

NYPA Hybrid Electric School Bus Evaluation Project

Emissions Test Results *Executive Summary*

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Submitted to:



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APPENDIX A – Test Routes

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OVERVIEW

This document provides a brief summary of the results of emissions and performance testing of hybrid-electric and standard diesel school buses. This emissions and performance testing was conducted as part of a larger Hybrid School Bus Evaluation Project which includes three one-year in-service evaluations of the buses in different school districts around New York. The first in-service evaluation, which is on-going, is being conducted at the Schenectady School District in Schenectady, NY, with the buses operated by Brown Coach. The other two deployments, which will follow the Schenectady evaluation, will be conducted in the New York City metro area and in Western New York. The test plans and results from these in-service evaluations are covered in separate documents.

The buses that were evaluated during emissions and performance testing included both a **Charge-sustaining hybrid-electric school bus (bus 301)** and a **Charge-depleting hybrid-electric school bus (bus 302)** which are owned by the New York Power Authority (NYPA). The buses are new, 2009 model year PB105 type C school buses built by the IC Corporation. The hybrid drive systems were built by ENOVA Systems, Inc. The performance of the hybrid-electric school buses was compared to the performance of one “baseline” diesel bus (bus 300), a new 2009 model year IC Corporation PB105 school bus that is being leased by NYPA for this test program. This bus is identical to the hybrid test buses except that it does not have a hybrid drive system.

During emissions testing a portable emissions monitoring system (PEMS) was installed in each test bus to collect information on exhaust emissions of carbon dioxide (CO₂), carbon monoxide (CO), nitrogen oxides (NO_x) and total hydrocarbons (THC). Testing was conducted with the buses operated on lightly used public roadways within and near an industrial park. For each bus data was collected on each of three test routes representing “typical” Urban, Suburban, and Rural/Hill school bus operation. Differences between the test cycles included the number of stops per mile, the distance between stops, and the peak and average speed achieved between stops.

In conjunction with the emissions testing, each bus was also tested for 0-40 MPH acceleration rate, and interior and exterior noise levels.

Details of the test plan and the full results of the emissions and performance testing can be found in separate documents.

On all three test routes the diesel fuel economy (miles per gallon, MPG) and per-mile carbon dioxide (CO₂) emissions of charge-sustaining hybrid bus 301 were very similar to those from the “baseline” diesel bus 300 (+4% to -7%); therefore bus 301 did not provide a significant fuel economy or green house gas reduction benefit compared to diesel bus 300 on any of the test routes.

On all three test routes the charge-depleting hybrid bus (bus 302) had significantly higher diesel fuel economy (+51% to +131%) and significantly lower per-mile CO₂ emissions than the other two test buses, especially on the first two repeats of each route. On the third repeat of each route diesel fuel economy from bus 302 was significantly



lower, and was similar to the other buses. This was due to depletion of the propulsion batteries and resultant reduced levels of “hybrid assist” on the third repeat. The cumulative distance over which bus 302 provided a significant improvement in diesel fuel economy compared to the other buses varied from approximately 10 miles on the urban route to 22 miles on the rural/hill route.

Diesel fuel economy does not account for the electrical energy added to bus 302 during overnight charging, or for the fuel used to produce this electricity. While bus 302 demonstrated an ability to reduce diesel fuel use, and replace it with electricity produced from other fuels, it did not provide a significant benefit in terms of overall energy consumption or green house gas reductions.

When evaluating the net environmental benefit of bus 302 compared to the other buses total estimated CO₂ emissions, including emissions from electricity production, provide the best “apples-to-apples” comparison because they account for all of the net energy sources required to drive each route. When projected CO₂ emissions from electricity production are added to measured tail pipe emissions, total per-mile CO₂ emissions from bus 302 on all three routes were roughly equivalent to measured CO₂ emissions from the other two test buses (+/- 6%).

Hybrid buses generally accrue most of their efficiency benefits from the capture and re-use of “regen energy” that is normally wasted in braking. Bus 301 was able to capture as regen energy between 25% and 50% of the inertial energy theoretically available on the different test routes, while bus 302 was able to capture between 18% and 28% of available inertial energy.

However, both hybrid buses are significantly heavier than a standard diesel bus, and therefore require more energy to drive a given route. Bus 301 was able to consistently collect as regen about twice as much energy as was required to overcome the additional weight of the hybrid system, providing a net energy benefit of approximately one half kilowatt-hour on the urban route and almost two kilowatt-hour on the rural/hill route.

This net energy benefit from regen collection for bus 301 was approximately five percent of total cycle energy on all three routes. The net energy benefit of regen offset diesel fuel usage by approximately 0.04 gallons/run on the urban route and 0.15 gallons/run on the rural/hill route. Bus 302, which is heavier than bus 301 due to its larger battery pack, generally was not able to collect enough regen energy to offset the estimated additional power required to move the weight of the hybrid system installed on the bus.



1. TEST BUSES

A total of three buses were evaluated during emissions and performance testing. These buses are described in Table 1-1.

| Bus Num | Type | Bus | | Engine | | | Transmission | Rear End Gear Ratio |
|---------|--------------------------|------------|----------------------|------------|---|-----------------|--------------------------|---------------------|
| | | Model Year | Make/Model | Model Year | Make/Model | After-treatment | | |
| 301 | Charge-Sustaining Hybrid | 2009 | IC Corporation PB105 | 2009 | International MaxxFORCE 7 6.4 liter V8 | Active DPF | Allison 2500 (automatic) | 6:17 |
| 302 | Charge-Depleting Hybrid | 2009 | IC Corporation PB105 | 2009 | International MaxxFORCE 7 6.4 liter V8 | Active DPF | Allison 2500 (automatic) | 6:17 |
| 300 | Standard Diesel | 2009 | IC Corporation PB105 | 2009 | International MaxxFORCE 7 6.4 liter V8 | Active DPF | Allison 2500 (automatic) | 6:17 |

Table 1-1 Test Buses for Emissions and Performance Testing

As shown in Table 1, the standard diesel bus is identical to the two hybrid buses other than the exclusion of a hybrid drive system (i.e. same age, bus body, engine, exhaust after-treatment, transmission, rear-end gear ratio, tires, and engine driven auxiliaries).

The hybrid-electric drive systems employed on test buses 301 and 302 were designed by ENOVA Systems, Inc. In the charge-sustaining hybrid the electric motor provides a power-assist to the diesel engine at speeds below 30 miles per hour, reducing the power required from the engine. During braking the motor acts as a generator, producing electricity while slowing the bus; this energy is directed to the battery pack where it is stored for later use (i.e. during the next acceleration). In this system the battery acts purely as a load leveler, allowing better management of total energy use throughout a transient drive cycle, and reducing net fuel use over a typical day of operation. All net energy required to drive the vehicle comes from diesel fuel (via the diesel engine). The battery pack in bus 301 has the ability to store approximately six kilo-watt hours (kWh) of electrical energy. This amount of energy is equivalent to the useful work that can be extracted from approximately 0.45 gallons of diesel fuel by a diesel engine.¹

The charge-depleting hybrid system is similar to the charge-sustaining system, but includes two larger battery packs and an on-board charger that can connect to a wall plug. The electric motor in the charge-depleting system provides a power-assist to the diesel engine at speeds up to 50 miles per hour (but with hybrid support limited above 30 mph). In this system the battery acts not just as a load leveler, but also as an additional net power source supplemental to the diesel engine. At night the bus is plugged into the

¹ Assuming #2 diesel fuel with 140,000 btu/gallon energy content and average diesel engine efficiency of 33%.



electrical grid, and the battery is fully charged. As the bus operates in service the next day energy is drawn from the battery pack over time, depleting the battery; at the end of the day the battery pack typically has much lower state of charge than when it started in service at the beginning of the day. In this system some of the net energy required to operate the bus is supplied by diesel fuel (via the diesel engine) and some is supplied from the electrical grid (via night time battery charging). The battery packs in bus 302 have the ability to store approximately 35 kWh of electrical energy. This amount of energy is equivalent to the useful work that can be extracted from approximately 2.5 gallons of diesel fuel by a diesel engine.¹

Both the charge-sustaining and the charge-depleting hybrid systems on the test buses are designed as an over-layer to the standard diesel drive system. On both test buses the hybrid system can be turned off by the bus operator, and the bus can still operate like a standard diesel bus, with no loss of performance capability.

