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Field Operations Program Toyota PRIUS Hybrid Electric Vehicle Performance Characterization Report

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EXECUTIVE SUMMARY

The U.S. Department of Energy's Field Operations Program evaluates advanced technology vehicles in real-world applications and environments. Advanced technology vehicles include pure electric, hybrid electric, hydrogen, and other vehicles that use emerging technologies such as fuel cells. Information generated by the Program is targeted to fleet managers and others considering the deployment of advanced technology vehicles. As part of the above activities, the Field Operations Program has initiated the testing of the Toyota Prius hybrid electric vehicle (HEV), a technology increasingly being considered for use in fleet applications. This report describes the Pomona Loop testing of the Prius, providing not only initial operational and performance information, but also a better understanding of HEV testing issues. The Pomona Loop testing includes both Urban and Freeway drive cycles, each conducted at four operating scenarios that mix minimum and maximum payloads with different auxiliary (e.g., lights, air conditioning) load levels.

The Prius is powered by a 70-hp, 1.5-liter, 4-cylinder gasoline engine and a 44-hp electric motor. The Prius also has a 274-volt battery comprising 228 1.2-volt cells.

The Prius exhibited test results of 35 to 58 mpg during the Urban Loop testing; the EPA estimate for city driving is 52 mpg. During the Freeway Loop testing, the Prius got 39 to 46 mpg; the EPA estimate for highway driving is 45 mpg. Even though the EPA tests are conducted on a dynamometer and the Pomona Loop tests are conducted as on-road driving tests, when tested with a minimum payload and no auxiliary loads, the mpg test results are the same for the Freeway Loop testing and the EPA highway testing. Under the same operating scenario, the Urban Loop results are 4 mpg higher than the EPA estimate for city driving.

The Pomona Loop testing of the Prius also demonstrated the difficulty of measuring fuel use. Unlike electric vehicles, where a kWh or amp-hour meter can accurately measure electron flows, the HEV's fuel use is determined by measuring how much gasoline was used; so a void must now be accurately measured. One option is to apply a known amount of fuel to the vehicle and run it until it stops. However, rarely will a perfectly uniform amount of fuel remain and even more rarely will the vehicle run out of fuel where it started, so this method is not practical for on-road testing.

Another issue is that variables such as driver behavior (the "lead" foot), the use of air conditioning and other auxiliary loads, or the type of driving cycle used can result in significant energy efficiency variations. The eight individual Urban Loop test results ranged from 35.3 to 54.5 mpg, a 54% differential.

The Prius testing not only provided an initial performance benchmark for the Prius but also highlighted HEV-specific testing issues. These will be used to prepare for expanded HEV testing, and to ensure accurate fuel-use measurements are taken in applications that are both meaningful and applicable to fleet managers.

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ACRONYMS

DOE	U.S. Department of Energy
EV	Electric Vehicle
EVTC	Electric Vehicle Technical Center
HEV	Hybrid Electric Vehicle
INEEL	Idaho National Engineering and Environmental Laboratory
kWh	kilowatt-hour
MPG	Miles per Gallon
NiMH	Nickel metal hydride (battery)
QVTs	Qualified Vehicle Testers
SCE	Southern California Edison Company
SOC	state-of-charge

Field Operations Program
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1. INTRODUCTION

The Field Operations Program provides fleet managers and other potential advanced technology vehicle (ATV) users with accurate and unbiased information on vehicle performance. This allows the purchaser to make informed decisions about acquiring and operating ATVs. Vehicle information is obtained by testing ATVs in conjunction with industry partners and disseminating the testing results. The ATVs are tested using three methods - Baseline Performance Testing, Accelerated Reliability Testing, and Fleet Testing. The testing results are disseminated via the Program's Website in the form of vehicle fact sheets, summary reports, and survey results (http://ev.inel.gov/fop). Additional information on the Website includes testing specifications and procedures as well as general information about ATVs, such as how they work and their histories.

The Field Operations Program signed a 5-year testing agreement in 1999 with the following group of Qualified Vehicle Testers (QVTs):

- Electric Transportation Applications (lead partner)
- American Red Cross.
- Arizona Public Service
- Bank One of Arizona
- Potomac Electric Power Company
- Salt River Project
- Southern California Edison
- Southwest Airlines
- Virginia Power

As part of the Field Operations Program testing activities, Southern California Edison (SCE) performed Pomona Loop testing on a Toyota Prius hybrid electric vehicle (HEV).

