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King County Metro Transit: Allison Hybrid Electric Transit Bus Laboratory Testing

R.R. Hayes, A. Williams, J. Ireland, and K. Walkowicz

Technical Report
NREL/TP-540-39996
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Prepared under Task No. FC06.3000

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National Renewable Energy Laboratory
1617 Cole Boulevard, Golden, Colorado 80401-3393
303-275-3000 • www.nrel.gov

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Abstract

The National Renewable Energy Laboratory's (NREL) ReFUEL facility conducted chassis dynamometer testing of two 60-foot articulated transit buses, one conventional and one hybrid. The testing period for the baseline vehicle was May 2, 2005 through May 17, 2005, while the testing period for the hybrid vehicle was June 27, 2005 through July 1, 2005. Both test vehicles were 2004 New Flyer buses powered by Caterpillar C9 8.8L engines, with the hybrid vehicle incorporating a GM-Allison advanced hybrid electric drivetrain. Both vehicles also incorporated an oxidizing diesel particulate filter. The fuel economy and emissions benefits of the hybrid vehicle were evaluated over four driving cycles; Central Business District (CBD), Orange County (OCTA), Manhattan (MAN), and a custom test cycle developed from in-use data of the King County Metro (KCM) fleet operation. The hybrid vehicle demonstrated the greatest improvement in fuel economy in the low speed, heavy stop-and-go driving conditions of the MAN test cycle (74.6%), followed by the OCTA (50.6%), CBD (48.3%), and KCM (30.3%).

Emission trends were similar to fuel economy improvement trends. The hybrid showed reductions in NO_x emissions over the MAN cycle (38.7%), the OCTA (28.6%), CBD (26.6%), and KCM (17.8%). In order to evaluate the effects of additional engine and vehicle loading due to air conditioning and grade, select cycles were repeated with and without these added loads. Vehicle exhaust emissions, fuel consumption, and state of charge of the energy storage system were measured for repeated test conditions. The remainder of this document includes the experimental setup, test procedures, and results from vehicle testing performed at the NREL ReFUEL laboratory.

Lab Description and Methods

The vehicles were tested at the ReFUEL laboratory, which is operated by NREL and located in Denver, Colorado. The lab includes a heavy-duty vehicle (chassis) test cell and an engine dynamometer test cell with emissions measurement capability. Researchers perform regulated emissions measurements using procedures consistent with the Code of Federal Regulations (CFR) title 40, section 86, subpart N. Extensive data acquisition and combustion analysis equipment can be used to relate the effects of different fuel properties and engine settings to performance and emissions. Other laboratory capabilities include: systems for sampling and analyzing unregulated emissions, on-site fuel storage and fuel blending equipment, high-speed data acquisition hardware and software to support in-cylinder measurements, and fuel ignition quality testing. Instrumentation and sensors at the laboratory are maintained with National Institute of Standards and Technology (NIST)-traceable calibration. Test procedures, calibrations, and measurement accuracies are maintained to meet requirements outlined in the current CFR title 40, section 86, subpart N.

Chassis Dynamometer

The ReFUEL Chassis Dynamometer is installed in the main high-bay area of the laboratory. The roll-up door to the high bay is 14 ft. x 14 ft., high enough to accept all highway-ready vehicles without modification. The dynamometer is installed in a pit below ground level, so that the only exposed part of the dynamometer is the top of the 40 in. diameter rolls. Two sets of rolls are installed, so that twin-axle tractors can be tested. The distance between the rolls can be varied between 42 in. and 56 in. The dynamometer will accommodate vehicles with a wheelbase between 89 in. and 293 in. The dynamometer can simulate up to 80,000 lb vehicles at speeds up to 60 mph.

The chassis dynamometer is composed of three major components: the rolls – which are in direct contact with the vehicle tires during testing, the direct current (DC) electric motor (380 hp absorbing / 360 hp motoring) dynamometer, and the flywheels.

The rolls are the means by which power is absorbed from the vehicle. The rolls are attached to gearboxes that increase the speed of the central shaft by a factor of 5. The flywheels, mounted on the back of the dynamometer, provide a mechanical simulation of the vehicle inertia.

The electric motor is mounted on trunnion bearings, and is used to measure the shaft torque from the rolls. The energy absorption capability of the dynamometer is used to apply the “road load,” which is a summation of the aerodynamic drag and friction losses that the vehicle experiences in use, as a function of speed. The road load may be determined experimentally if data are available, or estimated from standard equations. The electric dynamometer is also used to adjust the simulated inertia, either higher or lower than the 31,000 lb base dynamometer inertia, as the test plan requires. The inertia simulation range of the chassis dynamometer is 8,000 – 80,000 lbs. The electric motor may also be used to simulate grades and provide braking assist during decelerations.

The test vehicle is secured with the drive axles over the rolls. A driver’s aid monitor in the cab is used to guide the vehicle operator in driving the test trace. A large fan may be used to cool the vehicle radiator during testing. The chassis dynamometer is supported by 72 channels of data acquisition, in addition to the emissions measurement, fuel metering, and combustion analysis subsystems.

The dynamometer is capable of simulating vehicle inertia and road load during drive cycle testing. With the vehicle jacked up off the rolls, an automated dynamometer warm-up procedure is performed daily, prior to testing, to ensure that parasitic losses in the dynamometer and gearboxes have stabilized at the appropriate level to provide repeatable loading. An unloaded coast down procedure is also conducted to confirm that inertia and road load are being simulated by the dynamometer control system accurately. Between test runs a loaded coast down procedure is performed to further ensure stability of vehicle and dynamometer parasitic losses and accurate road load simulation during testing.

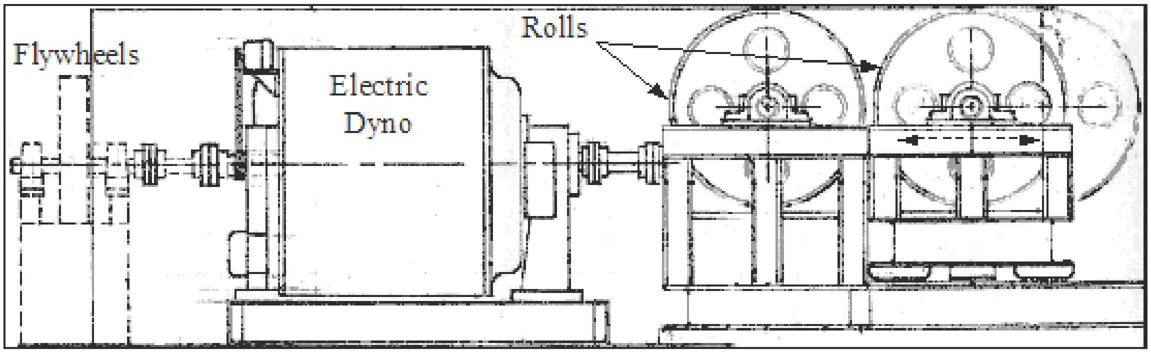

Figure 1. Chassis Dynamometer Schematic

Fuel Storage and Blending

Buildings designed specifically for safely storing and handling fuels are installed at the ReFUEL facility. The fuel storage shed is 8 ft. x 26 ft. and holds up to 48 drums (55-gal each). Features include heating/cooling, secondary containment to 25% of capacity, continuous ventilation, explosion-proof wiring/lighting, and a dry chemical fire suppression system.

The fuel blending can be performed on a gravimetric or volumetric basis, with capability for both large (L/kg) and small (cc/g) scale measurements. A fuel line inside a sealed conduit delivers the fuel from the supply drum to the fuel metering/conditioning system inside the ReFUEL laboratory, eliminating the need for bulk fuel storage inside the laboratory. Another fuel line in the same conduit delivers waste fuel back to the fuel blending shed for storage (waste fuel is generated only when a fuel changeover requires a flush of the system).

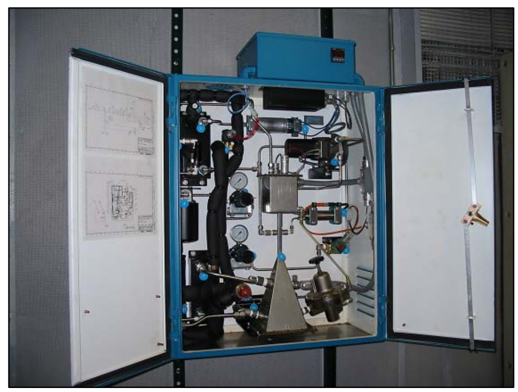

Figure 2.
Pierburg Fuel Metering System

Fuel Metering and Conditioning

The fuel metering and conditioning system, Pierburg Model PII 514, (shown in Fig. 2) supports test work for both the engine and the chassis dynamometers. The meter measures volumetric flow to an accuracy of +/- 0.5% of the reading, with a reproducibility of 0.2%. An in-line sensor measures the density at an accuracy of +/- 0.001 g/cc, allowing an accurate mass measurement over the test cycle even if the density of the fuel blend is not known prior to testing.

Air Handling and Conditioning

Dilution air and the air supplied to the test engine or vehicle for combustion are derived from a common source, a roof-mounted system that conditions the temperature of the air and humidifies as needed to meet desired specifications. This air is passed through a HEPA filter, in accordance with the (2007) CFR specifications, to eliminate background particulate matter as a source of uncertainty in particulate measurements.

Emissions Measurement

The ReFUEL laboratory's emissions measurement system supports both the engine and chassis dynamometers. It is based on the full-scale exhaust dilution tunnel method with a constant volume sampling (CVS) system for mass flow measurement. The system is designed to comply with the requirements of the 2007 CFR, title 40, part 86, subpart N. Exhaust from the engine or vehicle flows through insulated piping to the full-scale 18 in. diameter stainless steel dilution tunnel. A static mixer ensures thorough mixing of exhaust with conditioned, filtered, dilution air prior to sampling of the dilute exhaust stream to measure gaseous and particulate emissions.

