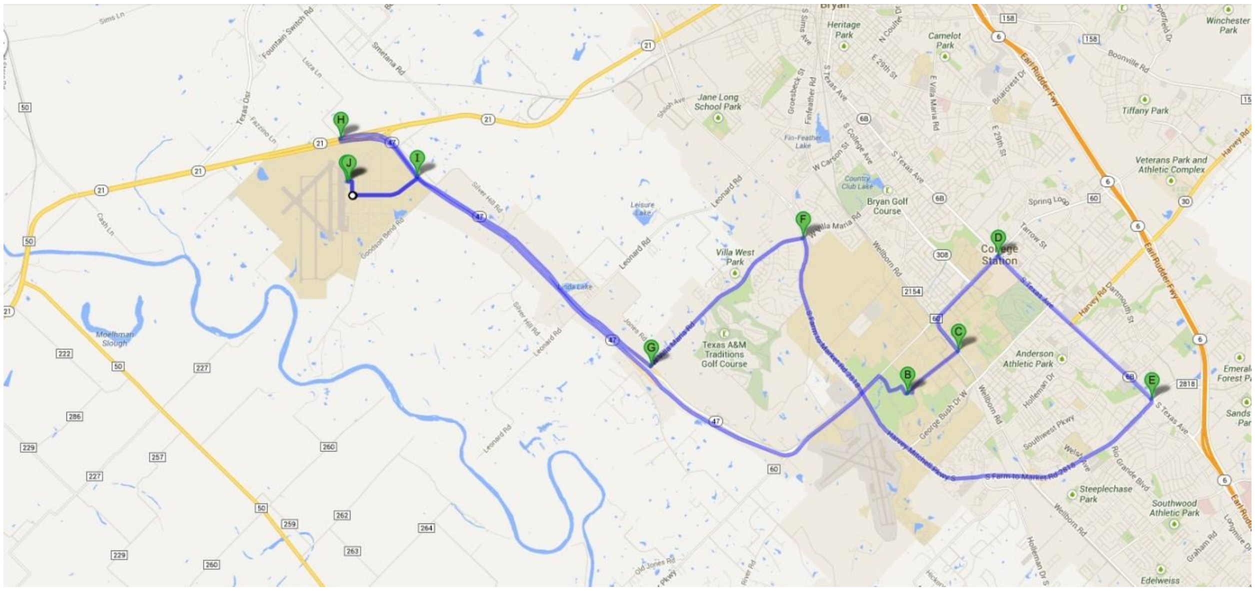

Figure 1: Test Route

Each vehicle travelled the test route multiple times each day. The first test of the day was done with the vehicle completely charged, and therefore operated in the CD mode. The second test of the day would begin with the vehicle in the CD mode, but during the second run the battery would deplete to a point where the vehicle would switch to the CS mode. The remaining runs for the day would be done in the CS mode, before the unit was charged again overnight in preparation for testing the following day. Each test was done with the A/C on and set to a temperature of 72°.

During this testing the battery energy usage data along with PHEV's driving characteristics data (speed profiles) were collected while the test PHEVs were being driven on the specified route. The collected data then allowed for the researchers to obtain specific battery energy usage during the CD mode operations of the test vehicle. The battery energy usage data, along with the CD mode driving characteristic data, was then used to estimate emissions from power generation associated with the CD mode operation of the vehicle. The total estimated emissions were then combined with tailpipe emissions to obtain the total emissions for PHEV operations (for both of CD and CS modes).

Battery Charge/Depletion Testing

The battery charge/depletion testing was conducted inside the EERF under the three different controlled test conditions shown in Table 1. At each test condition, the PHEV battery was charged by being plugged into an electrical (120V) outlet inside the chamber. While being charged, SOC of the PHEV battery was monitored and recorded.

Table 1: Idle and Battery Depletion Testing Conditions.

Condition	Chamber Temperature Settings	Chamber Relative Humidity Settings
1	95° F	70%
2	72° F	70%
3	23° F	N/A

In order to test the charging/depletion testing the vehicles were began with either a totally charged battery (for depletion testing) or totally depleted battery (for charging testing). During the testing the battery SOC was continuously monitored and recorded using the OBD data logger.

The testing would generally begin with a fully depleted battery. The test vehicle would be moved into the EERF facility, which was conditioned to one of the settings shown in Table 1 and the vehicle would be plugged in to the power outlet. At this point the data logger would begin monitoring the SOC of the batteries. This would continue until the vehicle was fully charged. Due to the amount of time it takes to fully charge the vehicles, these tests would generally start towards the end of a test day and continue overnight.

Once the charging was completed the depletion testing would begin. The depletion testing would begin by starting the vehicle. When the vehicle was turned on the A/C or heat would be turned on as well, depending on the test condition that was being tested. During the depletion portion of the testing, the A/C or heat would be adjusted between Max/Min and Off approximately every 30 minutes. This was done to see how the A/C or heat settings would affect the depletion rate of the batteries. The depletion testing continued until the SOC reached a level where the engine would kick in. Once the engine kicked in, the idle testing would begin.

Idle Testing (Cold Start and Idling Emissions)

The purpose of this testing was to examine the cold start and idling emissions of PHEVs in cases where PHEV batteries were completely depleted prior to startup. The idle testing was done in conjunction with the battery testing, and was done under the conditions shown in Table 1. The idle testing began as soon as the battery depletion testing was complete. Each vehicle was equipped with the PEMS equipment while they were subjected to the battery depletion testing. As the battery for the vehicle became completely depleted, the engine would kick in. After the engine would turn on the battery would be recharged, and the engine would then shut off until the battery was again fully depleted. This process was repeated a minimum of seven times for each condition under which the vehicle was tested. The battery SOC was also measured during both the depletion and idling portion of the test period. Figure 2 shows one of the vehicles prepared for testing.

Figure 2: Test Vehicles in Chamber for Battery and Idling Testing.

Test Vehicles

As mentioned previously, two Chevy Volts were tested under the described protocols. The first vehicle was a 2012 Volt owned and operated by Texas A&M University Transportation Services and the other Volt was a privately owned 2011 model. Each Volt has a 1.4L engine with a maximum output of 84 HP and a battery capacity of 16kWh.