The Pomona Loop testing of the Prius was conducted not only to gather its operational and performance information, but also to better understand HEV testing issues. For instance, what testing variables are unique to HEVs and can these variables significantly affect the accuracy of the test results? Another question is how should HEVs be tested so the results are meaningful to fleet managers and other potential HEV users? Informal conversations with other HEV testers indicate that some test methods do not always accurately reflect the performance of HEVs when they are used in fleet applications. In addition, there are Websites that post very high miles per gallon (mpg) results obtained by HEV drivers. Only when you read the "fine print" do you discover that these drivers employ behaviors that include "drafting" 3 feet from the back ends of tractor-trailers. Other such behavior associated with very high mpg includes limiting highway speeds to 50–55 mph when the speed limit is 65 mph or higher. These unsafe driving behaviors will hopefully not be encouraged by fleet managers nor practiced by fleet drivers.

Program personnel and the testing partners recognized that new test procedures and controls could be required for HEV testing. Because they wanted to determine whether past electric vehicle (EV) testing experience was applicable to HEV testing and not be presumptuous that they fully understood all of the HEV testing issues, they decided to apply a lessons-learned approach to the first HEV tests.

For example, when EVs are range tested, the distance traveled per charge was rarely greater than 100 miles and the energy used was usually 20 to 30 kWh. Electric energy use is easy to measure with kWh or amp meters, and the mathematics of distance traveled versus energy units used make range calculations very accurate. However, when testing gasoline use in HEVs, more miles must be accumulated to accurately measure either energy use per distance traveled or distance traveled per energy unit.

Pomona Loop testing is a relatively fast and inexpensive method to identify these and other issues such as the significant variations in fuel consumption that can occur in HEVs when driver behavior is variable. This can include not only the aggressiveness in how the test driver drives the HEV, but also what on-board vehicle options are turned on during the drive. For instance, air conditioning can have a significant energy use impact, especially with the smaller gasoline engines used in HEVs.

To more fully understand the above and other issues, as well as to prepare for more complex (and expensive) testing, the Field Operations Program partnered with SCE to Pomona Loop test the Prius.

SCE also has their own organizational interests that compelled them to want to test the Prius. These are briefly discussed below.

The Prius testing results discussed in this report are based on the SCE Prius testing report (TC-01-138-TR02). This report summarizes the results.

1.1 Southern California Edison’s Testing Interests

Over the years, new technologies have evolved that promise to have a significant impact in the transportation industry. One such technology is the hybrid power train. It is important that these early market entrants be evaluated and understood in terms of performance, energy efficiency, and emissions. Once different models have been tested, an evaluation of the benefits of the different hybrid configurations, including plug-in hybrids, will be possible. To this end, SCE partnered with the Field Operations Program to conduct a performance characterization of a Toyota Prius.

The purpose of SCE’s evaluation of EVs, HEVs, EV chargers, batteries, and related items is to support their safe and efficient use and to minimize potential utility system impacts. The following facts support this purpose:

- As a fleet operator and an electric utility, SCE uses EVs to conduct business.
- SCE must evaluate EVs, HEVs, batteries, and charging equipment in order to make informed purchase decisions.
- SCE must determine if there are any safety issues with EV equipment and their usage.

- SCE has a responsibility to educate and advise its customers about the efficient and safe operation of EVs and HEVs.

Tests performed were: weight certification, range, fuel efficiency, performance (acceleration, maximum speed, and braking), and sound measurements. They were conducted at SCE's Electric Vehicle Technical Center (EVTC) and on the Urban and the Freeway Pomona Loops. Testing was conducted in accordance with the SCE HEV test procedure.

2. MANUFACTURER'S SPECIFICATIONS

Table 1. Toyota Prius manufacturer specifications.[a]