2. EMISSIONS TEST PLAN

Emissions tests were conducted with each test bus in “simulated” service while operating on limited access public roadways within and near an industrial park. Three test routes were laid out with simulated bus stops, and data was collected from three repeats for each bus on each route.

Prior to emissions and performance testing each bus was weighed, and loaded with eighty 50-pound salt bags to simulate a nominal half seated passenger load weight (33 seats x 120 lb per seated passenger = 3,960 lbs).

Emissions data was collected for three repeats one each of three test routes. Each test run took between 27 and 36 minutes.

Bus 302 (charge-depleting hybrid) was plugged into a wall socket to recharge the battery to a minimum 90% state-of-charge before beginning testing on each route. As discussed below, by the time the bus had completed three repeats of each route the battery was significantly depleted.

After emissions testing, acceleration and noise data was collected for bus 300 (diesel) and bus 301 (charge-sustaining hybrid). Due to time constraints this data was not collected for bus 302.

2.1. Emissions Test Equipment

Emissions data was collected using a Semtech DTM Portable Emissions Monitoring System (PEMS), which consists of a gas analyzer, an exhaust flow meter (EFM), and a J1939 interface box which connects through a diagnostic port to the engine’s electronic control module (ECM) for recording engine data.

The EFM is connected to the vehicle exhaust to measure exhaust flow. The gas analyzer is installed inside the bus, with a heated sample line connected to the flow



meter for continuous collection and analysis of an exhaust gas sample. See Figure 2-1 for photos of the test equipment installed in a bus.

For the hybrid buses a lap-top computer was also used to collect and record instantaneous battery voltage and current during each test run. This data was provided by the ENOVA Panther™ diagnostic system.



Figure 2-1 Emissions Test Equipment Installed in a Bus

2.2. Test Routes

Three test routes were set up within and around the Scotia Industrial park to represent “typical” school bus operation in URBAN, SUBURBAN, and RURAL/HILL environments. Each route was a loop and one “run” consisted of two or more loops of the route. The nominal characteristics of each route are shown in Table 2-1. The URBAN and SUBURBAN loops were relatively flat, while the RURAL/HILL loop included a significant change in elevation.

To ensure consistency between runs each route was kept simple, with a limited number of stops and consistent operation between stops (acceleration rate, maximum speed). The same bus operator was used to operate each test bus on all routes. The operator was instructed to operate the bus as he would in normal school service (acceleration rates away from each stop, braking rates into each stop). For each run on each route the following sequence was followed:

- Accelerate away from BUS STOP 0 until target maximum speed is achieved
- Hold speed steady until slowing to a stop at BUS STOP 1
- Apply emergency brake and open door. Dwell for a specific time period with door open.

- Close door, release emergency brake and accelerate away from BUS STOP 1 until target maximum speed is achieved
- Hold speed steady until slowing to a stop at BUS STOP 2
- REPEAT until the end of the route.

See Appendix A for maps of each test route.

| Metric | Unit | Test Route | | |
|-----------------------------|---------|------------|----------|-------|
| | | Urban | Suburban | Rural |
| Length of Route Loop | Miles | 1.9 | 1.9 | 7.9 |
| Number of Loops for one run | Num | 3 | 4 | 2 |
| Total Length of Run | Miles | 5.5 | 7.5 | 15.7 |
| Average Speed | MPH | 13 | 16 | 25 |
| Run Time | Minutes | 27 | 27 | 36 |
| Number of Stops | Num | 11 | 7 | 8 |
| Dwell time at each stop | Seconds | 30 | 30 | 30 |
| Stops per mile | Num | 2 | 0.9 | 0.5 |
| Idle Time | % | 27 | 18 | 14 |
| Change in Elevation | FT | 10 | 10 | 537 |

Table 2-1 Nominal Characteristics of Test Routes

2.3. Test Route Adherence

In order to provide a relevant comparison between the different technologies to be tested, it is important to minimize, to the extent possible, variability in the actual route driven by each bus during each test (length, average and maximum speeds, acceleration rates, idle time).

The following procedures were used to minimize run-to-run and bus-to-bus variability for each test route:

- The same bus operator drove all test buses on all routes. The operator was a professional school bus operator familiar with the test buses (Brown Coach employee)
- Each test route was kept simple (see Appendix A)
- A route map was developed for each route which showed the locations of all stops, and which noted the maximum speed to be attained between each set of stops. A “coach” rode the bus during all tests to remind the bus operator as to



stop locations, and to independently monitor bus speed and provide feed back to the bus operator.

- A GPS-based dash speedometer, independent of the bus speedometer, was used by the driver to monitor speeds for all buses on all routes.
- A count-down timer was used to maintain a consistent dwell time at all bus stops for all routes.

2.4. Charge-sustaining Hybrid State-of-Charge Correction

For a charge-sustaining hybrid-electric vehicle (HEV), it is necessary to determine if any energy was added to or removed from the energy storage system during each emission test run. If the State of Charge (SOC) changes significantly over the total length of a test run it may impact the Net Energy Change (NEC) to a great enough extent that the data must be “corrected”. This is known as SOC correction. This procedure is necessary in order to compare the emission results of a charge-sustaining HEV to those from a conventional vehicle.

The procedures for determining the NEC and SOC and performing an SOC correction are outlined in *SAE J2711: Recommended Practice for Measuring Fuel Economy and Performance of Hybrid-Electric and Conventional Heavy-Duty Vehicles*. This procedure is intended for use with chassis dynamometer testing; the inherently greater variance in run-to-run test cycles typically seen with in-use testing makes application of the SOC correction procedure less precise. None the less, these guidelines were followed for this project to correct measured emissions values for Bus 301.

Note that bus 302 is a charge-depleting hybrid bus. Because charge depleting hybrid systems are designed to sustain large changes in battery state-of-charge during driving, the SOC correction procedures outlined in SAE J2711 are not applicable or appropriate for this type of bus. For bus 302 all tail-pipe emissions results are reported here without correction. For bus 302 we also report total emissions, including estimated emissions from electricity production required for over night battery charging.



3. Emissions Test Results

Measured emissions and diesel fuel economy for all three test buses on all three test routes are shown in Table 3-1 and Figures 3-1 through 3-5. The results from bus 301 (charge-sustaining hybrid) were “corrected” for changes in battery state-of-charge (see section 2.4). Table 3-1 includes both measured and corrected values. Only the corrected values are shown in Figures 3-1 through 3-5.