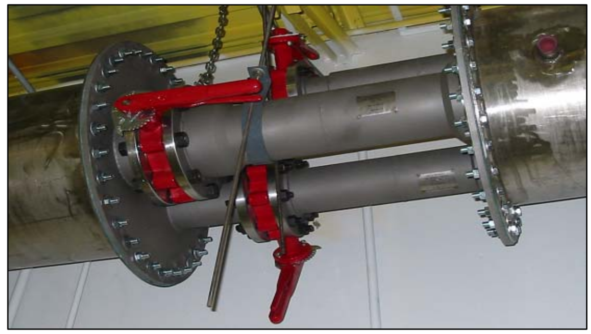

Figure 3. Venturi Nozzles

A system with three Venturi nozzles is employed to maximize the flexibility of the emissions measurement system. Featuring 500 cfm, 1000 cfm, and 1500 cfm Venturi nozzles and gas-tight valves, the system flow can be varied from 500 cfm to 3000 cfm flow rates in 500 cfm increments. This allows the dilution level to be tailored to the engine size being tested (whether on the engine stand or in a vehicle), maximizing the accuracy of the emissions measurement equipment.

The gaseous emissions bench is a Pierburg model AMA-2000. It features continuous analyzers for total hydrocarbons (HC), oxides of nitrogen (NO_x), carbon monoxide (CO), carbon dioxide (CO_2), oxygen (O_2). The system features auto-ranging, automated calibration, zero check, and span check features as well as integrating functions for calculating cycle emissions. It communicates with the ReFUEL data acquisition systems through a serial interface. There are two heated sample trains for gaseous emissions measurement: one for HC, and another for the other gaseous emissions. NO_x and HC measurements are performed on a wet basis, while CO, CO_2 and O_2, are done on a dry basis. Sample probes are located in the same plane in the dilution tunnel.

The particulate matter sample control bench is managed by the ReFUEL data acquisition system through a serial connection. It maintains a desired sample flow rate through the particulate matter (PM) filters in proportion to the overall CVS flow, in accordance with the CFR. Stainless steel filter holders, designed to the 2007 CFR requirements, house 47 mm diameter Teflon membrane filters through which the dilute exhaust sample flows. The PM sampling system is capable of drawing a sample directly from the large full-scale dilution tunnel or using secondary dilution to achieve desired

Figure 4. Pierburg Emissions Bench

temperature, flow, and concentration characteristics. A cyclone separator, as described in the CFR requirements, is employed to mitigate tunnel PM artifacts.

A dedicated clean room/environmental chamber is installed inside the ReFUEL facility. It is a Class 1000 clean room with precise control over the temperature and humidity (+/- 1°C for temperature and dew point). This room is used for all filter handling, conditioning, and weighing.

The microbalance for weighing PM filters features a readability of 0.1 μg (a CFR requirement) and features a barcode reader for filter identification and tracking, and a computer interface for data acquisition. The microbalance is installed on a specially designed table to eliminate variation in the measurement due to vibration. The microbalance manufacturer (Sartorius) was consulted on the design of the clean room to ensure that the room air flow would be compatible with the microbalance.

Figure 5. Class 1000 Clean Room, Filter Housing, and Microbalance

Project Specific Setup and Methods

The test vehicles were installed on the chassis dynamometer as shown in Figure 6. A process and instrumentation diagram of each vehicle test setup is included as Figures 11 and 12 in Appendix A, which contains detailed information regarding sensor description and placement (which were used to ensure accurate operation of vehicle and test equipment). Additional data from the engine control unit were also recorded for quality assurance using a pc-based acquisition system connected via serial interface.

Figure 6. Chassis Cell with Test Vehicle

Test Vehicles

The baseline, conventional test vehicle was a 2004 New Flyer bus powered by the Caterpillar C9 8.8L 330 hp diesel engine. The hybrid test vehicle, which was based on the same 2004 New Flyer platform also incorporated the Cat C9 engine along with Allison's EP50 hybrid electric drive train (parallel hybrid). Both vehicle descriptions are shown in Appendix B, Table 8. The hybrid electric drive system uses two induction motors, each with a continuous power rating of 100 hp and a peak power rating of 200 hp. The nickel metal hydride battery pack has a nominal voltage of 650 V. Conditioned cooled air was supplied to the hybrid vehicle battery pack for controlled cooling and ventilation in an attempt to more closely simulate operating conditions in King County, WA. Each test vehicle was equipped with an Englehard diesel particulate filter (DPF).

Test Fuel

The same DPF was used on each vehicle during testing (see Appendix B, Table 8 for description). All testing was performed with low sulfur diesel (BP15). The fuel supplied to the engine of each test vehicle was continuously conditioned and metered. Fuel analysis information is also included in Appendix C.

Air and Exhaust

Intake air was conditioned and supplied to each test vehicle by the ReFUEL system with continuous recorded measurements of ambient pressure, inlet restriction, humidity, and temperature of the inlet air (as described in Figure 11 and 12). Approximately 44 ft. of 6 in. diameter, insulated, stainless steel tubing connected the test vehicle exhaust pipe to the dilution tunnel, with recorded temperatures measured at the outlet of the vehicle exhaust pipe, at the entrance to the dilution tunnel, and at the plane of the emissions sampling probes. Exhaust pressures were also measured to ensure back pressures did not exceed those specified by the manufacturer. Typical peak exhaust back pressures resulting from the emissions sampling systems were 4 in. H_20.

Vehicle Simulation

The simulated vehicle inertia test weight for the test vehicle was calculated as half of the loaded vehicle weight, equaling 49,200 lb. for the conventional and 50,500 lb. for the hybrid. The vehicle loss coefficients are shown in Table 1. Road load coefficients for the baseline vehicle were derived from track coast down data provided by Allison. Two sets of track coast down data were provided by Allison for the hybrid bus; each resulting in different curves. These data sets were obtained at different times under different conditions with two different hybrid buses, one being the test vehicle. The coast down data of the other hybrid bus was of better quality than the test vehicle track coast down data, so this was used as the basis for generating road load curves for the test hybrid bus.

Table 1. Road Load Coefficients

Coefficient	Conventional Bus	Hybrid Bus
A	545 lb.	545 lb.
B	4.1967 lb./mph	1.3778 lb./mph
C	0.06262 lb./mph^2	0.09100 lb./mph^2

Road load coefficients for the hybrid vehicle were thus derived based on a combination of track coast down data provided by Allison and coast down data measured on the dynamometer at ReFUEL. The coefficients used during the dynamometer testing for the hybrid bus match very well with the track coast down at speeds above 15 mph, and match well with the behavior during

the dynamometer measured coast downs below 15 mph. Plots of the vehicle road load and coast down curves used for the simulation are shown in Appendix D.
The appropriate chassis dynamometer load settings were then derived to simulate the calculated road load coefficients for the test vehicle so that the load forces simulated on the chassis dynamometer rolls during testing would best match the target road load curves.

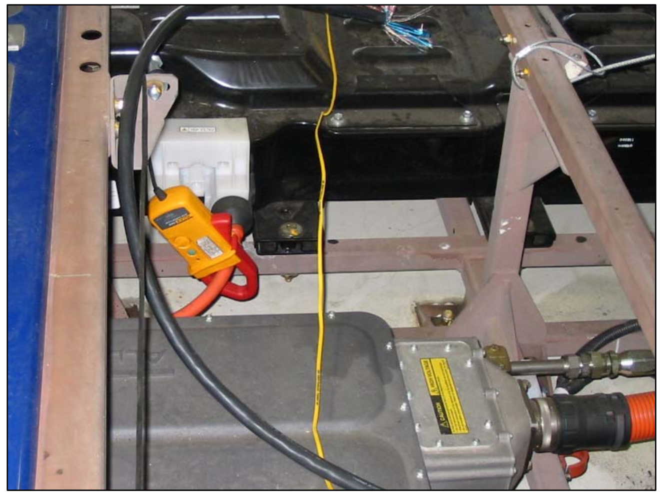

Figure 7. Current Clamp

State Of Charge Considerations

The Society of Automotive Engineers (SAE) Recommended Practice J2711 is a recommended protocol for measuring fuel economy and emissions of hybrid-electric and conventional heavy-duty vehicles. The recommended practice provides a description of state of charge (SOC) correction for charge-sustaining HEVs.

Using the nominal battery pack voltage of 650 V and a continuously recorded measurement of DC current (Figure 7) into and out of the battery pack the net energy change (NEC) was calculated for each test run. Note that the percentage change in state of charge on all cycle runs was less than 1%, thus there was no need to correct data per SAE J2711.

Drive Cycles

With the assistance of KCM technical staff, in-use duty cycle data were logged during actual bus operation to capture representative speed-vs-time-vs-grade on some of KCM's typical routes. NREL derived a custom drive cycle (the KCM cycle) based on this data, to best simulate the real world duty cycle during testing. It consisted of four distinct modes to demonstrate highway and city (variable speeds and grades) driving. In addition, the overall KCM cycle was performed both with and without simulated grade and air conditioning to assess the effects of these conditions on performance. Testing was also performed using standard transit bus test cycles including the CBD, MAN, and OCTA. To ensure that the NEC of the charge sustaining Energy Storage System (ESS) was >1% of the total cycle energy, the shorter drive cycles were lengthened. The MAN cycle was doubled in length, giving a total cycle time of 2178 seconds and the CBD was tripled, for a total time of 1722 seconds. Plots of the CBD, MAN, OCTA, and custom KCM test cycles along with tabulated cycle statistics are shown in Appendix E. Additional test cycles were performed using both vehicles with the air conditioning system turned on throughout the test run over both CBD and KCM drive cycles. The SAE J2711 procedure outlines a specified tolerance for how closely the actual measured test speed versus time data matches the target test cycle trace. All test runs were validated based upon this procedure.

Test Description and Results

Initially, on each test day the chassis dynamometer was run through a standard automated warm-up procedure to ensure that dynamometer parasitics had stabilized. Periodic unloaded and loaded coast downs were also performed to ensure that inertia and road load were being simulated correctly according to the set inputs.

Each test vehicle was operated over repeated hot-start runs for each of the four drive cycles. For the purposes of this report, a valid hot-start run is defined as a test run performed following a previous similar run, separated by a soak time of 20 - 30 minutes. In order to evaluate the effects of additional auxiliary loads the CBD and KCM cycles were repeated with and without air conditioning. To evaluate the effects of grade the KCM cycle was repeated with and without grade simulation.

Two different drivers were used during baseline, conventional vehicle testing to evaluate driver-to-driver variability. Hot start CBD and KCM cycles were repeated three times with each driver. A statistical analysis showed no significant difference of NO_x emissions or fuel economy between the two drivers at the 95% confidence level. All hybrid vehicle data presented in this report was collected with a single driver, with the exception of a triplicate CBD data set.