Gasoline Engine	
Type:	Aluminum double overhead cam (DOHC)
Displacement (cc)	1497
Horsepower @ rpm	70 @ 4500
Torque @ rpm	82 @ 4200
Compression Ratio	13.0:1
Valvetrain:	16-Valve with Variable Valve Timing with intelligence (VVT-i)
Fuel System:	Multi-Point EFI w/ Electronic Throttle Control System w/ Intelligence (ETCS-i)
Ignition System:	Electronic w/ Toyota Direct Ignition system (TDI)
Emission Rating:	Super Ultra Low Emission Vehicle (SULEV)
Electric Motor/ Generator	
Motor Type	Permanent Magnet
Power Output	33 kW/44 hp @ 1040 - 5600 rpm
Electric Power Storage	
Battery Type	Sealed Nickel-Metal Hydride (NiMH)
Output	273.6 V (228 1.2-V Cells)
Drivetrain	
Type:	Front-Wheel Drive
Transmission:	Electronically Controlled CVT
Body/Suspension/Chassis	
Body Type:	Aluminum monocoque
Front Suspension:	MacPherson Strut w/ stabilizer bar
Rear Suspension:	Torsion Beam w/ stabilizer bar
Electric Power Steering (EPS)	Rack-and-Pinion w/ electric power-assist
Turning Diameter, Curb-to-Curb (ft.)	31.6
Power-Assisted Ventilated Front Disc/Rear Drum	
4-Wheel Anti-Lock Braking System (ABS)	
Wheels:	14-in. Alloy
Tires:	P175/65 R14 Low Rolling-Resistance
Interior Dimensions	
Head room (in., front/rear)	38.8/37.1
Leg room (in., front/rear)	41.2/35.4
Shoulder Room (in., front/rear)	52.8/52.2
Hip room (in., front/rear)	50.7/51.9
Cargo Volume (cu. ft.)	11.8
Passenger Volume (cu. ft.)	88.6
Exterior Dimensions	

Wheelbase (in.)	100.4
Length (in.)	169.6
Height (in.)	57.6
Width (in.)	66.7
Track (in., front/rear)	58.1/58.2
Curb Weight (lbs.)	2765
EPA Mileage Estimates††/Fuel Capacity	
City/Highway/Combined	52/45/48
Fuel (gal.)	11.9
Fuel Required	Regular Unleaded
†† Final EPA mileage estimate. Actual mileage may vary.	
a. Source – http://prius.toyota.com/details/specs.html	

3. RANGE AND FUEL USE TEST RESULTS

The Pomona Loop Testing consists of two types of on-road drive cycles:

1. The Urban Loop is 19.3 miles long with approximately 50 stop signs and traffic lights, and the elevation ranges from about 900 to 1,500 feet above sea-level (Appendix A). The Urban Loop is located in the greater Pomona, California area and it consists of city and residential area streets.
2. The Freeway Loop is 37.2 miles long with elevation ranges from about 700 to 1,150 feet above sea-level (Appendix A). The Freeway Loop is located in the much greater Pomona, California area and it consists of Southern California freeways.

Four vehicle-operating scenarios are used for each of the Pomona Loops, including operating the test vehicles with minimum or maximum payloads and either no auxiliary or auxiliary loads (Table 2). The Prius was tested twice at each of the four operating scenarios for both the Urban and Freeway Loops, so that a total of 16 drive cycles were performed.

Table 2. Pomona Loop operating scenarios for test vehicles.

Pomona Urban Loop Vehicle Operating Scenarios	
UR-1	Urban Range Test, Min Payload, No Auxiliary Loads
UR-2	Urban Range Test, Min Payload, A/C on High, Headlights on Low, Radio On
UR-3	Urban Range Test, Max Payload, No Auxiliary Loads
UR-4	Urban Range Test, Max Payload, A/C on High, Headlights on Low, Radio On
Pomona Freeway Loop Vehicle Operating Scenarios	
FW-1	Freeway Range Test, Min Payload, No Auxiliary Loads
FW-2	Freeway Range Test, Min Payload, A/C on High, Headlights on Low, Radio On
FW-3	Freeway Range Test, Max Payload, No Auxiliary Loads
FW-4	Freeway Range Test, Max Payload, A/C on High, Headlights on Low, Radio On

For a full discussion of the Urban and Freeway Pomona Loop testing, the Southern California Edison Pomona Loop Test Procedures Report can be accessed at the following address http://ev.inel.gov/fop

3.1 Urban Loop Test Results

The Prius was tested twice for each of four operating scenarios on the Urban Pomona Loop (Table 3). For urban driving with a minimum payload and no auxiliaries used (UR-1), the average fuel economy was 55.6 mpg. With a minimum payload and the auxiliary loads turned on (UR-2), the fuel economy dropped to an average of 49.5 mpg. With the maximum payload and no auxiliaries on (UR-3), the fuel economy was 47.5 mpg. With the maximum payload and the auxiliary loads turned on (UR-4), the fuel economy dropped to 35.7 mpg. It should be noted that while the driver was not supposed to play the radio during the no-auxiliary load tests, the radio was played during all of the mileage tests, including the no-auxiliary load tests (Loops UR-1 and UR-3).