Quality assurance procedures also indicated that the PEMS flow meter measured flow inaccurately at idle for bus 302 on the Urban route. This idle flow data was corrected downward based on comparison of measured fuel flow as reported by the engine ECM, to fuel flow as calculated by carbon balance from measured CO₂ emissions (carbon in fuel = carbon out in exhaust). This correction had the effect of reducing gram per mile emissions for this bus on the urban route. Table 3-1 shows both the measured and corrected values for each pollutant. Figures 3-1 through 3-5 show the corrected values only.

In figures 3-1 through 3-5 the wide solid bars for bus 300 (diesel) and bus 301 (charge-sustaining hybrid) indicate the average measured emissions for all three runs on each route. The thin black lines on top of the solid bars indicate one standard deviation around the average value, based on actual variability from run-to-run. The horizontal yellow lines on Figures 3-2 through 3-5 represent the minimum effective detection limit of the test equipment used.

For bus 302 (charge-depleting hybrid) results from each run on each route are shown separately. As discussed below, by the end of the third run on each route the battery in this bus was significantly depleted, which reduced the amount of hybrid assist and increased the energy required from the engine to drive the route. The run-to-run variation in emissions was therefore much greater for this bus than for the other buses.

Figures 3-2 (CO₂ Emissions) and 3-3 (NO_x Emissions) include, for bus 302, both measured tail pipe emissions and an estimate of the emissions created from production of electricity required to re-charge the batteries to replenish the net energy removed to operate the route. These emissions were estimated using average emissions factors and line losses for electricity production in New York State, and they account for transmission line losses, as well as losses incurred in bus charging².

² Average emissions from electricity production in New York were 365.1 grams CO₂/kWh and 0.41 grams NO_x/kWh in 2007, per data published by the U.S. Department of Energy, Energy Information Administration. Average line losses for distribution of electricity in New York were 4.8%. The bus charger efficiency was assumed to be 78%

PEMS (Urban)

Gram/Mile

| | Time (seconds) | Distance (mi) | Fuel Cons. (mpg) | ECM Fuel (mpg) | gram/mile Emission Rates | | | | | | Accel mph/s |
|---------------|-------------------|------------------|---------------------|-------------------|--------------------------|------|------|------|------|------|----------------|
| | | | | | CO2 | CO | HC | NO | NO2 | NOx | |
| 300 | 1639 | 5.52 | 5.87 | 6.22 | 1735 | 0.99 | 0.01 | 6.20 | 3.59 | 9.79 | 1.149 |
| 301 Raw | 1548 | 5.46 | 5.47 | 6.08 | 1802 | 1.03 | 0.01 | 5.22 | 4.24 | 9.46 | 1.231 |
| 301 SOC | 1548 | 5.46 | 5.47 | 6.08 | 1802 | 1.03 | 0.01 | 5.22 | 4.24 | 9.45 | 1.231 |
| 302 - 1 Raw | 1608 | 5.45 | 10.91 | 13.94 | 931 | 2.05 | 0.21 | 5.14 | 0.47 | 5.61 | 1.185 |
| 302 - 1 Corr. | 1608 | 5.45 | 12.23 | 13.94 | 831 | 1.90 | 0.18 | 4.59 | 0.44 | 5.03 | 1.185 |
| 302 - 2 Raw | 1515 | 5.45 | 10.90 | 13.95 | 931 | 1.62 | 0.47 | 4.66 | 0.26 | 4.92 | 1.238 |
| 302 - 2 Corr. | 1515 | 5.45 | 11.98 | 13.95 | 847 | 1.55 | 0.45 | 4.31 | 0.25 | 4.55 | 1.238 |
| 302 - 3 Raw | 1556 | 5.45 | 6.56 | 7.58 | 1550 | 1.31 | 0.09 | 7.03 | 2.66 | 9.68 | 1.235 |
| 302 - 3 Corr. | 1556 | 5.45 | 6.94 | 7.58 | 1463 | 1.22 | 0.08 | 6.54 | 2.37 | 8.91 | 1.235 |

PEMS (Suburban)

Gram/Mile

| | Time (seconds) | Distance (mi) | Fuel Cons. (mpg) | ECM Fuel (mpg) | gram/mile Emission Rates | | | | | | Accel mph/s |
|---------|-------------------|------------------|---------------------|-------------------|--------------------------|------|------|------|------|------|----------------|
| | | | | | CO2 | CO | HC | NO | NO2 | NOx | |
| 300 | 1639 | 7.40 | 5.71 | 6.17 | 1781 | 1.04 | 0.01 | 5.51 | 4.36 | 9.87 | 1.223 |
| 301 Raw | 1614 | 7.30 | 5.78 | 6.39 | 1686 | 1.03 | 0.02 | 4.90 | 3.53 | 8.43 | 1.279 |
| 301 SOC | 1614 | 7.30 | 5.78 | 6.39 | 1709 | 1.03 | 0.02 | 4.90 | 3.53 | 8.40 | 1.279 |
| 302 - 1 | 1631 | 7.29 | 13.24 | 13.97 | 768 | 1.16 | 0.24 | 5.06 | 0.30 | 5.36 | 1.205 |
| 302 - 2 | 1694 | 7.29 | 10.62 | 11.20 | 957 | 0.88 | 0.14 | 6.35 | 0.27 | 6.62 | 1.216 |
| 302 - 3 | 1778 | 7.27 | 6.71 | 7.21 | 1514 | 0.94 | 0.03 | 5.11 | 2.00 | 7.12 | 1.242 |

PEMS (Rural)

Gram/Mile

| | Time (seconds) | Distance (mi) | Fuel Cons. (mpg) | ECM Fuel (mpg) | gram/mile Emission Rates | | | | | | Accel mph/s |
|---------|-------------------|------------------|---------------------|-------------------|--------------------------|------|------|------|------|------|----------------|
| | | | | | CO2 | CO | HC | NO | NO2 | NOx | |
| 300 | 2180 | 15.74 | 6.14 | 6.75 | 1661 | 0.83 | 0.01 | 3.02 | 2.49 | 5.64 | 1.102 |
| 301 Raw | 2294 | 16.05 | 5.84 | 6.67 | 1686 | 0.38 | 0.01 | 2.71 | 2.65 | 5.35 | 1.240 |
| 301 SOC | 2294 | 16.05 | 5.84 | 6.67 | 1686 | 0.38 | 0.01 | 2.71 | 2.65 | 5.34 | 1.240 |
| 302 - 1 | 2495 | 16.03 | 9.25 | 10.05 | 1099 | 1.26 | 0.01 | 2.89 | 1.50 | 4.39 | 1.095 |
| 302 - 2 | 2455 | 16.01 | 8.71 | 9.39 | 1166 | 0.56 | 0.02 | 2.63 | 1.56 | 4.18 | 1.094 |
| 302 - 3 | 2312 | 15.45 | 6.77 | 7.30 | 1557 | 0.68 | 0.00 | 2.47 | 2.16 | 4.62 | 1.120 |