Plots of the averaged data for each test vehicle on each drive cycle are shown for fuel economy, fuel consumption, and NO_x emissions in Figures 8 through 10, with error bars representing the 95% confidence interval of the means. Detailed tabulated data from each test run are also included as Appendix G.

Driving Style Impact on Hybrid Vehicle Testing

According to the recommended practices of SAE J2711, adherence to the drive cycle is confirmed by a regression analysis comparing actual speeds with target speeds. If the resulting trend line when plotting actual versus target speed varies from unity by more than 10% or an R^2 of less than 0.8 then the test run is considered invalid. Over the course of testing the hybrid vehicle on several CBD cycles, it was noticed that different driving styles, each producing valid results according to the recommended practice of SAE J2711, could potentially produce measurable differences in fuel economy. When operating the hybrid vehicle the drivers indicated that they perceived a higher sensitivity in the vehicle's throttle response due to the powertrain's high torque and regenerative braking capability when trying to maintain steady cruise speed (20 mph) repetitively during the CBD test cycle.

Upon review of the data, it was noticed that dithering of the throttle during cruise segments of the CBD cycle was correlated with higher integrated cycle energy than compared to the baseline. A triplicate of hot start CBD runs was completed with each driving style (with relatively more and less acceleration overshoot and throttle dither). The data, which indicates the difference in total cycle energy (approx 10% between styles) and fuel economy is tabulated in Appendix G. The difference in average hybrid bus fuel economy on the CBD test cycle between the two sets of runs, is approximately 4%-5%. Figure 19, Appendix F, shows a snap shot of two such cycles compared to the CBD target driver's trace that best illustrate the extremes.

As the drivers became more accustomed to the throttle response of the hybrid and consciously matched the CBD trace more steadily, less throttle dither was observed. All of the averaged data comparing hybrid CBD results to the conventional bus, plotted in Figures 8-10, are based on the latter test runs with less throttle dither. Conscious driver effort was not made to reduce throttle dither during CBD runs with the conventional bus. While formal driver style studies were not within the scope of this project and different styles were not rigorously tested, these results suggest that the hybrid vehicle may have a higher sensitivity to driving style on fuel economy performance than the baseline vehicle, especially over a test cycle dominated by repeated steady target cruise speeds.

Fuel Economy

The average measured fuel economy and fuel consumption over each test cycle for both vehicles are plotted in Figures 8 and 9. The same results are also shown in Table 2 for both vehicles, along with absolute improvement in miles per gallon of the hybrid bus versus the conventional bus.

Percentage improvements in fuel consumption and fuel economy for the hybrid versus the conventional bus over each test cycle are summarized in Table 2. A breakdown of fuel consumption and economy for the composite KCM cycle is summarized in Table 3. The hybrid vehicle demonstrated the highest percentage improvement in fuel economy (mpg basis) over the MAN driving cycle (74.6%), followed by the OCTA (50.6%), CBD (48.3%), and KCM (30.3%) test cycles. The benefits of the hybrid powertrain are most pronounced during lower speed, stop-and-go driving.

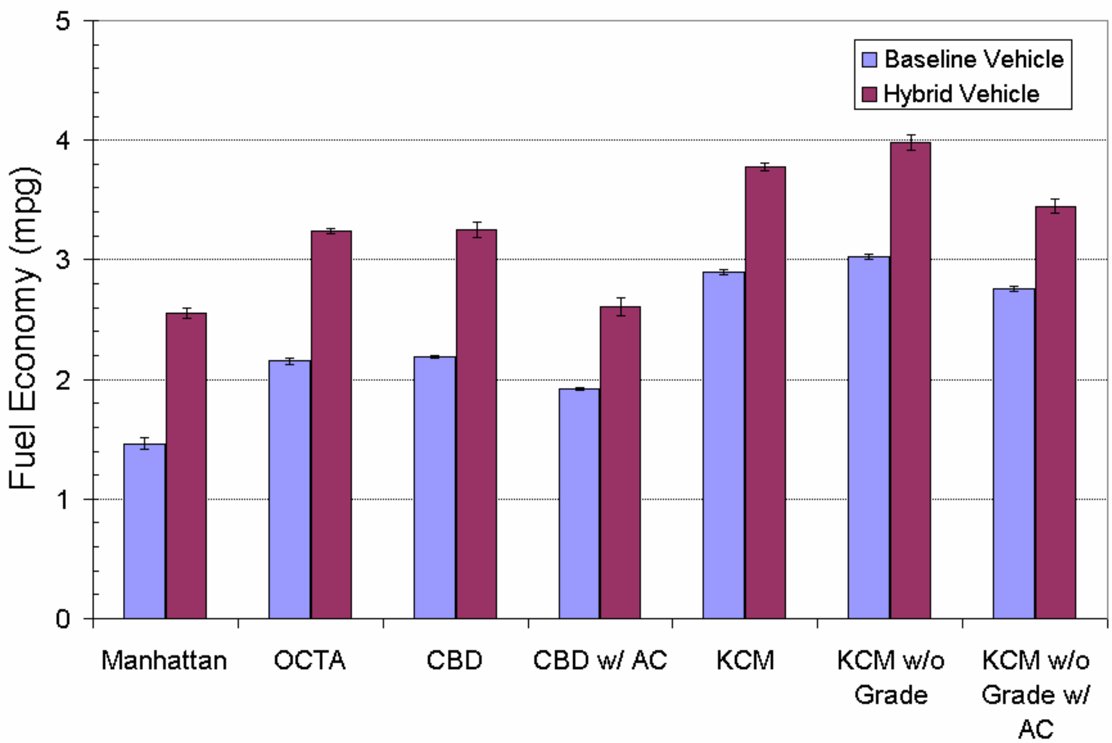

Figure 8. Average Fuel Economy

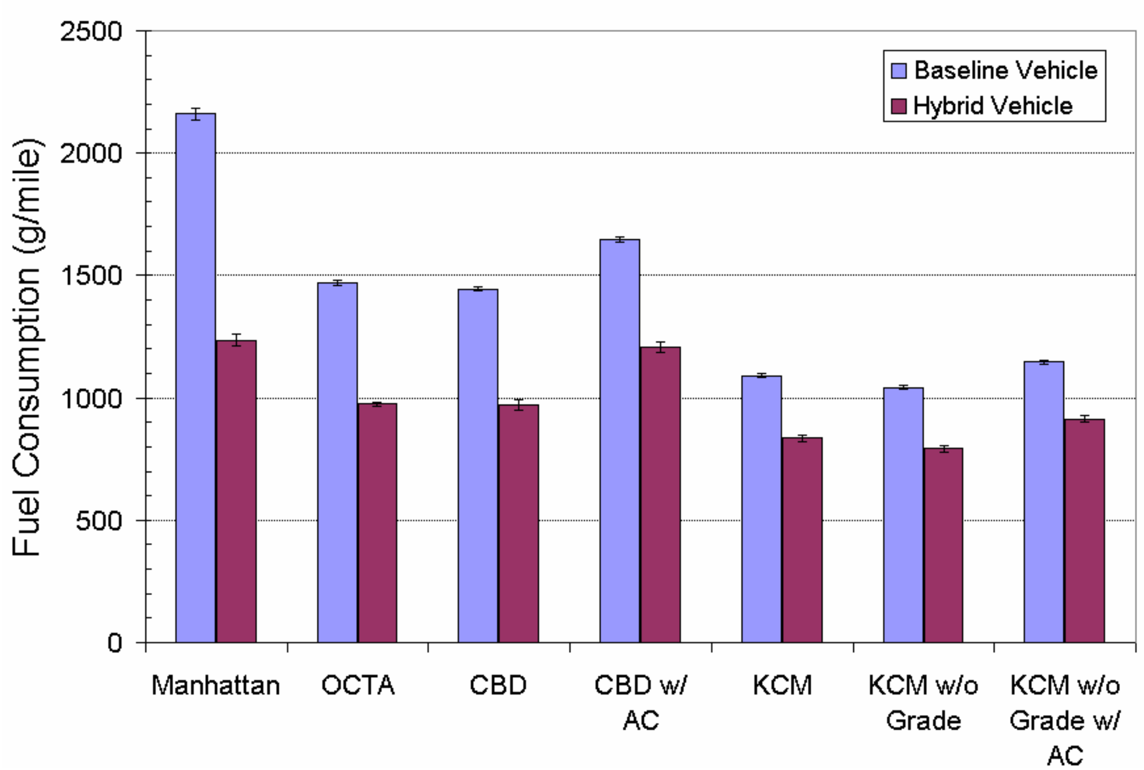

Figure 9. Average Fuel Consumption

Table 2. Measured Fuel Economy

	Manhattan	OCTA	CBD	CBD w/AC	KCM	KCM no grade	KCM no grade w/ AC
Conventional Bus Fuel Economy (mpg)	1.46	2.15	2.19	1.92	2.90	3.03	2.76
Hybrid Bus Fuel Economy (mpg)	2.56	3.24	3.15* 3.25	2.61	3.78	3.98	3.45
Fuel Economy Increase with Hybrid Bus (mpg)	1.09	1.09	0.96* 1.06	0.69	0.88	0.95	0.69

*Earlier runs, with more throttle dither and higher total cycle energy

Table 3. Measured Fuel Economy KCM Composite Breakdown

	KCM (I5)	KCM (Rte 174)	KCM (Rte 120)	KCM (Rte. 106)
Conventional Bus Fuel Economy (mpg)	4.33	2.35	2.30	2.09
Hybrid Bus Fuel Economy (mpg)	4.82	3.17	3.36	2.86
Fuel Economy Increase with Hybrid Bus (mpg)	0.49	0.82	1.06	0.77

Table 4. Hybrid Vehicle Percentage Fuel Economy and Consumption Improvement

	Manhattan	OCTA	CBD	CBD w/ AC	KCM	KCM no grade	KCM no grade w/ AC
Fuel Economy (mpg % improvement)	74.6%	50.6%	43.8%* 48.3%	35.9%	30.3%	31.4%	25.0%
Fuel Consumption (gallon/mile % improvement)	42.9%	33.7%	30.5%* 32.8%	26.7%	23.4%	24.2%	20.2%

*Earlier runs, with more throttle dither and higher total cycle energy

Table 5. Hybrid Vehicle Percentage Fuel Economy and Consumption Improvement KCM Composite Breakdown

	KCM (I5)	KCM (Rte 174)	KCM (Rte 120)	KCM (Rte 106)
Fuel Economy (mpg % improvement)	11.4%	34.6%	45.8%	37.2%
Fuel Consumption (gallon/mile % improvement)	10.3%	25.8%	31.5%	27.2%

Percentage differences in measured fuel economy due to grade and auxiliary loading from air conditioner operation are shown in Table 6. Auxiliary load testing indicates that the hybrid vehicle experienced a slightly larger penalty in fuel economy as a result of air conditioning when compared to the conventional bus. The percentage change in fuel economy due to simulated grade during the KCM cycle was similar for both vehicles.