Unlike other conventional hybrid vehicles, the Volt is powered by the electric motors at all times. The ICE in the Volt acts as a generator to recharge the batteries once they are depleted. Similar to a conventional hybrid, like the Toyota Prius, the engine also does help to propel the vehicle after the battery is depleted in order to improve the overall efficiency[10].

[10] Chevy Volt FAQs, http://gm-volt.com/chevy-volt-faqs/

CHAPTER 3: RESULTS

This chapter details the results of the testing following the protocol previously described. The results are shown based on the data collected during the testing, and then compared to a conventional vehicle using MOVES emission rates.

Battery Charging and Depletion Results

The battery recharging results are shown below in Table 2. The SOC % below is based on the readings from the data logger that was connected to the OBDII port during the testing. It should be noted that the actual percentages do not go from 0-100%. The numbers that are reported to the data logger from the vehicle range from 20% up to 86.6%, and can vary slightly from between vehicles and tests. The numbers below represent the fully depleted (starting) to the fully charged (ending) numbers reported by the vehicle.

Table 2: Battery Charging Results

	Test Condition		Recharging Duration (hours)	SOC (%)			Recharging Rate (SOC(%)/hour)
	T(°F)	Relative Humidity (%)		Starting	Ending	Recharged	
Volt #1	23	N/A*	10.4	20.0	85.7	65.7	6.34
	72	70	11.2	19.8	85.7	65.9	5.88
	95	70	11.3	19.8	85.7	65.9	5.86
Volt #2	23	N/A*	8.7	23.2	86.7	63.4	7.33
	72	70	8.1	26.7	86.6	59.9	7.35
	95	70	10.9	18.3	86.6	68.3	6.28

* N/A: Not Applicable – relative humidity control at low temperatures is not meaningful because water contents in the air at this temperature are very low.

As seen in the table both vehicles charged quicker under the hot testing condition. The other conditions varied, but in general Volt #2 charged quicker than Volt #1. This could be due to the difference in model year, age of battery, or the way that the vehicle is normally operated and maintained.

The battery depletion testing results are shown in Table 3. For all battery depletion testing the temperature on the thermostat was set to 72°F while the fan setting was adjusted between Min, Max, and Off. This allows for the depletion rate for each idling condition to be monitored. The results show similar depletion rates for most scenarios, except for the cold testing when the AC was on. Just as with the charging results Volt #2 was depleted quicker than Volt #1 for this test scenario.

Table 3: Battery Depletion Results

	Depletion Rate by Ambient Temperature and AC Fan Speed (SOC(%)/h)								
	Cold Test (23°F)			Room T Test (72°F & 70% RH)			Hot Test (95°F & 70% RH)		
	Max	Min	Off	Max	Min	Off	Max	Min	Off
Volt #1	25.6	11.5	3.0	11.0	3.7	2.8	13.5	6.2	2.85
Volt #2	32.5	18.1	4.3	10.4	3.8	3.1	13.8	8.45	3.1

Table 4 and

Table 5 below show the summary of the idle testing results for both vehicles tested. Each table shows emissions and fuel rates for both cold start and normal idle operations. As previously discussed the Volt engine kicks in when the battery reaches its fully depleted state. The first time this happens is considered the cold start. The engine then runs until the battery reaches a certain SOC, when it turns off. The amount of time the engine operates is shown as the "duration" in the table; the amount of time between when the engine turned off and turned back on is reported as the "interval". Each vehicle was tested under each condition a total of 7 times, with the first being the cold start. The total time of engine operation for each vehicle then allowed for the emissions rates to be calculated on a per hour basis in order to compare the results to conventional vehicles.

Table 4: Volt #1 Idle Testing Results

		Time		Fuel (gal)	Emissions (g)			
		Duration	Interval		CO2	CO	NOx	HC
Cold	**Cold Start**	0:02:31	-	0.035	319	0.3435	0.0078	0.1413
	AVG (all but cold start)	0:01:40	0:08:33	0.029	270	0.1452	0.0002	0.0034
	Coefficient of Variation (COV) (%)	4.7%	21.3%	5.9%	5.9%	21.4%	244.9%	61.6%
Room T	**Cold Start**	0:02:14	-	0.042	374	1.996	0.0541	0.8789
	AVG (all but cold start)	0:01:53	0:05:29	0.037	338	0.2573	0.0045	0.0036
	COV (%)	1.6%	2.5%	1.0%	1.0%	20.1%	77.0%	87.2%
Hot	**Cold Start**	0:02:04	-	0.037	329	1.495	0.0442	0.2398
	AVG (all but cold start)	0:01:48	0:06:59	0.035	318	0.1636	0.0027	0.0022
	COV (%)	0.8%	1.9%	0.9%	0.9%	41.3%	149.9%	127.2%

Table 5: Volt #2 Idle Testing Results

		Time		Fuel (gal)	Emissions (g)			
		Duration	Interval		CO2	CO	NOx	HC
Cold	Cold Start	0:01:31	-	0.023	212	0.4171	0.0401	0.1797
	AVG (all but cold start)	0:01:29	0:06:43	0.026	240	0.2502	0.0082	0.0111
	COV (%)	1.9%	8.0%	1.9%	1.8%	38.5%	136.8%	61.7%
Room T	Cold Start	0:02:04	-	0.036	328	1.0368	0.1070	0.6413
	AVG (all but cold start)	0:01:39	0:06:03	0.031	279	0.2684	0.0031	0.0045
	COV (%)	0.8%	2.8%	0.5%	0.5%	53.3%	89.8%	145.3%
Hot	Cold Start	0:01:57	-	0.034	301	2.1288	0.0668	0.3033
	AVG (all but cold start)	0:01:47	0:05:28	0.035	312	0.2160	0.0009	0.0050
	COV (%)	6.7%	23.7%	8.5%	8.6%	30.9%	82.9%	105.9%

In general both vehicles had longer engine operation times, higher fuel consumption, and higher emissions during the cold start, as expected. The only outliers from this were the fuel and CO_2 for the cold and hot tests on Volt #2. The cold test for Volt #2 was also the only one that did not show at least a 10 second difference in the duration between the cold start and the average of all other duration. One possible reason for this is the engine for Volt #2 ran for a short amount of time during the depletion testing, which occurred prior to the idling testing. This short time the engine was on could have warmed it up enough to eliminate the later cold start, therefore the shorter duration and fuel consumption in that period.