Table 3-1 Average Emissions Results



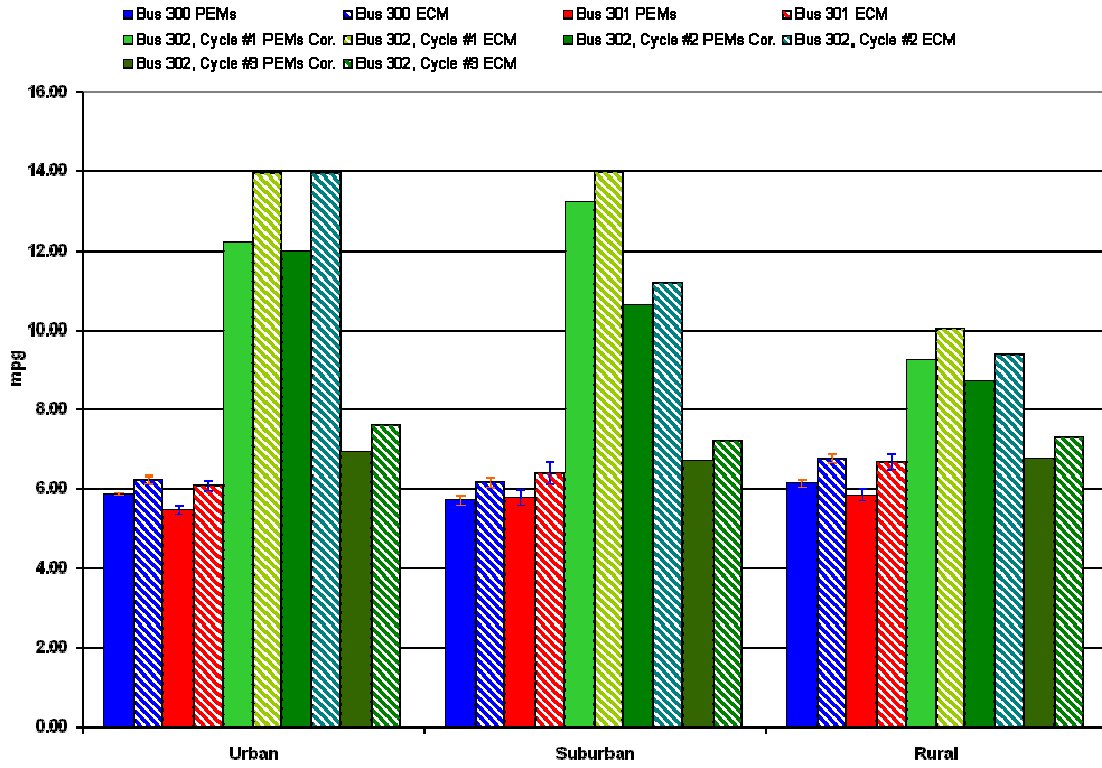


Figure 3-1 Average Diesel Fuel Economy (MPG)

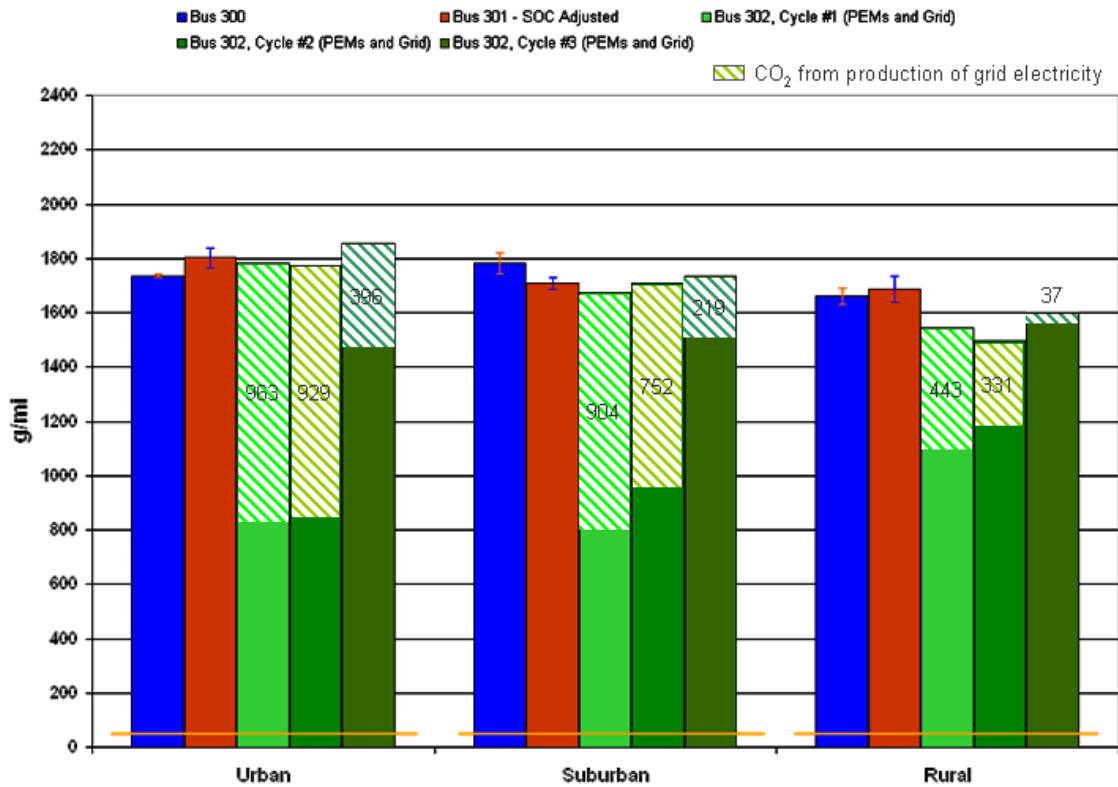


Figure 3-2 Average CO₂ Emissions (g/mi) – Including Emissions from Electricity Production (bus 302)

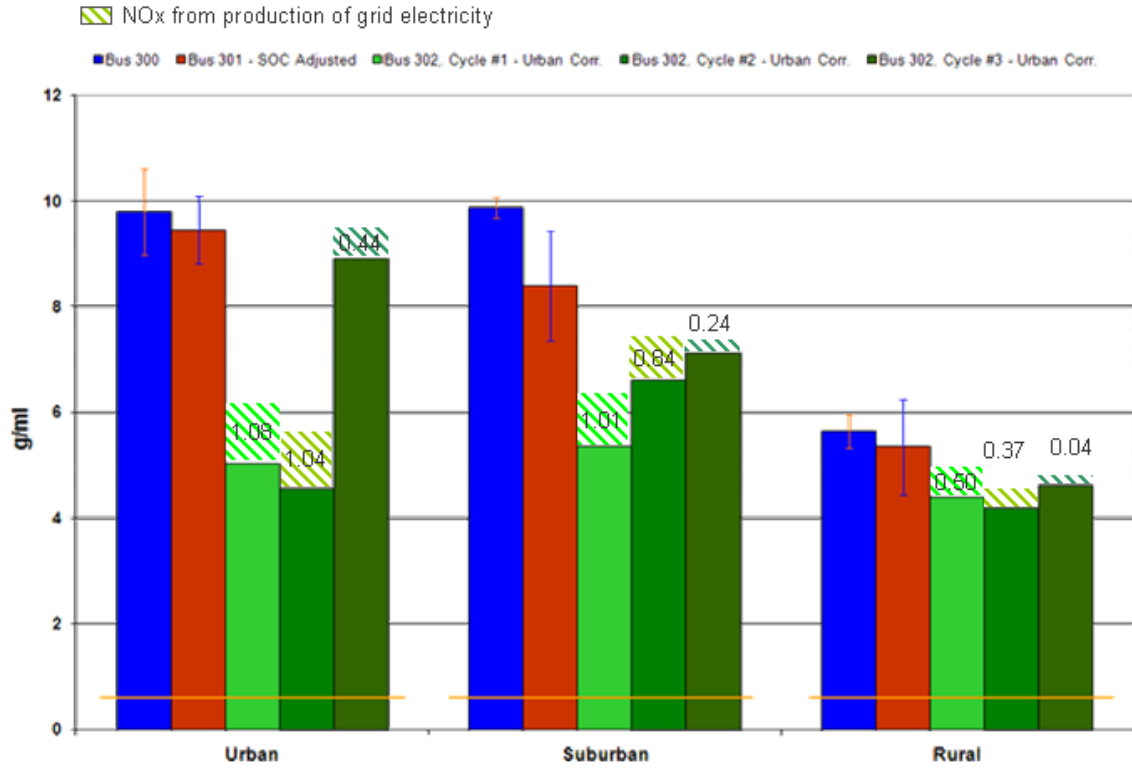


Figure 3-3 Average NO_x Emissions (g/mi) – Including Emissions from Electricity Production (bus 302)