Table 6. Fuel Economy Penalties from AC and Grade

	CBD		KCM	
	Conventional	**Hybrid**	**Conventional**	**Hybrid**
Air Conditioning (mpg % penalty)	12.3%	19.7%	8.9%	13.3%
Grade (mpg % penalty)	-	-	4.3%	5.0%

Emissions

Average NO_x emissions from both vehicles over each cycle are plotted in Figure 10. Similar in trend to fuel economy improvements, the hybrid vehicle showed highest percentage reduction in NO_x emissions over the MAN driving cycle (38.7%), followed by the OCTA (28.6%), CBD (26.6%), and KCM (17.8%) cycles. Other measured emissions, including CO, THC, and PM were generally very low for both vehicles as a result of the exhaust aftertreatment (DPF) system. Most data sets showed a statistically significant reduction in CO, THC ,and PM emissions for the hybrid vehicle. Tabulated results for each vehicle are shown in Appendix G. Average percentage reductions in emissions for each driving cycle are tabulated in Table 7. Due to either relatively high variability in the data over small datasets or small differences in the mean, some data sets did not exhibit statistically significant differences in emissions between vehicles at the 95% confidence level, using the Student's t-test and pooled variances. Significant variability was seen when comparing CBD PM datasets between driving styles.

Table 7. Hybrid Vehicle Emissions Percentage Reductions

	Manhattan	OCTA	CBD		KCM
NO_x (gallon/mile, % reduction)	38.7%	28.6%	26.4%*	26.6%	17.8%
PM (gallon/mile, % reduction)	92.6%	50.8%	88.2%*	97.1%	ns
CO (gallon/mile, % reduction)	ns**	32.0%	22.0%*	48.0%	59.5%
THC (gallon/mile, % reduction)	ns	ns	66.7%*	75.2%	56.3%

*Earlier runs, with more throttle dither and higher total cycle
**ns = not statistically significant at 95% confidence or not enough data to determine