Driving Testing

The driving results are broken down into two categories: CD mode testing and CS mode testing. During the CD mode the main focus of data collection focused on the SOC of the battery as it operated the vehicle. After completing all the driving portions of the testing the driving was broken down into MOVES bins, and the change in the SOC for each bin was then calculated based on the data points collected during driving. During the CS mode testing, TTI staff used the PEMS equipment to measure the emissions of the test vehicle as it drove along the test route. As with the CD mode testing, the data was collected during the driving and then broken into MOVES bins. This gave an emissions rate for each pollutant for each MOVES bin.

Table 6 below shows the average emissions and battery depletion results for both Chevy Volts based on MOVES bins. Detailed tables that show each Volt's results can be found in Appendix B.

Table 6: Emissions and Battery Depletion Rates for Chevy Volts

Opmode Bin #	CS Mode Rates				CD Mode
	CO_2 (g/s)	CO (g/s)	NO_x (g/s)	HC (g/s)	Δ SOC (%)
0	1.003026	0.025341	0.000115	0.000416	-0.0003
1	0.00628	0	0.00000167	0.00000174	0.0000199
11	0.779045	0.001842	0.00006562	0.0002288	0.000053
12	0.409049	0.001235	0.00008464	0.0003175	0.0000991
13	0.54289	0.001144	0.00008199	0.0003075	0.000272
14	0.57421	0.00151	0.00009384	0.0001634	0.000393
15	0.748674	0.002917	0.00008476	0.00007523	0.00051
16	1.494205	0.009	0.0001877	0.0002191	0.000915
21	3.711664	0.064985	0.0002890	0.0002274	-0.00012
22	4.229821	0.051471	0.0002663	0.0001417	0.0000856
23	4.464845	0.056826	0.0002461	0.0001577	0.000185
24	4.21438	0.053192	0.0002661	0.0001715	0.000289
25	4.178405	0.024003	0.000209	0.0004114	0.000462
27	3.980347	0.0323	0.0002868	0.0001766	0.00061
28	5.366564	0.03885	0.0005041	0.0003804	0.000983
29	5.186794	0.155553	0.000989	0.0008471	0.001334
30	7.141627	0.130668	0.0008232	0.0003365	0.001816
33	5.21666	0.189894	0.0002688	0.0003960	0.0000695
35	6.456352	0.173687	0.00036	0.0005774	0.000379
37	7.398575	0.301738	0.0005215	0.001376	0.000551
38	7.88436	0.045172	0.0004352	0.00140	0.000779
39	7.769111	0.645222	0.000349	0.000987	0.001186
40	8.973	1.0105	0.00031	0.001311	0.001892

Comparison to Conventional Vehicles

In order to get the full picture of the effects of PEV, their emissions rates must be compared to the emissions rates of conventional vehicles. In order to do that TTI staff compared the total emissions of the PEV, in both the CS and CD mode, to the total emissions of a conventional vehicle over different drive cycles. TTI used a total of four drive cycles in order to give a perspective of the different driving modes that each drive cycle represents. The drive cycles used are described below and graphs of each are included in Appendix C. A table showing the MOVES bin breakdown of each drive cycle is also included in the appendix.

- Urban Dynamometer Driving Schedule (UDDS) - The UDDS drive cycle, also referred to as the city test, represents the driving conditions seen in a city environment. The drive cycle covers a total of 7.45 miles and has an average speed of almost 20 mph.
- US06 - The US06 drive cycle represents an aggressive drive cycle, including high acceleration rates. The total distance is 8.01 miles and averages 48.37 mph.
- Highway Fuel Economy Driving Schedule (HWFET) - The HWFET drive schedule simulates highway driving, at speeds under 60 mph. The total distance for the cycle is 10.26 miles at an average speed of 48.3 mph.
- Federal Test Procedure (FTP) - The FTP drive cycle includes a portion of the UDDS drive cycle, followed by an additional transient phase, and then another portion of the UDDS cycle. This drive cycle is used by the state of California to determine the emissions standards of vehicles.[11] The drive cycle covers 11.04 total miles at an average speed of 21.2 mph.

Emissions Comparison

In order to compare the emissions between the PHEV and conventional vehicle the total emissions for each drive cycle emissions for each drive cycle were calculated for each pollutant. The results obtained are shown in

Table 7. The CD mode and CS mode results represent emissions for the entire drive cycle when the vehicle operates in that mode only.

The rates for the CD and CS modes are the average taken from both PEV units tested. The rates for the CD mode were calculated using the EPA Power Profiler described in Chapter 1. The energy source used in the calculations was the City of College Station. It should be noted that these emissions are associated with electricity consumption and technically do not fit into the mobile source emissions category. Due to the limitations of the Power Profiler the CO and HC rates are not available for CD mode driving. The rates for the CS mode represent the ICE engine emissions during operation of the test PHEVs. The MOVES estimates for a conventional vehicle (CV) represent a combined average of a 2011 and 2012 passenger vehicle, which was considered as the conventional vehicle for comparison purposes.

[11] http://www.dieselnet.com/standards/us/ld_ca.php

Table 7: Total Emissions Based on Drive Cycles

		UDDS	US06	HWFET	FTP
CD Mode (Operating on Battery)	**CO_2 (kg)**	1.3	2.325	1.965	1.955
	CO (g)	NA			
	NOx (g)	0.79	1.41	1.23	1.185
	HC (g)	NA			
CS Mode (Operating on ICE)	**CO_2 (kg)**	2.71	3.055	3.925	4.11
	CO (g)	42.95	124.15	88.9	69.95
	NOx (g)	0.205	0.20	0.235	0.3
	HC (g)	0.30	0.425	0.31	0.425
Conventional Vehicle (MOVES estimates)	**CO_2 (kg)**	3.352	3.047	3.062	4.759
	CO (g)	6.07	15.79	5.76	8.79
	NOx (g)	0.257	0.572	0.224	0.402
	HC (g)	0.042	0.108	0.035	0.0624

Table 8 shows the results of the CD mode emissions (electricity-based emissions for PHEV when operating on battery only) and CS mode emissions (when the PHEV operates using the ICE) expressed as a ratio of conventional vehicle emissions for the same drive cycle. As seen from the results, emissions associated with PHEV operation vary in relation to conventional vehicle emissions depending on operating mode, drive cycle, and pollutant type.