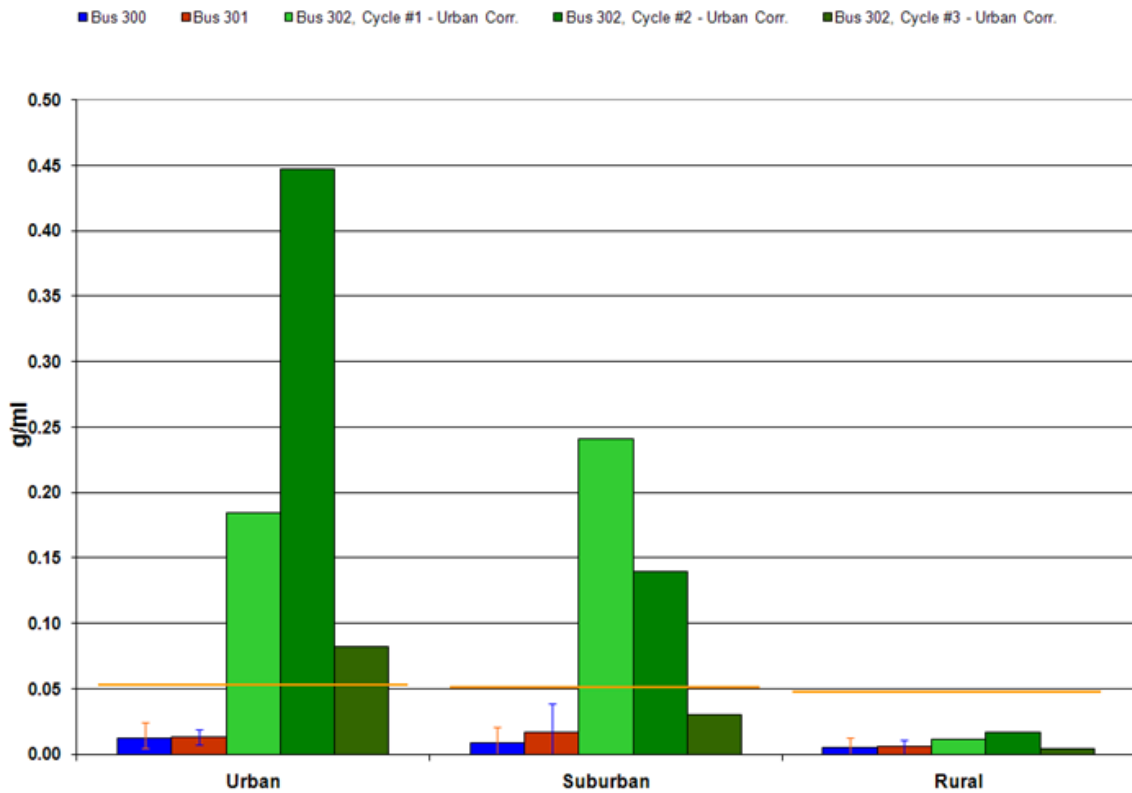


Figure 3-4 Average Total Hydrocarbon (THC) Emissions (g/mi)

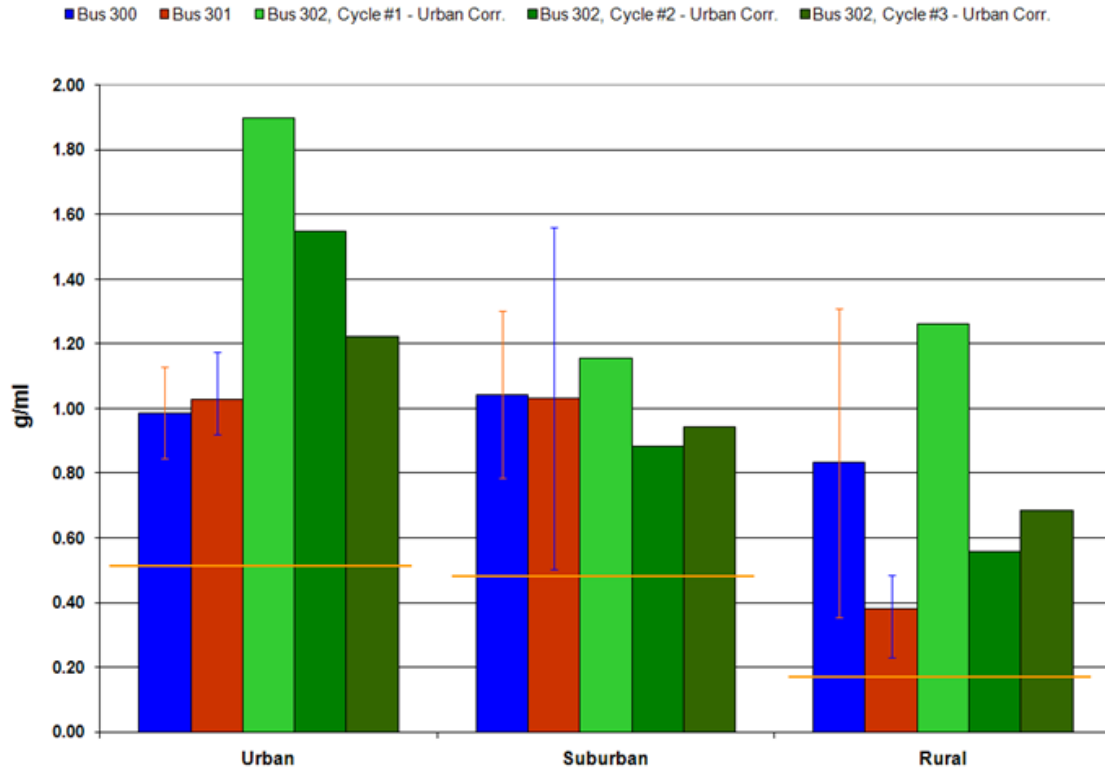


Figure 3-5 Average Carbon Monoxide (CO) Emissions (g/mi)

Fuel Economy & CO₂ Emissions

As shown in Figure 3-1, charge-depleting hybrid bus 302 had the highest diesel fuel economy (MPG) on all three test routes. This measured diesel fuel economy only accounts for the fuel burned by the bus’s diesel engine; for bus 302 (unlike the other buses) some net energy required to drive each route was also provided by the land-side electrical grid, via over-night charging of the bus’s battery pack. Measured diesel fuel economy does not account for the electricity added to the battery pack during over-night charging, or for the fuel required to produce this electricity.

Table 3-1 and Figure 3-1 include fuel economy as measured by the PEMS unit using carbon balance, and fuel economy as reported by the engine electronic control module (ECM). The ECM measurement of fuel economy was consistently higher than the PEMS measurement (5%-10%) for all three buses on all routes. The difference was somewhat greater for bus 302 on the urban route.