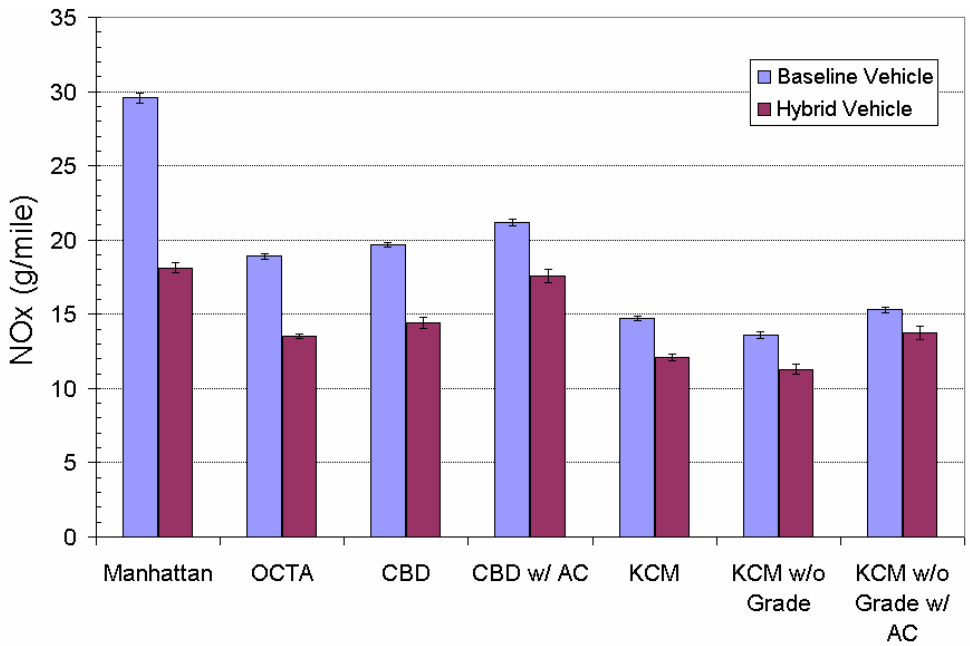

Figure 10. NO_x emissions

Appendix A. Test Cell Instrumentation

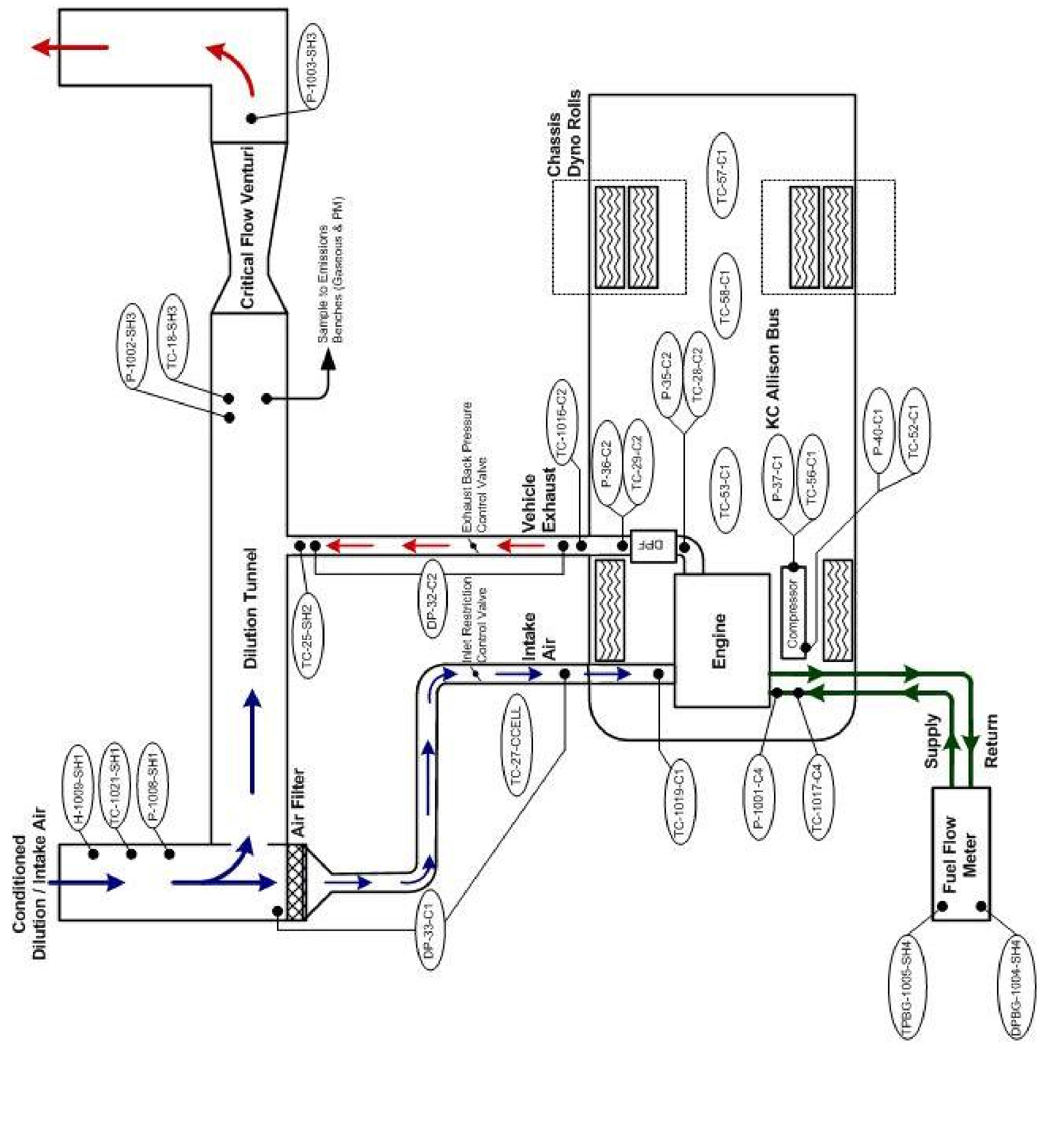

Figure 11. Baseline Vehicle Process and Instrumentation Diagram

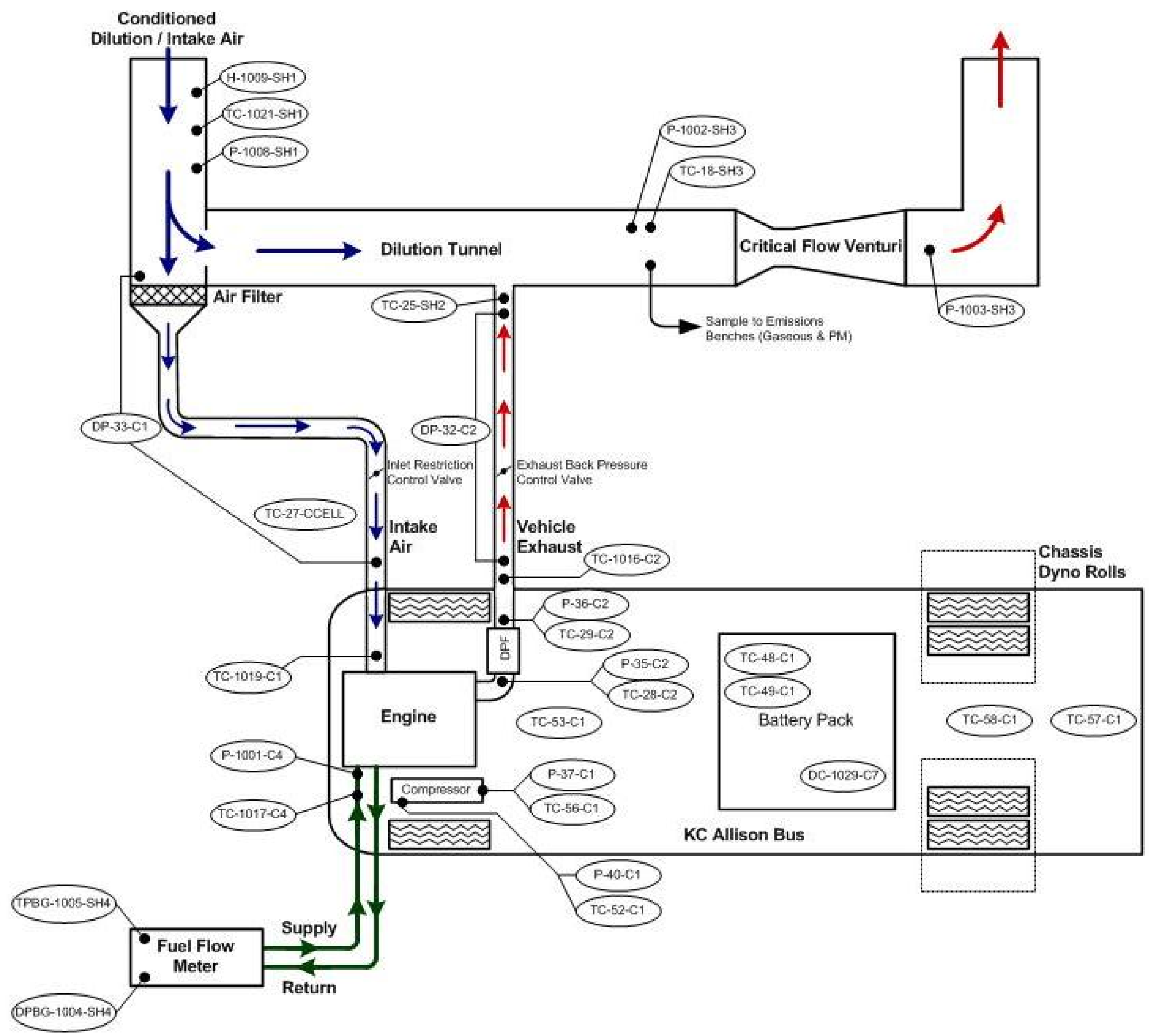

Figure 12. Hybrid Vehicle Process and Instrumentation Diagram

Appendix B. Test Vehicle Information

Table 8. Detailed Vehicle Information

Vehicle Description	**Baseline**	**Hybrid**
Model Year	Jun-04	Jul-04
Make	New Flyer	New Flyer
Odometer	25,188	94,871
Vin	5FYD2UW024U026978	5FYH2UW004U026690
Model	D60LF	DE60LF
Inertia Weight Class	66,790	66,790
Test Weight	49,200	50,500
Engine	**Baseline**	**Hybrid**
Manufacturer	Cat	Cat
Date of Man.	Sep-05	N/A
Displacement	8.8 L	8.8 L
Serial Number	MTB01121	MTB01232
Model	C9	C9
Power	330	330
Torque	1149	1149
Fuel	BP15	BP15
ECM #	1045006KA	17546257IE
Personality #	1593231-01	2601435-00
Aftertreatment Device	CAT DOC/DPF	CAT DOC/DPF
Chassis	**Baseline**	**Hybrid**
Axle Ratio	N/A	N/A
Transmission Type	Allison	Allison
Transmission Model	B500 Auto	Hybrid EP
Trans. Model #	N/A	N/A
Brake Type Front	Air Drum	Air Drum
Brake Type Rear	Air Drum	Air Drum
Wheelbase	N/A	N/A
Tires	**Baseline**	**Hybrid**
	Front	
Size	305/70 R225	305/70 R225
Make	Firestone	Firestone
Tread Depth	0.710/0.700 in	0.710/0.700 in
Pressure D/P	130/130 psig	
	Center	
Size	305/70 R225	305/70 R225
Make	Firestone	Firestone
Tread Depth Out D/P	0.685/0.675 in	0.685/0.675 in
Inside D/P	0.725/0.705 in	0.725/0.705 in
Pressure Out D/P	135/130 psig	135 psig nominal
Inside D/P	N/A	N/A
	Rear	
Size	305/70 R225	305/70 R225
Make	Firestone (siped)	Firestone (siped)
Tread Depth Out D/P	0.355/0.542 in	0.355/0.542 in
Inside D/P	0.375/0.465 in	0.375/0.465 in
Pressure Out D/P	130/125 psig	135 psig nominal
Inside D/P	90/125 psig	N/A

Appendix C. Test Fuels

Table 9. BP15 Test Fuel Analysis

Property	ASTM Test Method	Low Sulfur Diesel (BP15)
Cetane Number	D613	51.1
Cloud Point, °C	D2500	-12
Density, kg/m^3	D4052	837
Kinematic Viscosity, 40 °C, CSt	D445	2.5
Carbon, mass %	D5291	86.04
Hydrogen, mass %	D5291	13.48
Sulfur, ppm	D5453	13
Flash Point, °C	D93	63.5
Aromatics, vol%	D1319	29
Heat of Combustion, MJ/kg	D240	45.7