Table 3. Toyota Prius Urban Loop testing results.

Drive Cycle	Test Date	Average Ambient Temp (F)	Total fuel usage (gal)	Miles driven	Calculated MPG	Manufacturer MPG[1]
UR-1	07/31/01	79.0	1.76	101.3	57.6	54.4
UR-1	08/22/01	75.0	1.89	101.5	53.7	54.0
UR-2	08/01/01	79.0	1.99	102.5	51.4	52.4
UR-2	08/20/01	85.0	2.15	102.3	47.6	43.5
UR-3	08/07/01	90.0	2.15	103.1	47.9	49.1
UR-3	08/15/01	100.0	2.17	102.1	47.1	47.8
UR-4	08/09/01	84.0	2.91	102.2	35.2	35.3
UR-4	08/14/01	92.0	2.86	103.9	36.3	36.9

[1] Fuel Economy Meter MPG is average of 21 readings.

The estimated range calculation is based on the nominal 11.9 gallon fuel tank and the above testing results. The average estimated ranges are listed by operating scenarios:

- UR-1, minimum payload and no auxiliaries – 662 miles
- UR-2, minimum payload and auxiliaries on – 589 miles
- UR-3, maximum payload and no auxiliaries – 565 miles
- UR-4, maximum payload and auxiliaries – 425 miles

The total mileage driven during the eight urban drive cycles (four types of urban tests, each driven twice) was 818.9 miles and the total fuel used was 17.88 gallons. Therefore, the overall fuel economy during the eight urban drive cycles was 45.8 mpg, and based on the 11.9-gallon fuel tank, the average range would be 545 miles.

3.2 Freeway Loop Test Results

The Prius was also tested twice for each of the four operating scenarios on the Freeway Pomona Loop (Table 4). For freeway driving with a minimum payload and no auxiliaries used (FW-1), the average fuel economy was 45.4 mpg. With a minimum payload and the auxiliaries turned on (FW-2), the fuel economy dropped to an average of 42.6 mpg. With maximum payload and no auxiliaries on (FW-3), the fuel economy was 44.5 mpg. Again, with maximum payload and the auxiliary load on (FW-4), the fuel economy dropped to 40.0 mpg. It should be noted that while the driver was not supposed to play the radio during the no-auxiliary load tests, the radio was played during all of the mileage tests, including the no-auxiliary load tests (Loops FW-1 and FW-3).

Table 4. Toyota Prius miles driven and fuel use results from the Freeway Loop testing.

Drive Cycle	Test Date	Average Ambient Temp (F)	Total fuel usage (gal)	Miles driven	Calculated MPG	Manufacturer MPG[1]
FW-1	08/02/01	79.5	2.28	103.2	45.2	47.4
FW-1	08/16/01	87.0	2.22	100.9	45.5	51.8
FW-2	08/03/01	79.0	2.52	106.5	42.3	43.1
FW-2	08/21/01	78.0	2.37	102.0	42.9	41.5
FW-3	08/06/01	89.0	2.33	104.2	44.8	44.4
FW-3	08/10/01	83.0	2.37	104.8	44.2	46.1
FW-4	08/08/01	89.0	2.54	103.5	40.8	42.7
FW-4	08/13/01	87.0	2.58	101.0	39.1	41.6

[1] Fuel Economy Meter MPG is average of 21 readings.

The estimated range calculation was based on the 11.9-gallon fuel tank and the above testing results. The average estimated freeway ranges are listed by operating scenarios:

- FW-1, minimum payload and no auxiliaries – 540 miles
- FW-2, minimum payload and auxiliaries on – 507 miles
- FW-3, maximum payload and no auxiliaries – 530 miles
- FW-4, maximum payload and auxiliaries – 476 miles.

The total mileage driven during the eight freeway drive cycles (four types of freeway tests, each driven twice) was 826.1 miles and the total fuel used was 19.21 gallons. Therefore, the overall fuel economy during the eight freeway drive cycles was 43.0 mpg, and based on the 11.9 gallon fuel tank, the average range was 512 miles.