Bus 302 diesel fuel economy was up to 108% greater than the fuel economy of diesel bus 300 on the urban route, while it was up to 131% higher on the suburban route and up to 51% higher on the rural/hill route. The diesel fuel economy of hybrid bus 302 was significantly lower on the third repeat of the route than on the first two repeats, for all three test routes. Once the battery state-of-charge fell below about 40% on this bus the amount of energy being delivered by the battery fell off significantly and the diesel

engine had to work harder, thus reducing diesel fuel economy. This is discussed further below in Section 4.

Charge-sustaining hybrid bus 301 had marginally higher average fuel economy than diesel bus 300 on the suburban route (+1% to +3%), and marginally lower average fuel economy (-1% to -7%) on the urban and rural/hill routes.

Consistent with higher measured fuel economy, bus 302 also had the lowest tailpipe CO₂ emissions (grams per mile, g/mi) of all three buses. Tail pipe CO₂ emissions from bus 300 and 301 were also consistent with the fuel economy results and were similar for these two buses on all routes (Figure 3-2).

When estimated CO₂ emissions from grid electricity production are included, bus 302 had roughly equivalent g/mile total CO₂ emissions as bus 300 and bus 301, on all three test routes (+/- 6%). When evaluating the net environmental benefit of bus 302 compared to the other buses total estimated CO₂ emissions, including emissions from electricity production, provide the best “apples-to-apples” comparison because they account for all of the net energy sources required to drive each route.

NO_x Emissions

As shown in Figure 3-3, charge-depleting hybrid bus 302 had significantly lower average g/mi tail pipe NO_x emissions (18% - 54% lower) than diesel bus 300 on all three test routes. The greatest differences were on the first two repeats of the urban and suburban routes.

When estimated NO_x emissions from grid electricity production are included, bus 302 still had significantly lower g/mile total NO_x emissions than bus 300 on the first two repeats of the urban route and on all three repeats of the suburban route, but only slightly lower total NO_x emissions than bus 300 on the rural/hill route. When evaluating the net environmental benefit of bus 302 compared to the other buses total estimated NO_x emissions, including emissions from electricity production, provide the best “apples-to-apples” comparison because they account for all of the net energy sources required to drive each route.

Charge-sustaining hybrid bus 301 also had lower average g/mi NO_x emissions than diesel bus 300 on all three test routes. However, at the 85% confidence level the measured differences in g/mi NO_x emissions between bus 301 and bus 300 were not statistically significant on any of the routes; the variation from run-to-run for each bus was greater than the average difference between the buses. In general, g/mi NO_x emissions from buses 300 and 301 were much more variable from run-to-run than were CO₂ emissions and fuel use, for all three test routes.

THC & CO Emissions

As shown in Figure 3-4, average g/mi total hydrocarbon (THC) emissions from all three test buses were very low on all three test routes. For bus 300 and bus 301 average THC



emissions were below the minimum effective detection limit of the PEMS device on all three routes (this detection limit is shown by the yellow line in the figure).

For bus 302 measured THC emissions were below the minimum effective detection limit of the PEMS device on the rural route, and on the third repeat of the urban and suburban routes, while they were elevated on the first two repeats of these routes.

Average carbon monoxide (CO) emissions from all three test buses were also low on all three test routes, and were only marginally higher than the minimum effective detection limit of the PEMS device. Measured differences in average CO emissions from bus 300 and bus 301 were not statistically significant; the variation from run-to-run for each bus was generally greater than the average difference between the buses.

The increase in THC emissions (and to a lesser extent CO emissions) from bus 302 compared to the other buses is likely explained by differences in exhaust temperature. All three buses rely on a diesel oxidation catalyst to oxidize CO and THC produced in the engine. Oxidation catalysts require a minimum level of exhaust temperature to drive the oxidation reaction. Exhaust temperature data collected during the emissions testing shows that bus 302 exhaust temperature on the first two repeats of the urban and suburban routes was significantly lower than the exhaust temperature of the other two buses. It also shows that bus 302 exhaust temperature was higher on the third repeat of the urban and suburban routes and on all three repeats of the rural/hill route.

Bus 302 had lower exhaust temperature because the engine was not working as hard as the engines in the other buses. As discussed below, the hybrid assist provided on this bus significantly reduced engine load, particularly on the first two repeats of each route.



4. Hybrid System Performance

Hybrid system performance on buses 301 and 302 during emissions testing is highlighted in Figures 4-1 through 4-8. For each bus these figures highlight the amount of regenerative energy (regen) collected by the battery pack on each run, as well as the amount of energy supplied by the battery pack (hybrid assist) versus the amount of energy provided by the engine to operate the bus over each route. For each run, data on engine-supplied power was collected from the engine's electronic control module (ECM). Data on hybrid battery voltage and current was collected from the ENOVA Panther™ diagnostic system. This data was used to calculate instantaneous power (kWh) in and out of the battery, and the change in battery state of charge (SOC) over each run³. For bus 302 (charge-depleting hybrid) the net change in battery energy over each run is equivalent to the net amount of grid electricity required to recharge the battery overnight⁴.

Figure 4-1 shows instantaneous power in and out of the hybrid battery pack of charge-sustaining hybrid bus 301 over one repeat of the urban route. Figure 4-2 shows the same information for charge-depleting hybrid bus 302. In these figures the red line represents the speed of the bus (MPH – right vertical scale) and the blue line represents power in and out of the battery (kw at 3 hz – left hand scale). Blue lines above the zero line represent power leaving the battery (hybrid assist) and blue lines below the zero line represent power entering the battery (regen collection).

As shown in Figure 4-1, bus 301 collected 1.2 kilowatt-hour (kw-hr) of regen energy during this run. Bus 301 also provided 0.91 kw-hr of hybrid assist to help move the bus. The diesel engine on bus 301 provided the rest of the power required to drive the cycle, a little over 10 kw-hr. Over-all, approximately 8% of the total energy required to drive the route was provided by the hybrid system and 92% was provided by the diesel engine.

As shown in Figure 4-2, bus 302 also collected about the same amount of regen energy (0.98 kw-hr), but it provided a much greater amount of hybrid assist (over 11 kw-hr). As a result the diesel engine did not have to work nearly as hard. For this run the diesel engine on bus 302 provided only 2.67 kw-hr of power. Over-all, approximately 81% of the total energy required to drive the route was provided by the hybrid system and only 19% was provided by the diesel engine. This is why bus 302 got much better diesel fuel economy than bus 301. Of the energy provided by the hybrid system, approximately 9% was collected as regen energy on the route, and 91% was provided by over-night charging of the battery pack.

³ To calculate changes in battery state-of-charge (kWh), instantaneous measured battery current was multiplied by the nominal voltage of the battery pack rather than the measured instantaneous voltage. This method accounts for internal resistance losses during charge and discharge of the pack.

⁴ The total amount of electricity that must be produced to recharge the battery is approximately 46% greater than the net change in battery energy, due to transmission line losses (4.8%) and losses incurred during battery charging (28%).