Appendix D: Road Load

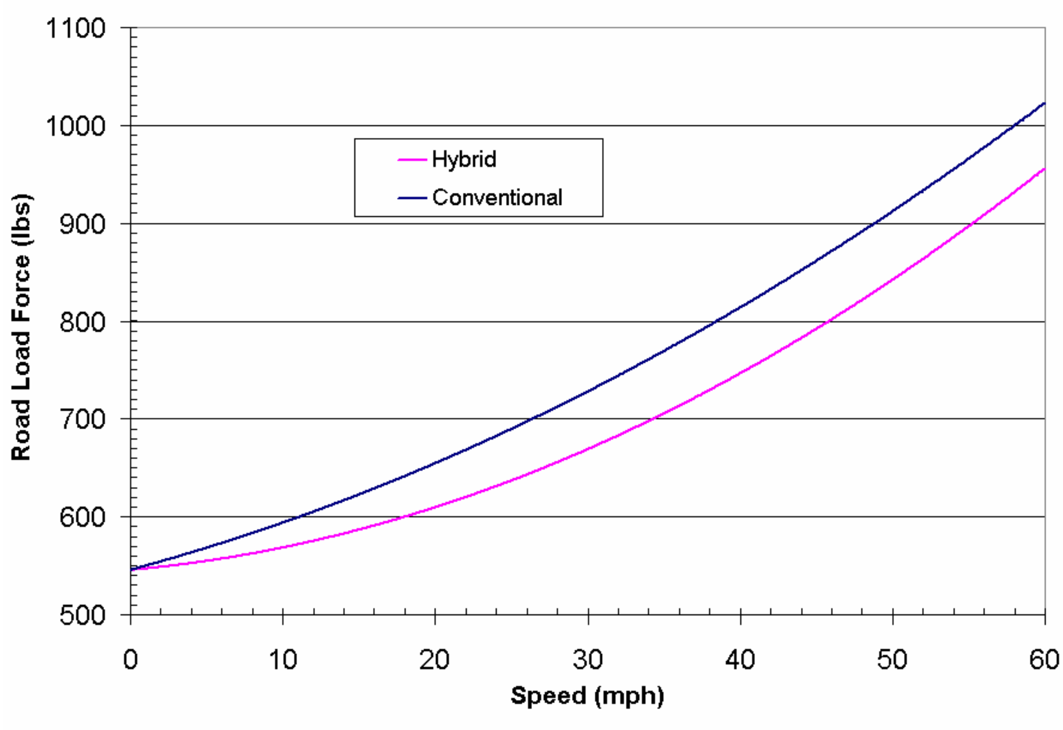

Figure 13. Road Load Curves

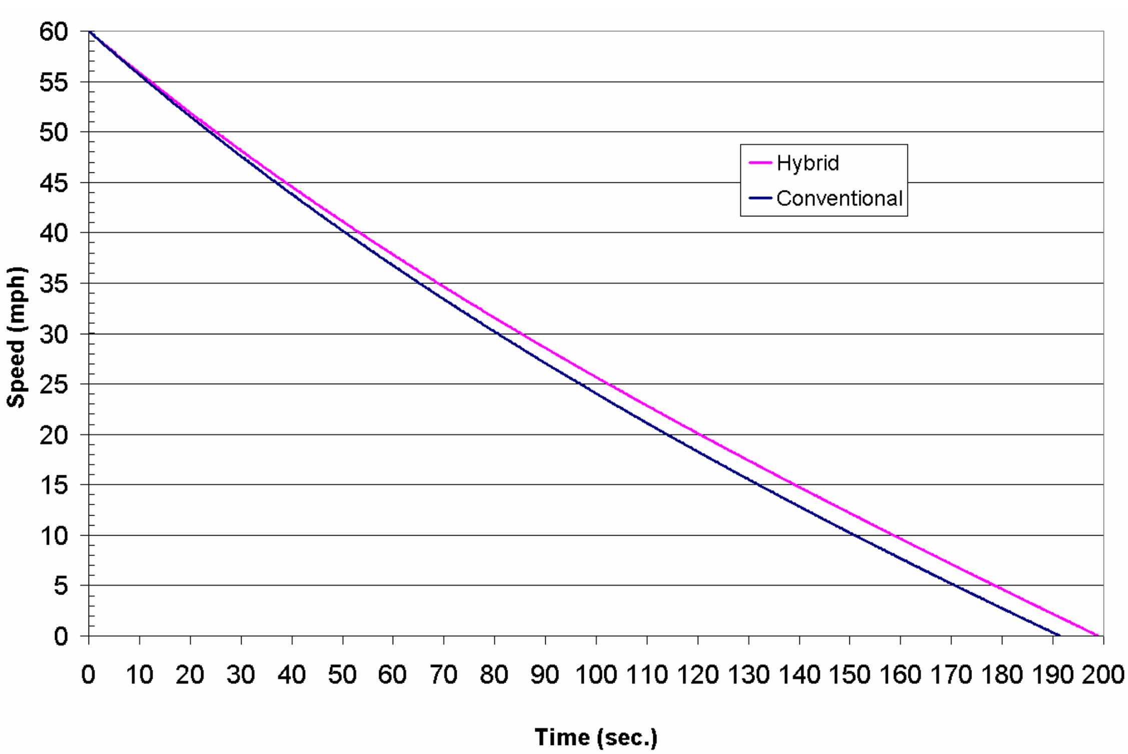

Figure 14. Coast Down Curves

Appendix E: Test Cycles

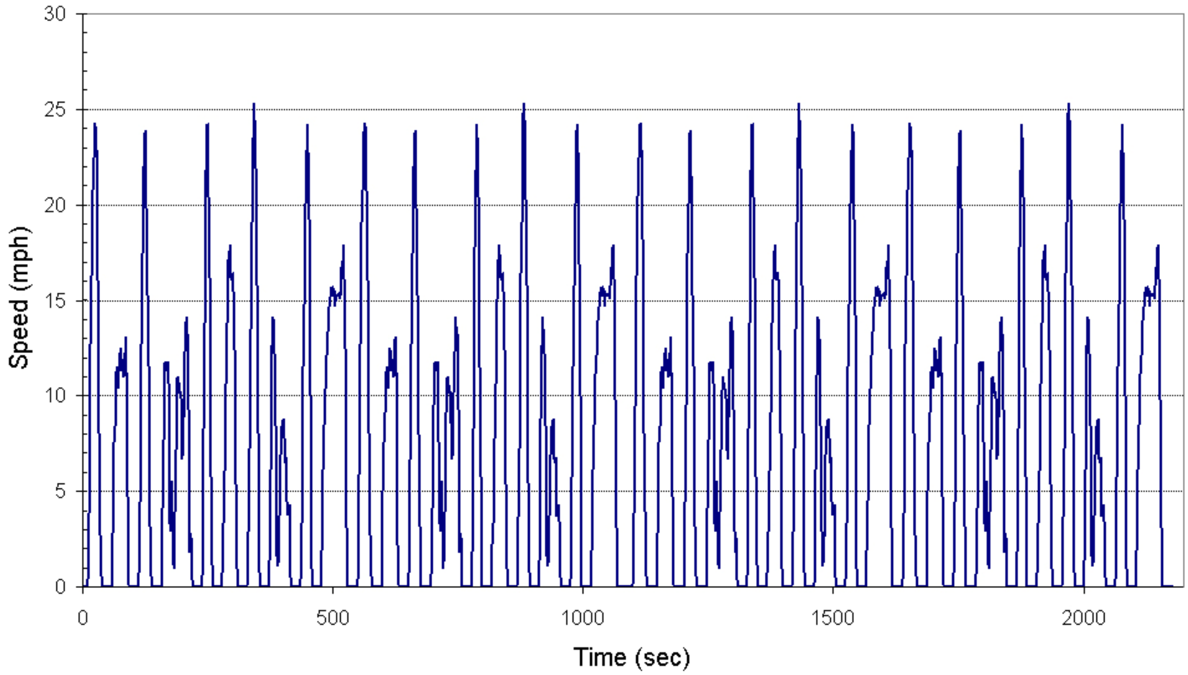

Figure 15. Manhattan x2 Test Cycle

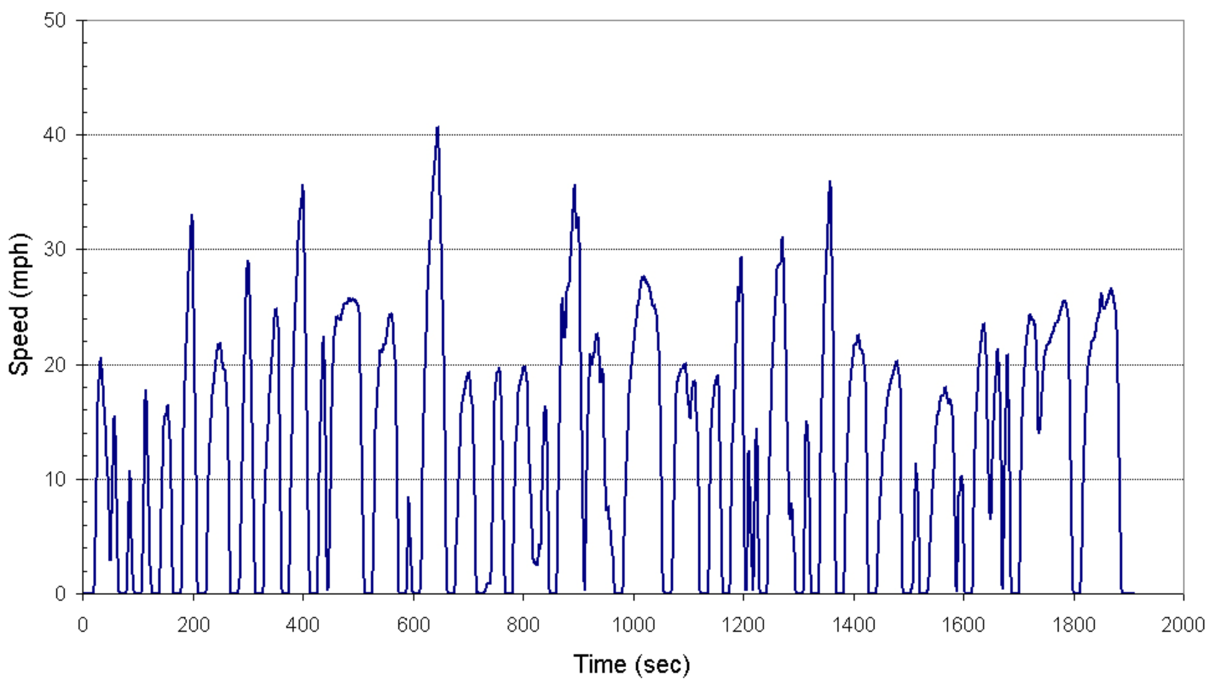

Figure 16. Orange County Test Cycle

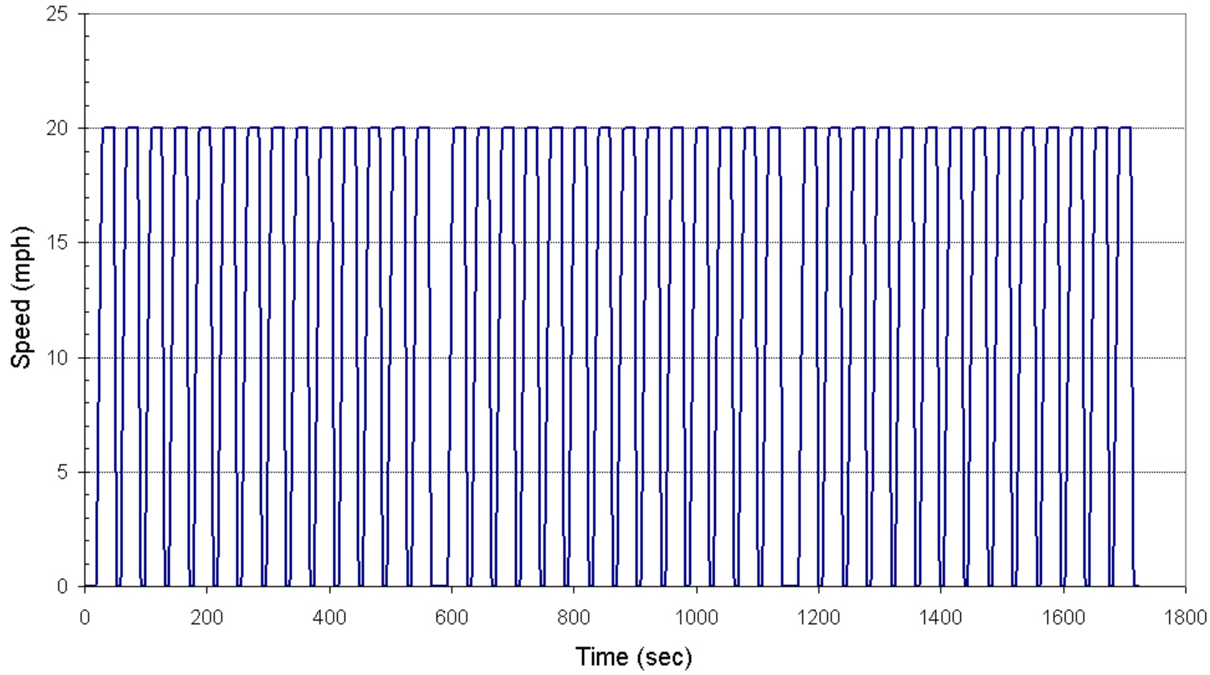

Figure 17. CBD x 3 Test Cycle

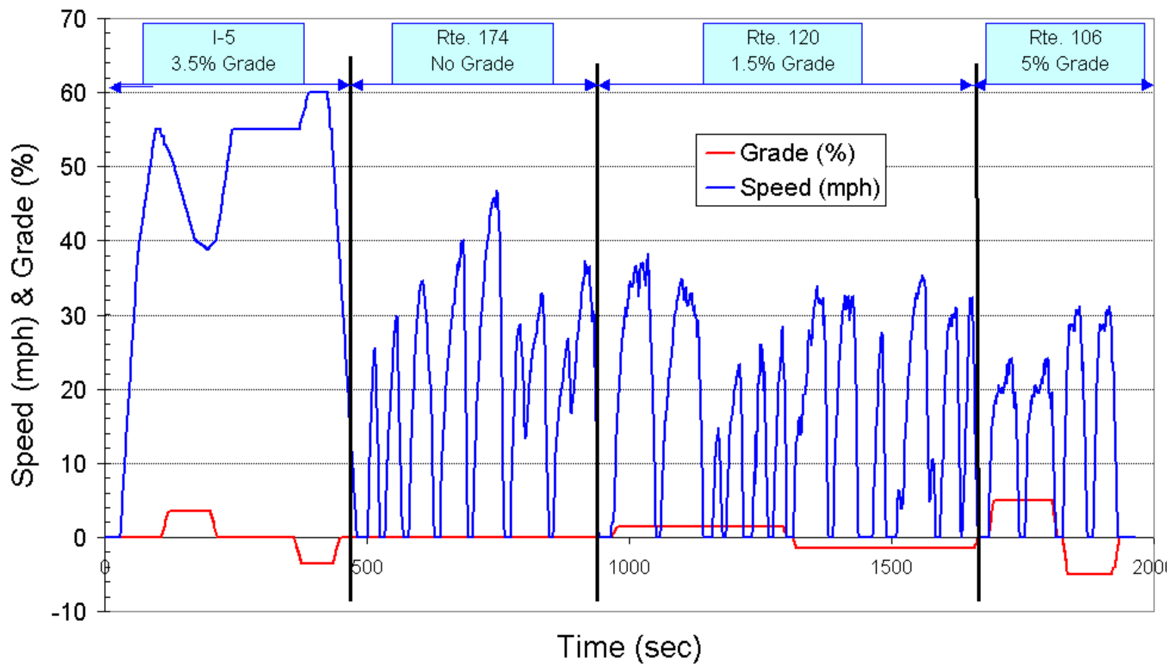

Figure 18. King County Metro Test Cycle

Table 10. Cycle Statistics

Test Cycle	CBDx3	Manhattanx2	Orange Co	KCM
Total Time (sec)	1722	2178	1909	1964
Time at Idle (%)	20.0	36.1	21.3	18.9
Average Cycle Speed (mph)	12.58	6.83	12.33	23.42
Average Speed while driving (mph)	15.73	10.68	15.67	28.87
Maximum Speed (mph)	20.0	25.3	40.6	60.0
Total Distance (miles)	6.02	4.13	6.54	12.78
Number of Stops (stops/mile)	6.98	9.68	4.74	1.88
Average Acceleration Rate (ft/sec^2)	2.66	1.77	1.48	1.61
Maximum Acceleration Rate (ft/sec^2)	3.37	6.75	5.95	14.18