Table 8: Comparison on PEV Driving to Conventional Vehicle MOVES Estimates

		UDDS	US06	HWFET	FTP
CD Mode	**CO_2 (kg)**	38.78%	76.30%	64.17%	41.08%
	NOx (g)	307.39%	246.50%	549.11%	294.77%
CS Mode	**CO_2 (kg)**	80.85%	100.26%	128.18%	86.36%
	CO (g)	707.58%	786.26%	1543.40%	795.79%
	NOx (g)	79.77%	34.97%	104.91%	74.63%

	HC (g)	714.29%	393.52%	885.71%	681.09%

The CD mode rates are less than the conventional vehicle for CO_2 in each drive cycle. The CD mode driving accounts for anywhere from 38.78% to 76.3% of the emissions that a conventional vehicle would account for over the same drive cycle. The savings during the CS driving are much different, showing savings of 80.85% and 86.36% for the UDDS and FTP drive cycles, while emitting slightly more CO_2 for the US06 and HWFET drive cycles. As noted previously the US06 and HWFET drive cycles have much higher average speeds, therefore it seems as though the PHEVs tested performed much better on the lower MOVES bins than in the higher bins for CO. The MOVES rates for each bin are included in Appendix B.

The results for NO_x are much different than the CO_2 results. NO_x emissions for the PHEV operating in the CD mode were between 246.5% and 549.11% higher than shown in the MOVES estimates for conventional vehicles. During the CS mode driving, NO_x did show some savings on all but the HWFET drive cycle, which was almost equal to the MOVES rates.

Both CO and HC, which do not have rates for the CD mode, showed much higher emission rates when operating in the CS mode than MOVES estimated. The emissions rates where anywhere from 393% to 1543% higher than for equivalent operation of a conventional vehicle.

Concluding Remarks

The key findings from this set of testing demonstrates that: a) while mobile source emissions for CD mode operation of PHEVs is zero, the emissions associated with electricity consumption for battery charging are fairly significant, and as seen in the case of NOx emissions in the results, may even exceed the tailpipe emissions of conventional vehicles; b) in the case of CS mode operation (where the PHEVs engine is in operation), emissions again sometimes exceed emissions of a comparable conventional vehicle.

Based on these findings, it is seen that in order to determine the total impact of these vehicles on the overall air quality, the driving patterns and charging habits of the vehicle operators must be determined as a critical input. For an owner travelling short distances each day, and fully charging their vehicle each night, they might operate their vehicle 100% in the CD mode. Other vehicles might travel longer distances and reach higher speeds each day, and not be fully charged as often, therefore they may operate in the CS mode more frequently. These characteristics, which will vary widely from driver to driver, can have a huge effect on the overall emissions impact due to proliferation of PHEVs.

CHAPTER 4: CONCLUSIONS

This report summarized the findings from a study to evaluate emissions benefits of plug-in electric vehicles, and to discuss potential impacts on mobile source emissions, air quality and conformity. The findings of this report, based on in-use testing of PHEVs offer a mixed review of the possible implications for policy makers when looking at the increasing market share of PEVs. As mentioned previously, the key findings from the testing conducted were as follows:

- Even PHEVs operating on battery power alone (CD mode) result in emissions associated with electricity consumption for battery charging. These emissions are found to even exceed the tailpipe emissions of conventional vehicles for certain pollutants and drive cycles.
- When PHEVs operate on their ICE (in the case of CS mode operation), pollutant emissions are also found to be comparable to, and even exceed emissions of a conventional vehicle.

The overall impacts of PEVs, including PHEVs on emissions also depend on the driving habits and recharging practices of the vehicle operator. Data collected during this study show significant potential reduction of CO_2 as PEVs become more widely used. These savings are greatest at lower speeds, such as city driving, and operating in the CD mode. The combination of lower CO_2 rates from the recharging of PEVs with the lower use of battery capacity at these conditions lead to a higher savings potential. Other pollutants, such as NO_x, could potentially see an increase in overall emissions compared to that of a conventional vehicle (especially when considering emissions associated with electricity generation). While the emissions coming from the tailpipe of the vehicle during the CD mode are zero, the reduction in tailpipe emissions are offset by the emissions coming from the power plant needed to recharge the batteries.

The results seen for CO and HC also show a potential increase in emissions, even from the operation of a PHEV's internal combustion engine. The results from the vehicles tested in this study show very high rates of both CO and HC when compared to a conventional vehicle. The overall impact for these pollutants, as with the others, is dependent on the driver behavior. If the vehicle operates solely in the CD mode then a PEV could lower the overall emissions impact, however, if the vehicle operates more in the CS mode the emission could be much higher than having a conventional vehicle.

While this report does give an insight on how PEVs will affect air quality and conformity of an area, more data (including operational and charging data) is needed for different types of PEVs to determine the overall effect. This will continue to evolve as new and different types of PEVs become a bigger part of the overall fleet of operating vehicles and charging infrastructure becomes more widely available.

APPENDIX A

Test Equipment/Test Location

TTI Environmental and Emissions Research Facility

The EERF includes an environmentally controlled test chamber with dimensions of 75' long × 23' wide × 22' high, in which both of the test vehicles were placed for the battery and idling testing. The chamber can control both temperature and humidity and has a solar lighting array to simulate solar loading and fans to simulate wind chill effects. The chamber can control temperatures from -40°C to 55°C. Figure I shows a picture of the test chamber.

Figure I: TTI's EERF Test Chamber.

SEMTECH-DS

The SEMTECH-DS is a PEMS unit, which complies with the U.S. Environmental Protection Agency's (EPA) Code of Federal Regulations (CFR) Title 40 Part 1065 (so-called, 40 CFR 1065) emissions testing and is used for emissions testing during the idling tests and in-use real world tests. It consists of a set of gas analyzers to measure gaseous emissions of NO_x (both nitrogen oxide [NO] and nitrogen dioxide [NO_2]), HC, CO, CO_2, and oxygen (O_2) in the exhaust. The SEMTECH-DS is used in conjunction with the SEMTECH electronic flow meter (EFM), which measures the vehicle exhaust flow rate. This allows for the calculation of exhaust mass emissions from all measured gasses. Figure II shows the SEMTECH-DS and EFM installed on a Chevy Volt during the testing.