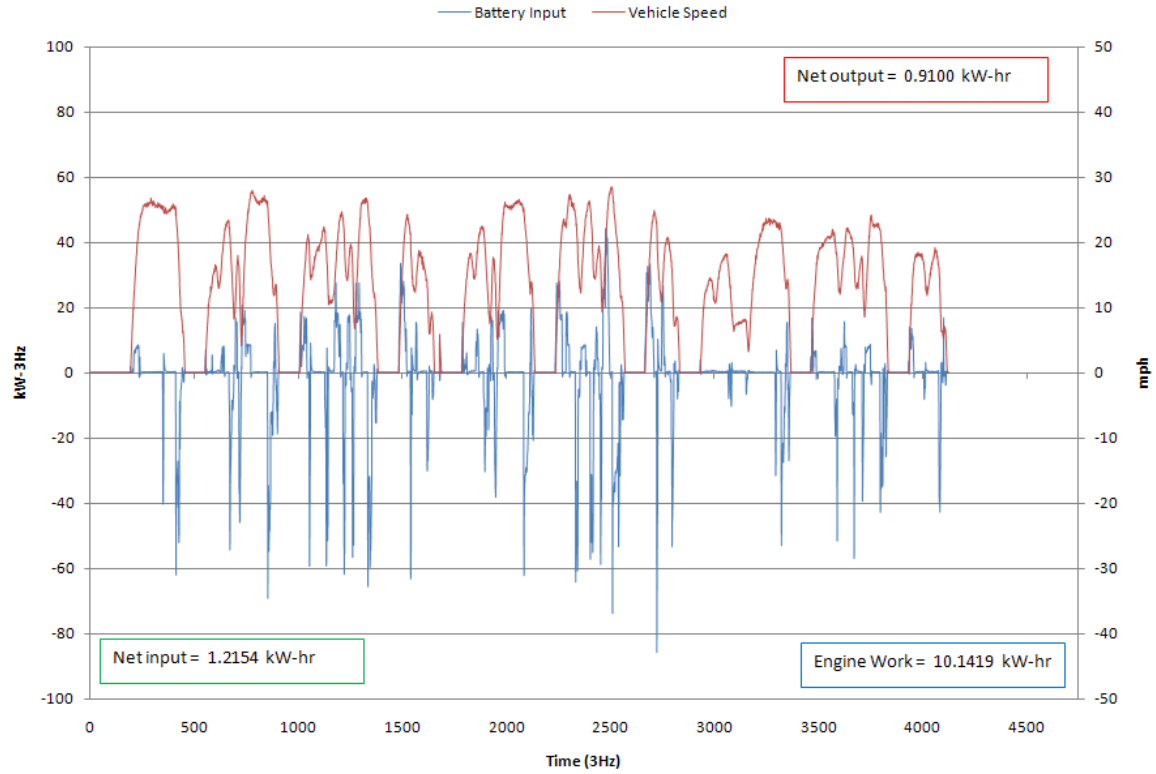


Figure 4-1 Energy In and Out of Battery pack – Bus 301 on the Urban Route

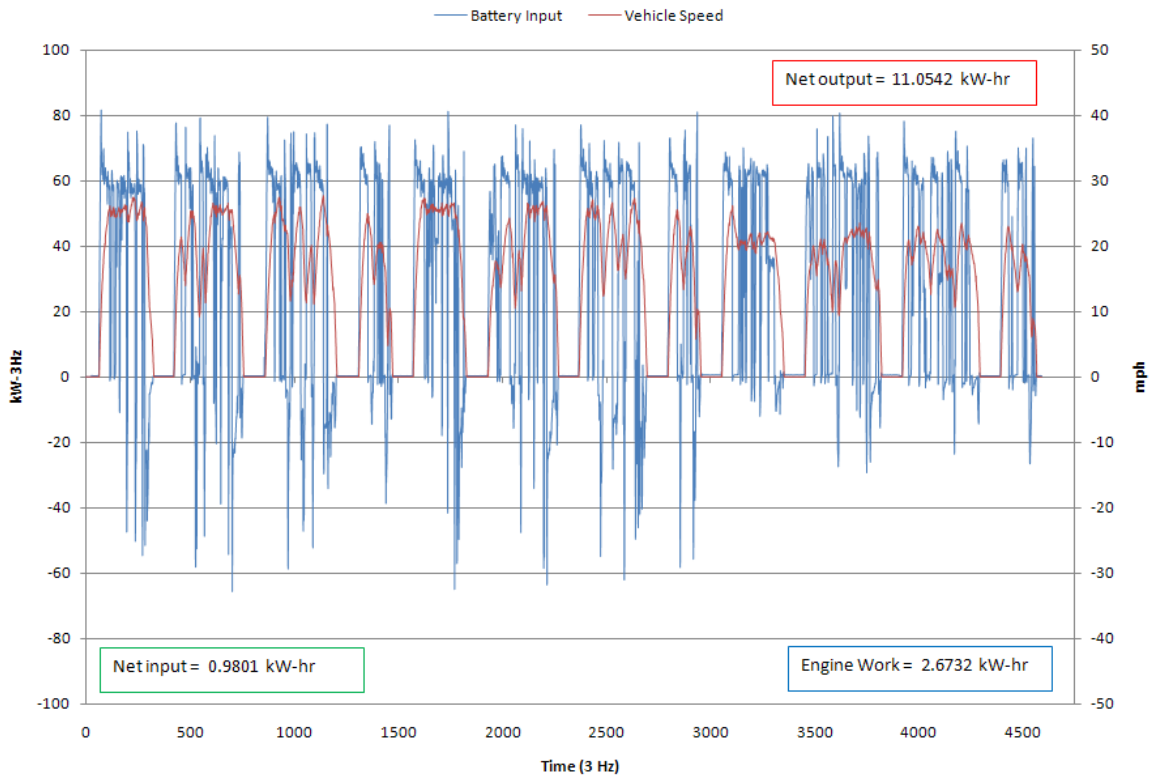


Figure 4-2 Energy In and Out of Battery pack – Bus 302 on the Urban Route

Figure 4-3 shows the battery power and engine power supplied by bus 301 on all repeats of each test route. For comparison, the average engine power supplied by bus 300 on each route is also shown. On the different runs, the hybrid system on bus 301 provided between 0.2% and 10% of the total energy required to drive the urban route and between 10% and 14% of the total energy required to drive the suburban and rural/hill routes.

Figure 4-4 shows the battery power and engine power supplied by bus 302 on all repeats of each test route. As shown, the hybrid system on bus 302 provided a much greater percentage of total cycle energy, particularly on the first two repeats of each route.

Figure 4-5 shows, for bus 301, the total energy required to drive each repeat of each test route, along with the amount of regen energy collected, and an estimate of the amount of energy that was required to overcome the additional weight of the hybrid system⁵. Figure 4-6 shows the same information for bus 302. Compared to bus 300, bus 301 is 1,460 pounds heavier and bus 302 is 2,960 pounds heavier.