Table 11. KCM Composite Breakdown - Cycle Statistics

Test Cycle	I-5	Rte 174	Rte 120	Rte 106
Total Time (sec)	499	460	724	278
Time at Idle (%)	10.02	18.04	23.07	25.54
Average Cycle Speed (mph)	41.85	19.61	16.39	14.98
Average Speed while driving (mph)	46.5	23.92	21.29	20.1
Maximum Speed (mph)	60	46.75	38.32	31.22
Total Distance (miles)	5.81	2.51	3.3	1.16
Number of Stops (stops/mile)	0.17	2.79	3.64	3.44
Average Acceleration Rate (ft/sec^2)	0.96	1.64	1.75	1.76
Maximum Acceleration Rate (ft/sec^2)	1.65	5.58	14.18	6.06

Appendix F: Driving Style

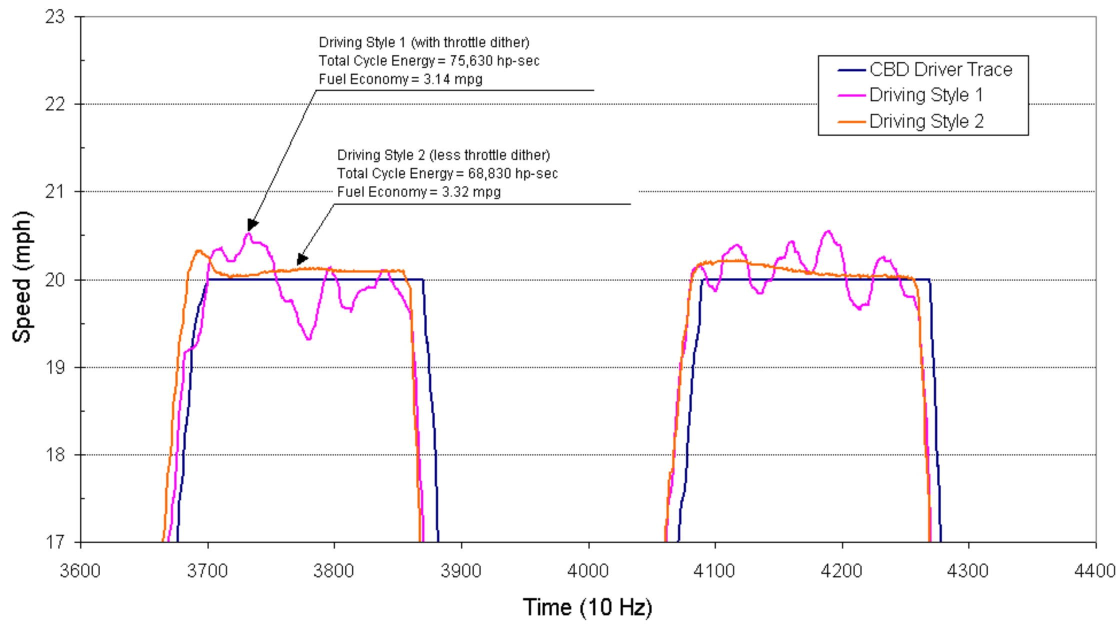

Figure 19. CBD Driving Styles

Appendix G: Tabulated Test Results

Table 12. Baseline Vehicle Data

Date	Run	Cycle	Driver	CO2 g/mile	NOx g/mile	THC g/mile	CO g/mile	PM g/mile	Fuel Consumption g/mile	Fuel Economy mpg	Distance miles	Energy From Vehicle hp-s
5/9/2005	554	OCTA	John	4584	18.95	0.03	2.20	0.047	1470	2.15	6.50	83259
5/9/2005	555	OCTA	John	4603	18.98	0.03	1.92	0.056	1476	2.14	6.50	84110
5/9/2005	556	OCTA	John	4550	18.81	0.03	2.75	0.046	1461	2.16	6.47	82701
avg				**4579**	**18.91**	**0.03**	**2.29**	**0.050**	**1469**	**2.15**	**6.49**	**83357**
std dev				*26.94*	*0.09*	*0.00*	*0.42*	*0.01*	*7.67*	*0.01*	*0.02*	709.56
cov				0.59	0.47	5.75	18.40	11.41	0.52	0.52	0.27	0.85
5/6/2005	544	Manhattan	Tom	6662	29.33	0.03	2.39	0.038	2147	1.47	4.15	65735
5/6/2005	545	Manhattan	Tom	6716	29.72	0.05	3.93	0.039	2160	1.46	4.13	64747
5/6/2005	546	Manhattan	Tom	6763	29.70	0.03	3.06	0.038	2173	1.45	4.10	65987
avg				**6714**	**29.58**	**0.04**	**3.13**	**0.038**	**2160**	**1.46**	**4.13**	**65490**
std dev				*50.49*	*0.22*	*0.01*	*0.77*	*0.00*	*13.04*	*0.01*	*0.03*	655.39
cov				0.75	0.73	30.58	24.61	1.42	0.60	0.65	0.61	1.00
5/4/2005	536	CBD	Tom	4586	19.56	0.16	1.27	0.112	1450	2.18	6.01	67754
5/4/2005	537	CBD	Tom	4599	19.58	0.10	1.56	0.115	1449	2.18	6.02	68591
5/4/2005	538	CBD	Tom	4581	19.52	0.10	1.49	0.105	1439	2.20	5.99	68084
5/4/2005	539	CBD	John	4607	19.74	0.10	2.22	0.093	1451	2.18	5.92	66723
5/4/2005	540	CBD	John	4569	20.01	0.14	1.89	0.098	1441	2.20	5.97	67919
5/4/2005	541	CBD	John	4580	19.62	0.11	2.16	0.081	1442	2.19	6.00	67649
avg				**4587**	**19.67**	**0.12**	**1.77**	**0.101**	**1445**	**2.19**	**5.98**	**67787**
std dev				*13.88*	*0.18*	*0.02*	*0.39*	*0.01*	*5.32*	*0.01*	*0.04*	617.13
cov				0.30	0.92	20.33	21.86	12.76	0.37	0.35	0.60	0.91
5/16/2005	582	CBD w/ AC	John	5227	21.26	0.03	0.91	0.071	1660	1.91	5.97	70180
5/16/2005	583	CBD w/ AC	John	5153	21.09	0.03	1.03	0.067	1637	1.93	6.02	70342
5/16/2005	584	CBD w/ AC	John	5181	21.25	0.02	1.03	0.085	1644	1.92	5.98	69689
avg				**5187**	**21.20**	**0.03**	**0.99**	**0.074**	**1647**	**1.92**	**5.99**	**70070**
std dev				*37.10*	*0.09*	*0.01*	*0.07*	*0.01*	*11.65*	*0.01*	*0.03*	340.03
cov				0.72	0.44	27.51	6.73	12.59	0.71	0.66	0.44	0.49
5/10/2005	558	KCM	Tom	3513	14.64	0.04	0.41	0.118	1112	2.84	12.64	150810
5/10/2005	559	KCM	Tom	3462	14.52	0.06	0.55	0.095	1092	2.90	12.66	148390
5/10/2005	560	KCM	Tom	3447	14.65	0.06	0.64	0.091	1090	2.90	12.68	150350
5/10/2005	561	KCM	John	3412	14.68	0.04	0.81	0.141	1081	2.92	12.76	150980
5/10/2005	562	KCM	John	3440	15.02	0.04	0.71	0.113	1091	2.90	12.67	150750
5/10/2005	563	KCM	John	3401	14.90	0.04	0.84	0.088	1081	2.92	12.70	149290
avg				**3446**	**14.74**	**0.04**	**0.66**	**0.108**	**1091**	**2.90**	**12.69**	**150095**
std dev				*40.00*	*0.19*	*0.01*	*0.16*	*0.02*	*11.10*	*0.03*	*0.04*	1033.78
cov				1.16	1.28	21.23	24.78	18.88	1.02	0.99	0.33	0.69
5/11/2005	567	KCM w/o Grade	Tom	3279	13.55	0.03	0.44	0.043	1041	3.04	12.78	132430
5/11/2005	568	KCM w/o Grade	Tom	3293	13.34	0.02	0.39	nm	1046	3.03	12.79	134080
5/11/2005	569	KCM w/o Grade	Tom	3281	13.26	0.01	0.48	0.032	1042	3.04	12.80	135140
5/17/2005	593	KCM w/o Grade	John	3297	13.90	0.02	0.69	0.021	1042	3.03	12.82	136310
5/17/2005	594	KCM w/o Grade	John	3330	13.93	0.02	0.56	0.030	1053	3.00	12.82	134260
avg				**3296**	**13.60**	**0.02**	**0.51**	**0.031**	**1045**	**3.03**	**12.80**	**134444**
std dev				*20.24*	*0.31*	*0.01*	*0.12*	*0.01*	*4.91*	*0.02*	*0.02*	*1430.81*
cov				0.61	2.29	31.13	23.52	28.72	0.47	0.56	0.14	1.06
5/16/2005	588	KCM w/o Grade w/ AC	John	3660	15.31	0.04	0.57	0.062	1164	2.72	12.72	130540
5/16/2005	589	KCM w/o Grade w/ AC	John	3590	15.40	0.04	0.36	0.072	1145	2.76	12.76	133270
5/17/2005	591	KCM w/o Grade w/ AC	John	3586	15.10	0.02	0.40	0.051	1133	2.79	12.75	133880
5/17/2005	592	KCM w/o Grade w/ AC	John	3590	15.13	0.02	0.56	0.041	1134	2.79	12.76	132100
5/13/2005	573	KCM w/o Grade w/ AC	Tom	3647	15.57	0.03	0.10	0.078	1155	2.74	12.68	130950
avg				**3615**	**15.30**	**0.03**	**0.40**	**0.061**	**1146**	**2.76**	**12.73**	**132148**
std dev				*35.90*	*0.20*	*0.01*	*0.19*	*0.02*	*13.45*	*0.03*	*0.03*	*1438.91*
cov				0.99	1.28	25.23	48.08	24.80	1.17	1.15	0.27	1.09