Figure II: SEMTECH-DS and EFM.

Axion

The PEMS used to collect PM was the Axion system (Axion) manufactured by Clean Air Technologies International, Inc. The Axion consists of gas analyzers, a PM measurement system, an engine diagnostic scanner, a GPS, and an on-board computer. For this study only the PM measurement system was used. The PM measurement capability includes a laser light scattering detector and a sample conditioning system. The PM concentrations are converted to PM mass emissions using concentration rates measured by the Axion and the exhaust flow rates collected by the SEMTECH EFM. During the testing, most of measured PM concentration was under the detection limits.

Auto Enginuity Scan Tool Data Logger

The Auto Enginuity Scan Tool data logger was used during the project to monitor the information being passed along the OBD-II system from the test vehicles. Figure III shows the picture of the data logger. The data logger supports all existing OBD-II protocols as well as additional information from the tested vehicles, including the hybrid battery data such as SOC. The data logger is fully configurable, allowing users to select which parameters are recorded, as well as the rate at which they are recorded. The data logger requires a laptop, with the Scan Tool software installed, where the data is saved. In addition to the data logging capability, the device also allows for a live data mode where the user can watch the data in real time.

Figure III: Auto Enginuity Data Logger[12].

[12] Picture from www.autoenginuity.com, Last Accessed August 2013.

APPENDIX B

Table I: Volt #1 CD Mode MOVES Bins Results

Opmode Bin #	Δ SOC (%; AVE)	COV of Δ SOC (%)	Data Points	95% CI
0	-0.0309%	-82.1%	1208	1.43E-05
1	0.0018%	186.4%	2606	1.3E-06
11	-0.0060%	-216.0%	773	9.17E-06
12	0.0090%	104.7%	754	6.7E-06
13	0.0249%	43.8%	442	1.02E-05
14	0.0378%	32.6%	406	1.2E-05
15	0.0481%	28.4%	247	1.7E-05
16	0.0884%	47.7%	186	6.06E-05
21	-0.0105%	-171.7%	1338	9.62E-06
22	0.0089%	134.7%	1006	7.4E-06
23	0.0181%	71.8%	1095	7.69E-06
24	0.0295%	46.2%	711	1E-05
25	0.0464%	44.7%	333	2.23E-05
27	0.0598%	48.6%	294	3.32E-05
28	0.1034%	50.7%	93	0.000106
29	0.1361%	47.1%	35	0.000212
30	0.1829%	22.7%	103	8.01E-05
33	0.0064%	457.0%	1618	1.43E-05
35	0.0376%	62.8%	1980	1.04E-05
37	0.0527%	49.8%	922	1.7E-05
38	0.0766%	50.0%	225	5.01E-05
39	0.1148%	45.4%	44	0.000154
40	0.1847%	21.0%	186	5.59E-05

Table II: Volt #2 CD Mode MOVES Bins Results

Opmode Bin #	Δ SOC (%; AVE)	COV of Δ SOC (%)	Data Points	95% CI
0	-0.0267%	-142.3%	549	3.18E-05
1	0.0025%	175.8%	966	2.8E-06
11	-0.0027%	-558.0%	211	2.05E-05
12	0.0125%	115.4%	266	1.74E-05
13	0.0338%	83.2%	150	4.5E-05
14	0.0447%	37.5%	112	3.1E-05
15	0.0573%	46.2%	111	4.93E-05
16	0.0974%	58.3%	98	0.000112
21	-0.0148%	-167.6%	694	1.84E-05
22	0.0080%	182.6%	598	1.17E-05

23	0.0190%	76.3%	724	1.05E-05
24	0.0276%	51.6%	352	1.49E-05
25	0.0457%	56.6%	174	3.85E-05
27	0.0635%	55.4%	146	5.71E-05
28	0.0881%	82.6%	47	0.000208
29	0.1306%	45.0%	35	0.000195
30	0.1796%	37.2%	66	0.000161
33	0.0080%	391.0%	853	2.11E-05
35	0.0383%	66.6%	1228	1.43E-05
37	0.0588%	50.5%	598	2.38E-05
38	0.0800%	54.7%	135	7.38E-05
39	0.1355%	44.3%	10	0.000372
40	0.1979%	28.5%	95	0.000114

Table III: CO2 Emissions Rates for CS Driving Mode

Opmode Bin #	**Volt #1**				**Volt #2**				**MOVES Rates**
	CO_2 (g/s)	**COV (%)**	**# of data**	**95% CI**	**CO_2 (g/s)**	**COV (%)**	**# of data**	**95% CI**	**CO_2 (g/s)**
0	0.991	174%	1873	0.08	1.020	160%	1327	0.09	1.17
1	0.007	2269%	4312	0.00	0.005	2453%	2424	0.00	1.11
11	0.766	223%	779	0.12	0.797	217%	566	0.14	1.68
12	0.323	353%	773	0.08	0.532	265%	541	0.12	2.25
13	0.327	357%	493	0.10	0.893	202%	304	0.20	2.99
14	0.262	383%	432	0.09	1.089	173%	262	0.23	3.73
15	0.667	231%	365	0.16	0.880	180%	227	0.21	4.41
16	0.894	187%	308	0.19	2.164	115%	276	0.29	5.24
21	3.752	68.4%	1934	0.11	3.663	68.7%	1603	0.12	2.27
22	4.283	55.6%	1531	0.12	4.170	53.5%	1361	0.12	2.47
23	4.362	54.3%	1716	0.11	4.588	47.5%	1433	0.11	2.94
24	4.242	64.1%	999	0.17	4.691	51.4%	665	0.18	3.72
25	3.916	80.5%	584	0.26	4.615	61.6%	351	0.30	4.94
27	3.665	94.9%	458	0.32	4.393	72.9%	350	0.34	6.38
28	4.747	81.8%	95	0.78	5.784	62.3%	141	0.60	8.59
29	4.363	90.7%	76	0.89	6.150	64.6%	65	0.97	11.77