The overall fuel use for all 16 tests averaged 43 mpg (UR&FW Average in Figure 1). Figure 1 also shows the average mpg results for the two tests performed for each operating scenario as well as the average mpg results for all eight urban tests (UR-Average) and all eight freeway tests (FW-Average). (See Table 2 for an explanation of the operating scenarios).

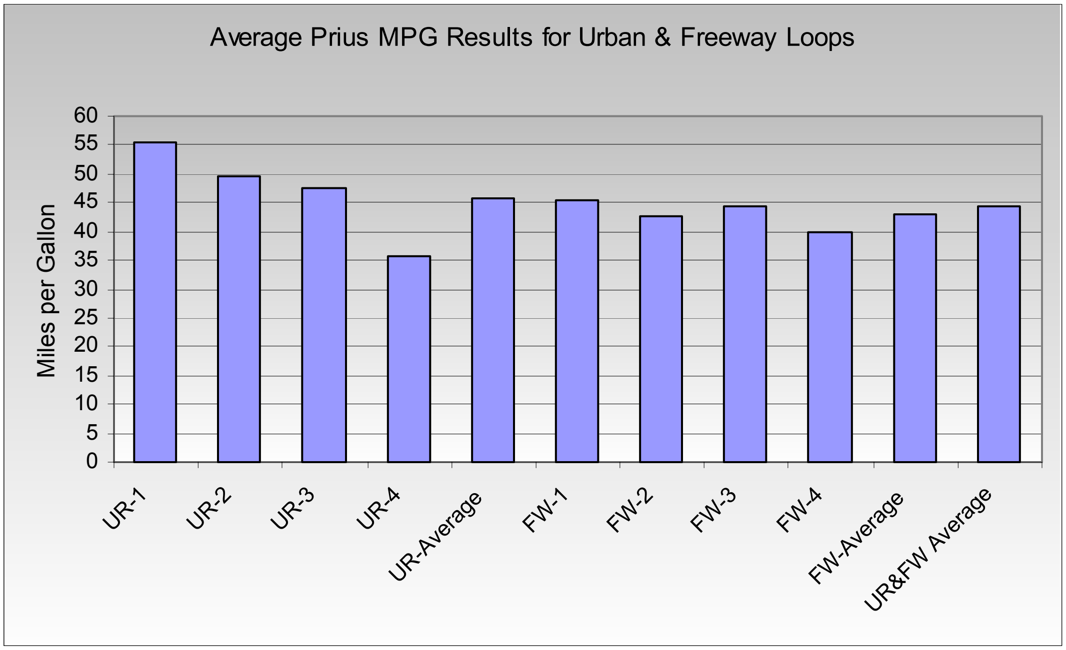

Figure 1. Average mph for each operating scenario used for the Urban and Freeway Pomona Loops.

3.3 Fuel Usage Measurement

As mentioned in the introduction, this initial round of Pomona Loop HEV Testing was not envisioned to be the most rigorous of quantitative tests of fuel use. The Prius was leased, which limited the fuel use measurement options to nonintrusive methods both because of the lease agreement and the desire to minimize testing (and vehicle repair) costs. Given these constraints, three low-cost, nonintrusive (or quasi–nonintrusive) fuel use measurement methods were considered, two of which were discarded.

One method would have relied on gas pump readings to determine the quantity of fuel used for a given test. When the vehicle tank was refilled, the “first click” of the pump nozzle would be accepted as indication of a “full” tank and the fuel quantity displayed by the pump would be read. However, the variability of this method is well known to anyone that has successfully added gasoline after the first “click”.

To improve the accuracy of the tests, a second method was considered and attempted. It relied on draining the vehicle tank with the fuel system pump (by temporarily disconnecting the fuel supply line and activating the pump with the “ignition key on”) and filling it with a known quantity of fuel. Measuring the make-up fuel would have yielded fuel usage. Unfortunately, it was not possible to get a consistent “empty tank” condition; successive reactivation of the fuel pump always drained an additional amount of fuel.

The third method relied on carefully refilling the vehicle tank in the EVTC lab, early in the morning (to minimize ambient temperature swings and gasoline expansion from movement), before each drive cycle with a lab-quality graduated cylinder (Figures 2 and 3). A notch in the tank filler tube was giving the necessary liquid level reference. Milliliter numbers were converted to gallons and logged (Tables 5 and 6). This method was used and it met the criteria of being nonintrusive and low cost, while elucidating HEV testing variables and issues.