Table 13. Hybrid Vehicle Data

Date	Run	Cycle	Driver	CO2	NOx	THC	CO	PM	Fuel Consumption	Fuel Economy	ESS vs Cycle Energy	NEC	Distance	Energy From Vehicle
				g/mile	g/mile	g/mile	g/mile	g/mile	g/mile	mpg	%	amp-hr	miles	hp-s
6/27/2005	652	OCTA	John	3015	13.34	0.04	1.48	0.021	979	3.22	-0.25	-0.30	6.56	86920
6/27/2005	653	OCTA	John	2989	13.48	0.03	1.69	0.024	970	3.26	-0.30	-0.35	6.55	85670
6/27/2005	654	OCTA	John	3001	13.70	0.03	1.49	0.029	973	3.24	0.22	0.25	6.53	84910
avg				**3001**	**13.51**	**0.03**	**1.55**	**0.024**	**974**	**3.24**	**-0.11**	**-0.13**	**6.55**	**85833**
std dev				*12.66*	*0.18*	*0.00*	*0.12*	*0.00*	*4.72*	*0.02*	*0.29*	*0.34*	*0.02*	*1014.91*
cov				0.42	1.33	7.27	7.70	16.63	0.48	0.48	-259.22	-256.34	0.23	1.18
%diff vs conv				**-34.5%**	**-28.6%**	**8.5%**	**-32.0%**	**-50.8%**	**-33.7%**	**50.6%**			**0.9%**	**3.0%**
6/27/2005	655	Manhattan	John	3718	17.89	0.07	3.47	0.002	1215	2.60	-0.61	-0.56	4.14	66170
6/27/2005	656	Manhattan	John	3790	18.18	0.07	3.07	0.002	1240	2.54	-0.47	-0.44	4.17	67780
6/27/2005	657	Manhattan	John	3806	18.30	0.01	1.88	0.005	1248	2.53	-0.48	-0.45	4.14	67140
avg				**3771**	**18.12**	**0.05**	**2.81**	**0.003**	**1234**	**2.56**	**-0.52**	**-0.49**	**4.15**	**67030**
std dev				*46.83*	*0.21*	*0.04*	*0.83*	*0.00*	*17.13*	*0.04*	*0.08*	*0.07*	*0.02*	*810.62*
cov				1.24	1.17	69.64	29.44	52.31	1.39	1.44	-15.39	-13.79	0.42	1.21
%diff vs conv				**-43.8%**	**-38.7%**	**29.4%**	**-10.2%**	**-92.6%**	**-42.9%**	**74.6%**			**0.6%**	**2.4%**
6/30/2005	681	CBD	John	3038	14.52	0.01	nm	0.003	984	3.20	-0.26	-0.29	6.08	69100
6/30/2005	682	CBD	John	2958	14.37	0.04	1.08	0.004	960	3.28	-0.79	-0.84	6.08	68790
7/1/2005	686	CBD	John	2978	14.43	0.04	0.75	0.002	968	3.26	-0.57	-0.62	6.08	69120
avg				**2991**	**14.44**	**0.03**	**0.92**	**0.003**	**971**	**3.25**	**-0.54**	**-0.58**	**6.08**	**69003**
std dev				*41.93*	*0.08*	*0.02*	*0.23*	*0.00*	*11.95*	*0.04*	*0.26*	*0.28*	*0.00*	*185.02*
cov				1.40	0.53	59.62	25.32	33.64	1.23	1.26	-48.72	-48.02	0.00	0.27
%diff vs conv				**-34.8%**	**-26.6%**	**-75.2%**	**-48.0%**	**-97.1%**	**-32.8%**	**48.3%**			**1.6%**	**1.8%**
6/30/2005	680	CBD w/ AC	John	3735	17.84	0.01	0.84	0.101	1211	2.60	-0.69	-0.93	6.07	70420
6/30/2005	672	CBD w/ AC	John	3724	17.36	0.03	0.52	0.042	1204	2.62	-0.63	-0.84	6.03	69270
avg				**3730**	**17.60**	**0.02**	**0.68**	**0.072**	**1207**	**2.61**	**-0.66**	**-0.89**	**6.05**	**69845**
std dev				*7.50*	*0.34*	*0.01*	*0.23*	*0.04*	*5.06*	*0.01*	*0.04*	*0.06*	*0.03*	*813.17*
cov				0.20	1.92	47.59	33.17	57.42	0.42	0.42	-6.14	-7.07	0.47	1.16
%diff vs conv				**-28.1%**	**-17.0%**	**-26.7%**	**-31.1%**	**-3.7%**	**-26.7%**	**35.8%**			**1.0%**	**-0.3%**
6/28/2005	659	KCM	John	2614	12.03	0.02	0.26	0.239	835	3.78	-0.10	-0.20	12.79	153270
6/28/2005	660	KCM	John	2624	12.18	0.02	0.31	0.135	839	3.76	0.63	1.21	12.78	152900
6/28/2005	661	KCM	John	2604	12.11	0.02	0.24	nm	832	3.79	0.17	0.32	12.79	152190
avg				**2614**	**12.11**	**0.02**	**0.27**	**0.187**	**836**	**3.78**	**0.23**	**0.45**	**12.79**	**152787**
std dev				*10.27*	*0.07*	*0.00*	*0.03*	*0.07*	*3.54*	*0.02*	*0.37*	*0.71*	*0.01*	*548.84*
cov				0.39	0.61	19.26	12.61	39.10	0.42	0.42	159.88	160.15	0.05	0.36
%diff vs conv				**-24.1%**	**-17.8%**	**-56.3%**	**-59.5%**	**73.7%**	**-23.4%**	**30.3%**			**0.8%**	**1.8%**
6/28/2005	662	KCM w/o Grade	John	2506	11.57	0.01	0.10	0.048	803	3.93	0.08	0.14	12.83	137080
6/30/2005	677	KCM w/o Grade	John	2472	11.18	0.03	0.17	0.015	786	4.01	-0.78	-1.43	12.82	134990
6/30/2005	679	KCM w/o Grade	John	2472	11.15	0.02	0.27	0.036	788	4.00	-0.54	-1.00	12.80	135070
avg				**2483**	**11.30**	**0.02**	**0.18**	**0.033**	**792**	**3.98**	**-0.41**	**-0.76**	**12.82**	**135713**
std dev				*19.67*	*0.24*	*0.01*	*0.09*	*0.02*	*9.25*	*0.04*	*0.44*	*0.81*	*0.02*	*1184.25*
cov				0.79	2.09	61.88	48.47	50.11	1.17	1.09	-106.09	-106.35	0.12	0.87
%diff vs conv				**-24.7%**	**-16.9%**	**-0.0%**	**-64.7%**	**6.5%**	**-24.2%**	**31.4%**			**0.0%**	**0.9%**
6/29/2005	668	KCM w/o Grade w/ AC	John	nm	nm	nm	nm	nm	924	3.41	-0.92	-2.00	12.82	141150
6/29/2005	670	KCM w/o Grade w/ AC	John	2854	13.74	0.01	0.43	0.062	907	3.47	-0.36	-0.77	12.77	134250
6/29/2005	671	KCM w/o Grade w/ AC	John	2874	13.78	0.01	0.34	0.051	913	3.45	-0.33	-0.70	12.79	135280
avg				**2864**	**13.76**	**0.01**	**0.39**	**0.056**	**914**	**3.45**	**-0.54**	**-1.16**	**12.79**	**136893**
std dev				*14.21*	*0.03*	*0.00*	*0.06*	*0.01*	*8.75*	*0.03*	*0.33*	*0.73*	*0.03*	*3722.18*
cov				0.50	0.23	3.36	16.65	13.41	0.96	0.89	-61.49	-63.04	0.20	2.72
%diff vs conv				**-20.8%**	**-10.1%**	**-66.7%**	**-2.5%**	**-8.2%**	**-20.2%**	**25.0%**			**0.0%**	**3.6%**
6/1/2005	629	CBD*	Tom	3082	14.49	0.02	1.21	nm	1007	3.14	0.40	0.45	6.03	75630
6/1/2005	630	CBD*	Tom	3088	14.54	0.04	1.34	nm	1008	3.14	0.81	0.90	6.03	76020
6/1/2005	631	CBD*	Tom	3045	14.38	0.04	1.59	nm	998	3.17	0.84	0.94	6.06	75360
avg				**3072**	**14.47**	**0.04**	**1.38**	**0.0119**	**1004**	**3.15**	**0.68**	**0.76**	**6.04**	**75670**
std dev				*23.41*	*0.08*	*0.01*	*0.19*	*0.006*	*5.58*	*0.02*	*0.25*	*0.27*	*0.02*	*331.82*
cov				0.76	0.56	31.71	14.01	0.5	0.56	0.54	35.98	35.71	0.29	0.44
%diff vs conv				-33.0%	-26.4%	-66.7%	-22.0%	-88.2%	-30.5%	43.8%			1.0%	11.6%

Note - Runs 629 through 631 are with driving style 1 (more throttle dither)

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14. ABSTRACT *(Maximum 200 Words)*
The National Renewable Energy Laboratory's (NREL) ReFUEL facility conducted chassis dynamometer testing of two 60-foot articulated transit buses, one conventional and one hybrid. This document includes the experimental setup, test procedures, and results from vehicle testing performed at the NREL ReFUEL laboratory.

15. SUBJECT TERMS
ReFUEL; chassis dynomometer; bus; hybrid; King County

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