30	6.015	81.4%	139	0.81	8.328	48.8%	132	0.69	14.78
33	5.193	49.6%	2428	0.10	5.248	49.1%	1833	0.12	3.06
35	6.231	32.6%	2815	0.07	6.722	30.3%	2388	0.08	4.75
37	7.193	28.8%	1142	0.12	7.612	27.9%	1100	0.13	6.11
38	7.953	29.1%	273	0.27	7.810	32.2%	252	0.31	7.96
39	7.388	28.9%	52	0.58	8.123	21.4%	56	0.46	10.61
40	8.814	23.4%	219	0.27	9.132	20.5%	219	0.25	13.52

Table IV: CO Emissions Rates for CS Driving Mode

Opmode Bin #	**Volt #1**				**Volt #2**				**MOVES Rates**
	CO (g/s)	**COV (%)**	**CO_2 (g/s)**	**95% CI**	**CO (g/s)**	**COV (%)**	**# of data**	**95% CI**	**CO (g/s)**
0	0.027	486%	1873	0.006	0.023	512%	1327	0.006	0.00055
1	0.000	2448%	4312	0.000	0.000	4713%	2424	0.000	0.00010
11	0.001	327%	779	0.000	0.003	564%	566	0.001	0.00344
12	0.000	525%	773	0.000	0.003	598%	541	0.001	0.00562
13	0.000	490%	493	0.000	0.003	459%	304	0.002	0.00518
14	0.000	496%	432	0.000	0.004	461%	262	0.002	0.00743
15	0.001	375%	365	0.000	0.006	566%	227	0.005	0.01078
16	0.009	473%	308	0.005	0.009	378%	276	0.004	0.01819
21	0.060	362%	1934	0.010	0.071	355%	1603	0.012	0.00449
22	0.043	416%	1531	0.009	0.061	374%	1361	0.012	0.00595
23	0.050	403%	1716	0.010	0.065	336%	1433	0.011	0.00765
24	0.044	437%	999	0.012	0.067	381%	665	0.019	0.01118
25	0.021	497%	584	0.009	0.029	520%	351	0.016	0.01268
27	0.031	416%	458	0.012	0.034	423%	350	0.015	0.01905
28	0.040	310%	95	0.025	0.038	310%	141	0.020	0.06457
29	0.168	305%	76	0.115	0.141	287%	65	0.098	0.13675
30	0.137	292%	139	0.066	0.124	264%	132	0.056	0.48028
33	0.180	242%	2428	0.017	0.203	210%	1833	0.020	0.00337
35	0.159	208%	2815	0.012	0.191	141%	2388	0.011	0.00575

37	0.288	127%	1142	0.021	0.316	129%	1100	0.024	0.00847
38	0.505	123%	273	0.074	0.394	126%	252	0.061	0.05918
39	0.863	90.8%	52	0.213	0.443	161%	56	0.187	0.06245
40	1.094	101%	219	0.147	0.927	108%	219	0.133	0.18353

Table V: NOx Emissions Rates for CS Driving Mode

Opmode Bin #	**Volt #1**				**Volt #2**				**MOVES Rates**
	NOx (g/s)	**COV (%)**	**# of data**	**95% CI**	**NOx (g/s)**	**COV (%)**	**# of data**	**95% CI**	**NOx (g/s)**
0	1.05E-04	428%	1873	2.04E-05	1.29E-04	505%	1327	3.50E-05	1.70E-05
1	1.88E-06	836%	4312	4.69E-07	1.30E-06	1499%	2424	7.75E-07	3.51E-05
11	4.37E-05	271%	779	8.32E-06	9.58E-05	388%	566	3.06E-05	3.22E-05
12	3.19E-05	440%	773	9.91E-06	1.60E-04	492%	541	6.64E-05	4.92E-05
13	4.19E-05	536%	493	1.98E-05	1.47E-04	304%	304	5.02E-05	0.00012
14	1.49E-05	393%	432	5.54E-06	2.24E-04	282%	262	7.66E-05	0.00020
15	3.61E-05	322%	365	1.19E-05	1.63E-04	310%	227	6.55E-05	0.00036
16	6.02E-05	312%	308	2.10E-05	3.30E-04	278%	276	1.08E-04	0.00751
21	2.90E-04	641%	1934	8.28E-05	2.88E-04	284%	1603	4.01E-05	6.37E-05
22	2.32E-04	688%	1531	7.99E-05	3.05E-04	248%	1361	4.02E-05	0.000103
23	1.92E-04	113%	1716	1.02E-05	3.11E-04	267%	1433	4.29E-05	0.000156
24	2.11E-04	104%	999	1.36E-05	3.49E-04	225%	665	5.98E-05	0.000264
25	1.88E-04	118%	584	1.80E-05	2.44E-04	150%	351	3.82E-05	0.00037
27	3.12E-04	1026%	458	2.93E-04	2.54E-04	195%	350	5.19E-05	0.000582
28	3.16E-04	164%	95	1.04E-04	6.31E-04	422%	141	4.40E-04	0.002143
29	1.09E-03	556%	76	1.37E-03	8.71E-04	392%	65	8.30E-04	0.003762
30	4.75E-04	485%	139	3.84E-04	1.19E-03	214%	132	4.35E-04	0.00495
33	2.37E-04	176%	2428	1.66E-05	3.11E-04	134%	1833	1.91E-05	0.000136
35	2.72E-04	148%	2815	1.49E-05	4.65E-04	104%	2388	1.94E-05	0.000375
37	3.92E-04	352%	1142	8.01E-05	6.56E-04	91.6%	1100	3.55E-05	0.000523
38	2.74E-04	104%	273	3.38E-05	6.10E-04	90.8%	252	6.84E-05	0.001819
39	2.86E-04	144%	52	1.12E-04	4.08E-04	118%	56	1.26E-04	0.002708