Figure 2. Fuel usage measurement equipment.

Figure 3. Tank filling operation.

4. VEHICLE PERFORMANCE TESTS

Performance testing was conducted at the Los Angeles County Fairplex drag strip in Pomona, California on August 27, 2001. The tests were started at 11:00 AM and completed by 12:30 PM. The ambient temperature was 92–93°F and wind speeds of 3–5 mph from the Northwest were present. Tire pressures were 34 psi (front wheels) and 36 psi (rear wheels).

4.1 Vehicle Acceleration Testing

Table 5 shows the results from the acceleration tests. The computer-generated average acceleration time for 0–30 mph was 4.5 seconds and for 0–60 mph it was 13.1 seconds. The 30–55 mph accelerations were hand timed; the average time was 7.0 seconds. One of the 0 to 60 mph acceleration tests is shown Figure 4. Table 6 shows the results of quarter-mile acceleration results. The average time was 19.4 seconds, with an average speed of 74.1 mph. In separate tests, the maximum recorded speeds were 87.9 mph (southbound) and 82.8 mph (northbound).

Table 5. Prius acceleration test results in seconds.

Sequence	Direction	0 – 30 mph (s)	0 – 60 mph (s)	30 – 55 mph (s)
1	S	4.3	12.2	6.5
2	N	4.7	14.4	7.2
3	S	4.4	12.6	6.7
4	N	4.5	13.3	7.6
	Average (s)	4.5	13.1	7.0

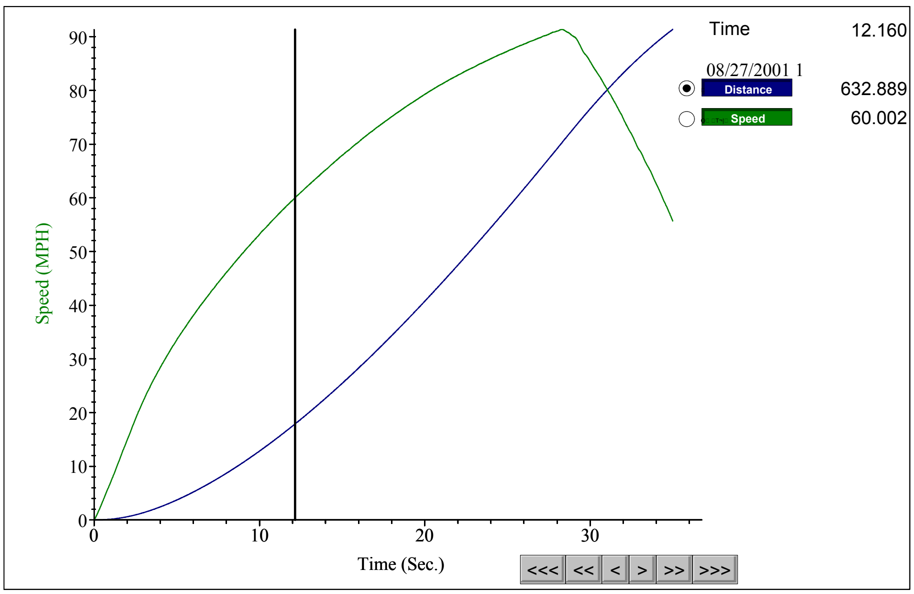

Figure 4. Zero to 60 mph acceleration test results.

Table 6. Quarter-mile acceleration test results

Sequence	Direction	Time (seconds)	Speed (mph)
1	S	18.9	77.1
2	N	20.0	70.5
3	S	19.2	75.9
4	N	19.6	72.8
	Average	19.4	74.1

4.2 Vehicle Braking Testing

Table 7 shows the results of the 25-mph braking tests. The results were obtained with a Vericom 2000 performance computer. The average stopping distance adjusted for 25 mph was 27.16 feet.

Table 7. Prius braking test results from 25 mph.

Sequence	Direction	Speed (mph)	Time (seconds)	Distance (feet)	25 mph Adjusted Distance (ft)
1	S	28.41	2.09	35.55	25.722
2	N	25.91	2.08	35.44	32.714
3	S	29.16	1.90	34.90	24.139
4	N	26.93	1.81	31.01	26.066
				Average (ft)	27.160

4.3 Sound Measurements

These measurements were made with a Sound Level Meter placed at head level in the front passenger seat area. The sound tests were conducted for approximately 47 minutes during the Urban Loop (Figure 5) and 33 minutes during the Freeway Loop (Figure 6). The sound averaged 60 decibels during the Urban loop and between 65 and 70 decibels during the Freeway Loop.