40	3.20E-04	79.8%	219	3.39E-05	3.00E-04	82.4%	219	3.27E-05	0.003411

Table VI: HC Emissions Rates for CS Driving Mode

Opmode Bin #	Volt #1				Volt #2				MOVES Rates
	HC (g/s)	COV (%)	# of data	95% CI	HC (g/s)	COV (%)	# of data	95% CI	HC (g/s)
0	5.48E-04	812%	1873	2.02E-04	2.30E-04	816%	1327	1.01E-04	2.65E-05
1	2.24E-07	3151%	4312	2.11E-07	4.45E-06	4118%	2424	7.30E-06	6.8E-05
11	2.49E-04	1037%	779	1.81E-04	2.01E-04	778%	566	1.29E-04	2.12E-05
12	2.29E-04	803%	773	1.29E-04	4.44E-04	539%	541	2.02E-04	1.62E-05
13	3.40E-04	829%	493	2.49E-04	2.55E-04	453%	304	1.30E-04	3.06E-05
14	9.89E-05	1244%	432	1.16E-04	2.70E-04	346%	262	1.13E-04	4.17E-05
15	6.58E-05	1164%	365	7.85E-05	9.04E-05	446%	227	5.24E-05	5.81E-05
16	2.48E-04	703%	308	1.95E-04	1.87E-04	445%	276	9.83E-05	9.28E-05
21	2.46E-04	795%	1934	8.71E-05	2.05E-04	663%	1603	6.65E-05	3.17E-05
22	1.29E-04	431%	1531	2.79E-05	1.56E-04	220%	1361	1.82E-05	2.91E-05
23	1.45E-04	1111%	1716	7.61E-05	1.73E-04	186%	1433	1.66E-05	3.14E-05
24	1.44E-04	1574%	999	1.41E-04	2.13E-04	195%	665	3.15E-05	5.98E-05
25	5.74E-04	1047%	584	4.88E-04	1.41E-04	294%	351	4.35E-05	5.96E-05
27	2.10E-04	730%	458	1.40E-04	1.33E-04	319%	350	4.43E-05	9.42E-05
28	6.38E-04	373%	95	4.78E-04	2.07E-04	306%	141	1.05E-04	0.000636
29	1.41E-03	232%	76	7.36E-04	1.89E-04	202%	65	9.32E-05	0.001129
30	3.37E-04	233%	139	1.30E-04	3.36E-04	151%	132	8.65E-05	0.001864
33	3.87E-04	477%	2428	7.35E-05	4.08E-04	295%	1833	5.50E-05	3.04E-05
35	5.26E-04	409%	2815	7.95E-05	6.38E-04	155%	2388	3.98E-05	4.23E-05
37	1.71E-03	483%	1142	4.80E-04	1.03E-03	125%	1100	7.59E-05	5.41E-05
38	1.75E-03	269%	273	5.59E-04	1.03E-03	137%	252	1.74E-04	0.000429
39	1.39E-03	168%	52	6.35E-04	6.13E-04	201%	56	3.22E-04	0.000624
40	1.81E-03	137%	219	3.28E-04	8.12E-04	126%	219	1.36E-04	0.000815

APPENDIX C

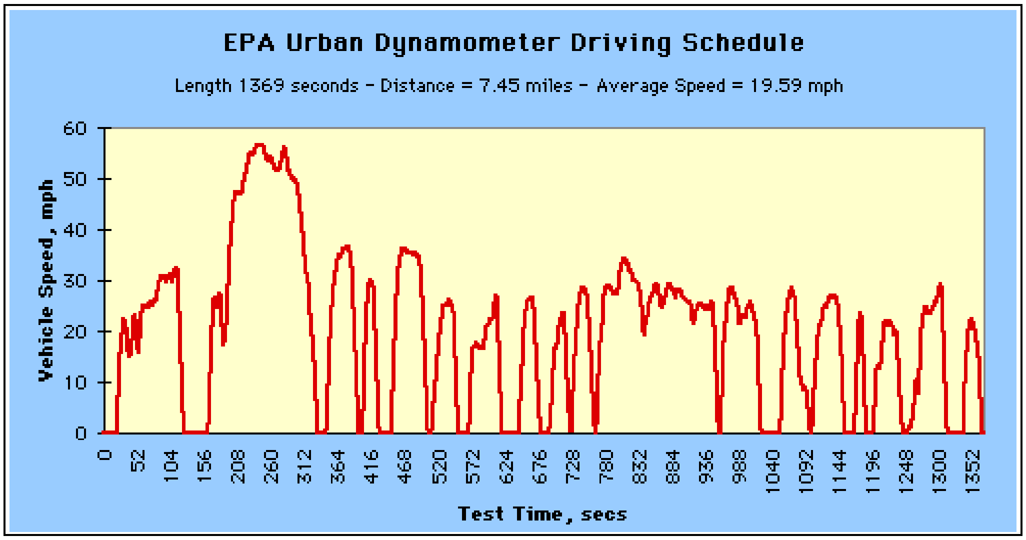

Figure IV: UDDS Drive Cycle[13]

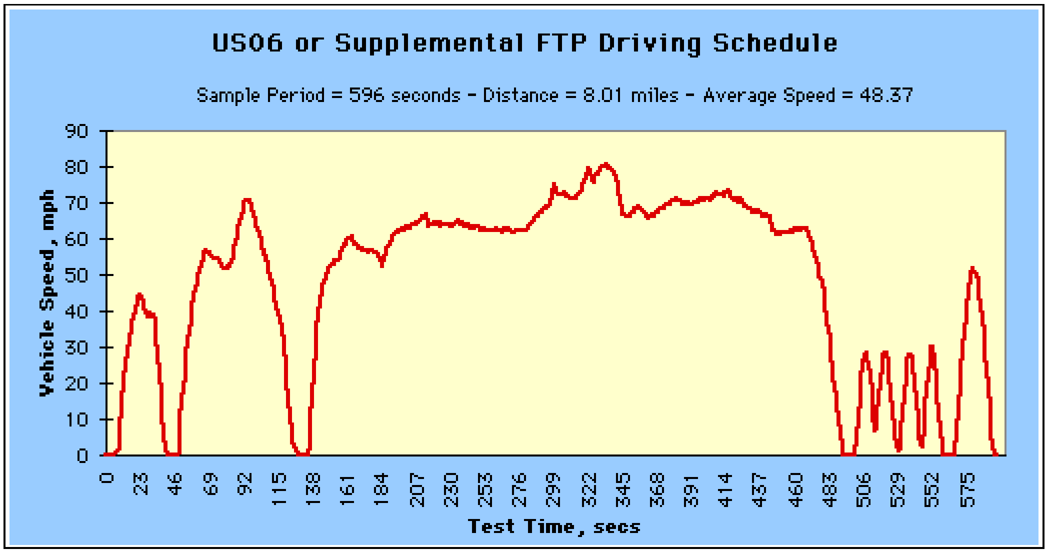

Figure V: US06 Drive Cycle[14]