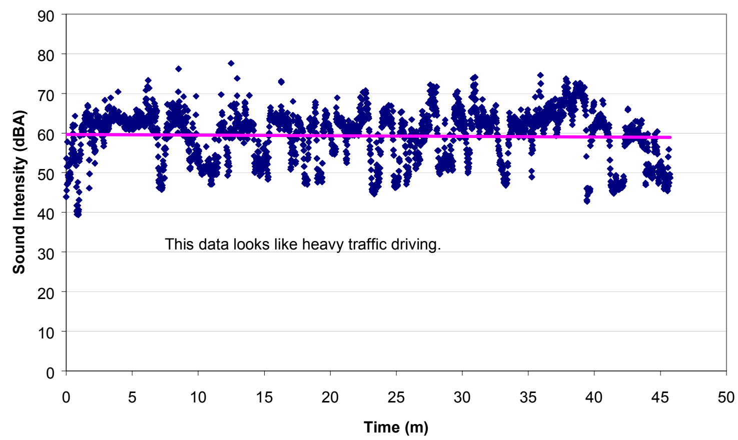

Figure 5. Urban Loop sound measurement results.

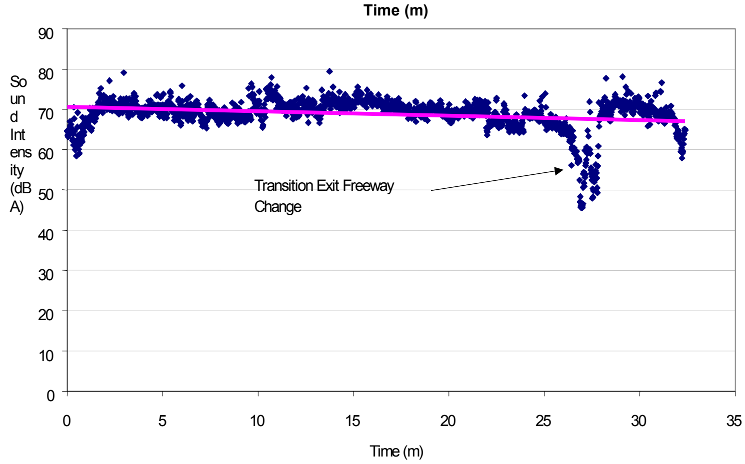

Figure 6. Freeway Loop sound measurement results.

4.4 Weight Certification

When weighed at a certified scale, the Prius was found to have a total available payload of 885 pounds (Table 8).

Table 8. Measured vehicle weight.

	Front Axle	Rear Axle	Total Weight
Sticker GVWR (lb)	1,970	1,685	3,655
Measured Weight (lb)	1,670	1,100	2,770
Available Payload (lb)	300	585	885

5. CONCLUSIONS

- The Pomona Urban Loop test most similar to the EPA test that estimates City mileage is the UR-1 scenario (minimum payload and no air conditioning). The UR-1 results averaged 55.6 mpg, or 3.6 mpg better than the 52 mpg EPA result. Overall, the Urban Loop mpg results ranged from 35.7 to 55.6 mpg for the five-passenger Prius.
- The EPA highway test result for the Prius is 45 mpg. The FW-1 loop results, which are closest to the EPA test conditions, were slightly higher at 45.4 mph. The overall Freeway test results ranged from 40 to 45.4 mpg.
- With the exception of the UR-1 and FW-1 operating scenarios, the other six operating scenarios all place greater energy requirements on the Prius than the EPA testing scenarios, so the fuel use results are not unexpected.
- Overall, the Prius performed well in these initial tests and the ability to carry five passengers should be attractive for fleet applications.
- The testing did highlight that future range and fuel use testing should include test distances that are much longer than traditionally used for the Pomona Loop testing (and other testing) due to the stingy fuel use rates; great care should be taken to accurately measure fuel use.
- The planned Field Operations Program Accelerated Reliability testing should provide insight into any long-term operational issues that the Prius may have such as battery life.
- Future grid-connected HEVs may require testing in pure electric modes, which include collecting kWh energy use, in addition to collecting gasoline use rates.

Appendix A: URBAN AND FREEWAY POMONA LOOP MAPS