[13] http://www.epa.gov/nvfel/methods/uddsdds.gif
[14] http://www.epa.gov/nvfel/methods/us06dds.gif

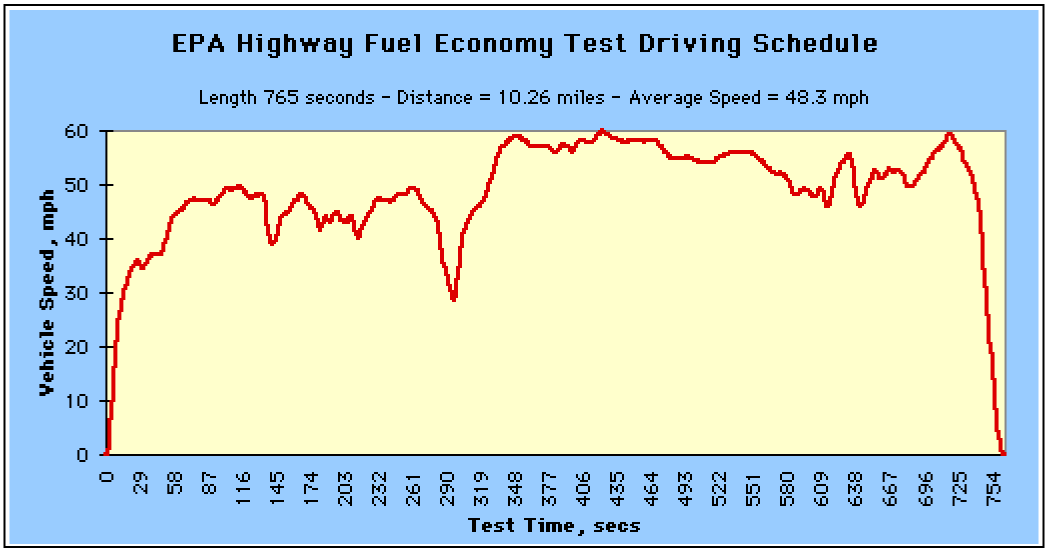

Figure VI: Highway Fuel Economy Drive Cycle[15]

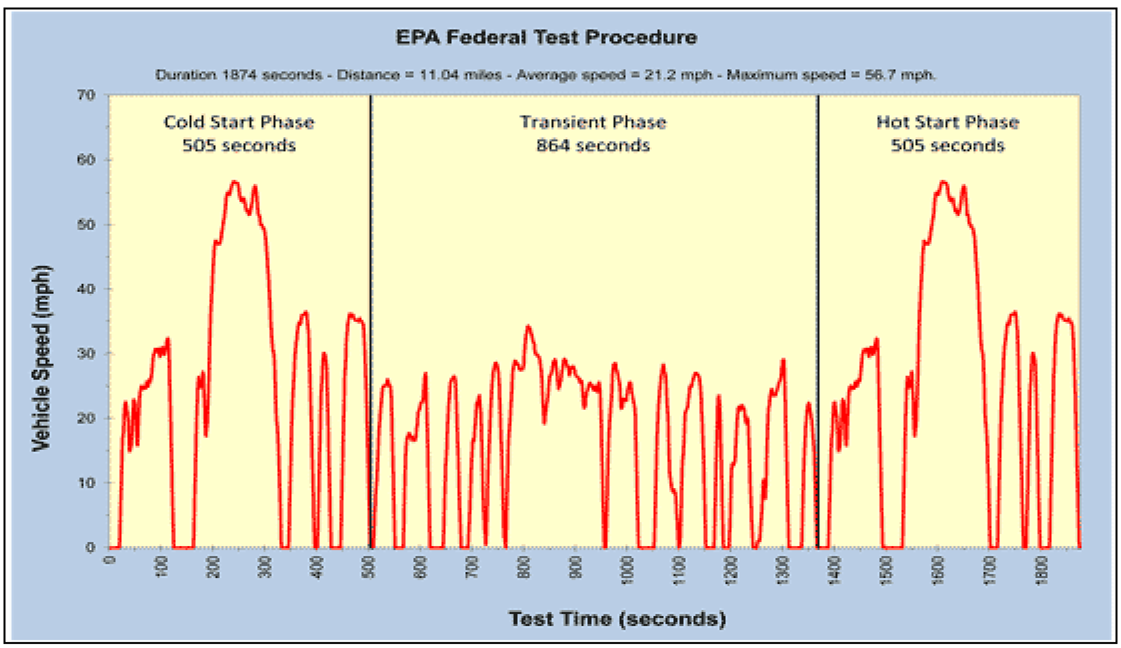

Figure VII: Federal Test Procedure Drive Cycle[16]

[15] http://www.epa.gov/nvfel/methods/hwfetdds.gif
[16] http://www.epa.gov/nvfel/methods/ftpdds.gif

Table VII: MOVES Bin Breakdown of Drive Cycles

Opmode Bin #	# of data points (seconds) for each bin			
	UDDS	US06	HWFET	FTP
0	111	56	16	152
1	260	42	4	357
11	112	11	4	134
12	152	5	1	174
13	136	3	2	153
14	67	3	2	86
15	16	4	4	29
16	5	22	0	10
21	83	30	35	124
22	170	2	36	214
23	120	5	95	179
24	32	1	154	53
25	15	1	36	29
27	11	9	19	22
28	3	11	0	6
29	0	9	0	0
30	0	6	0	0
33	27	60	61	54
35	36	105	254	72
37	13	124	42	26
38	0	60	0	0
39	0	12	0	0
40	0	15	0	0
Total	**1369**	**596**	**765**	**1874**
Total miles driven for each drive schedule	**7.5**	**8.01**	**10.26**	**11.04**