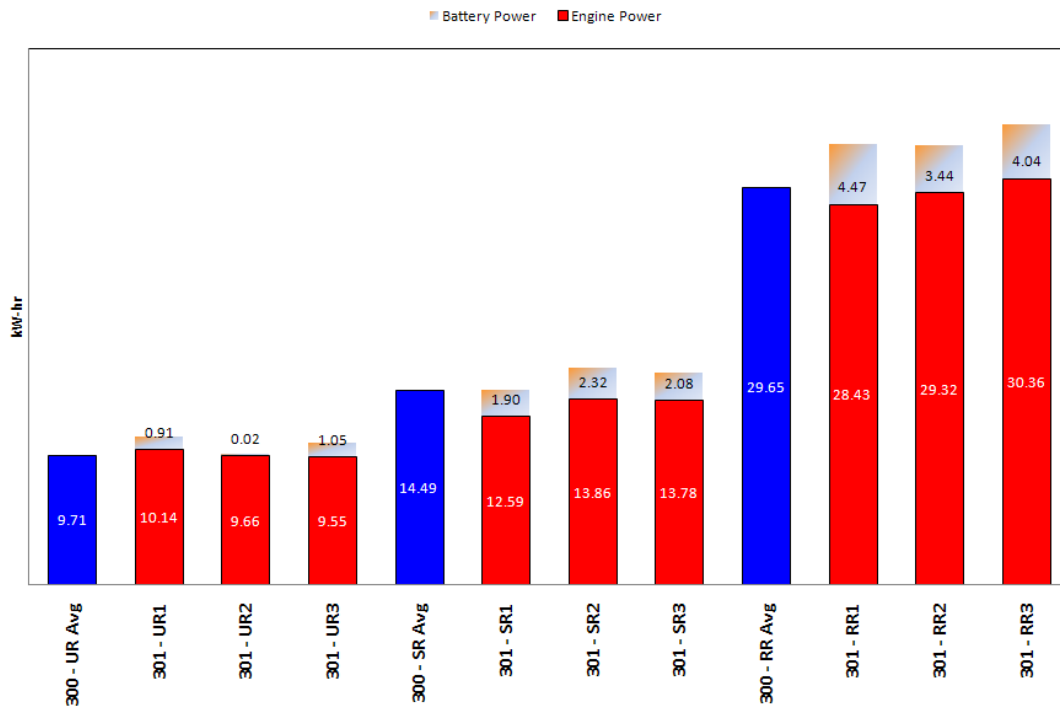


Figure 4-3 Battery vs Engine Power, Bus 300 and Bus 301

⁵ Additional bus weight increases required drive power due to increased rolling resistance and increased bus inertia. The equation used to estimate the increased power requirements was as follows: $\Delta Power = \Delta Inertial Power + \Delta Rolling Resistance Power = (\Delta Mass \times velocity \times acceleration \times time) + (\Delta Mass \times coefficient of rolling resistance \times gravity \times velocity \times time)$. For the rural/hill route both horizontal and vertical (i.e. hill climbing) velocity and acceleration were used to calculate the change in the power required for the inertial term.

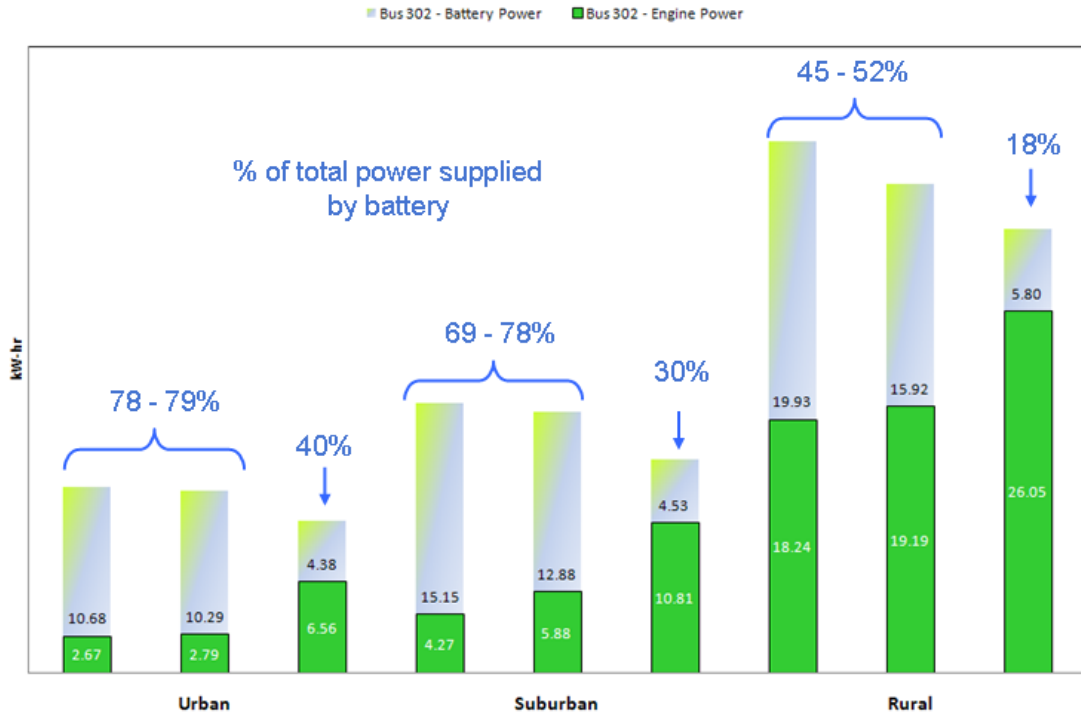


Figure 4-4 Battery vs Engine Power, Bus 302

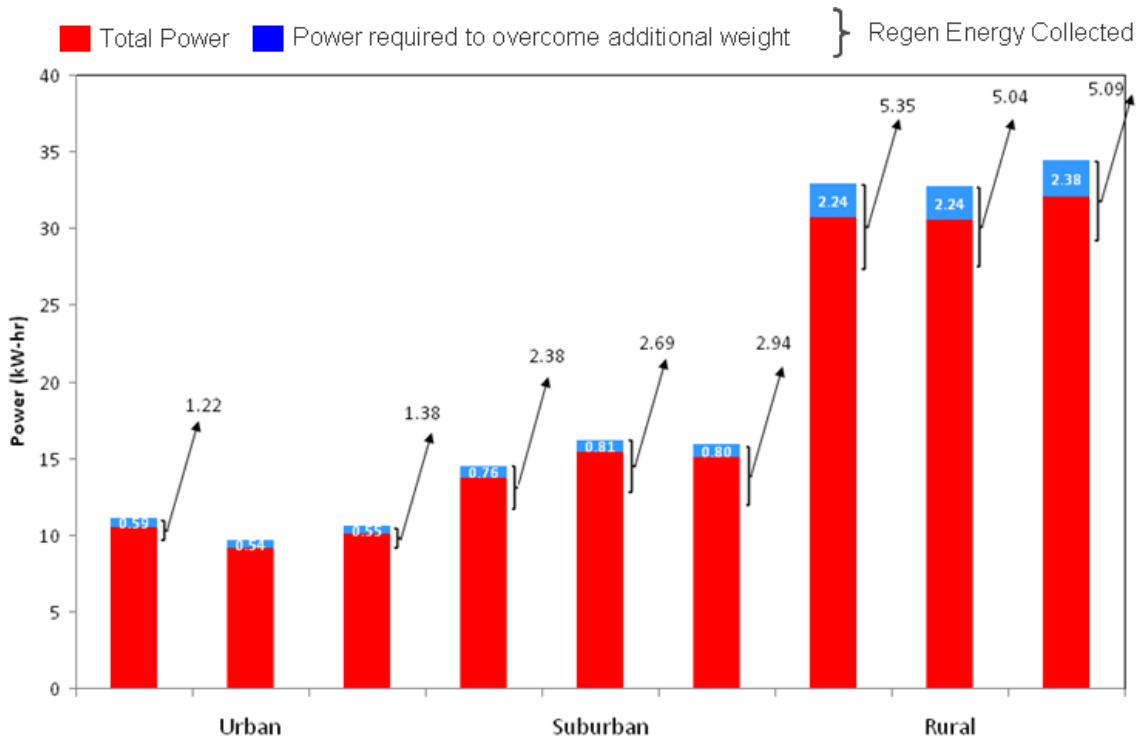


Figure 4-5 Regen Energy Collected vs Power Required to Overcome Weight of Hybrid System, Bus 301

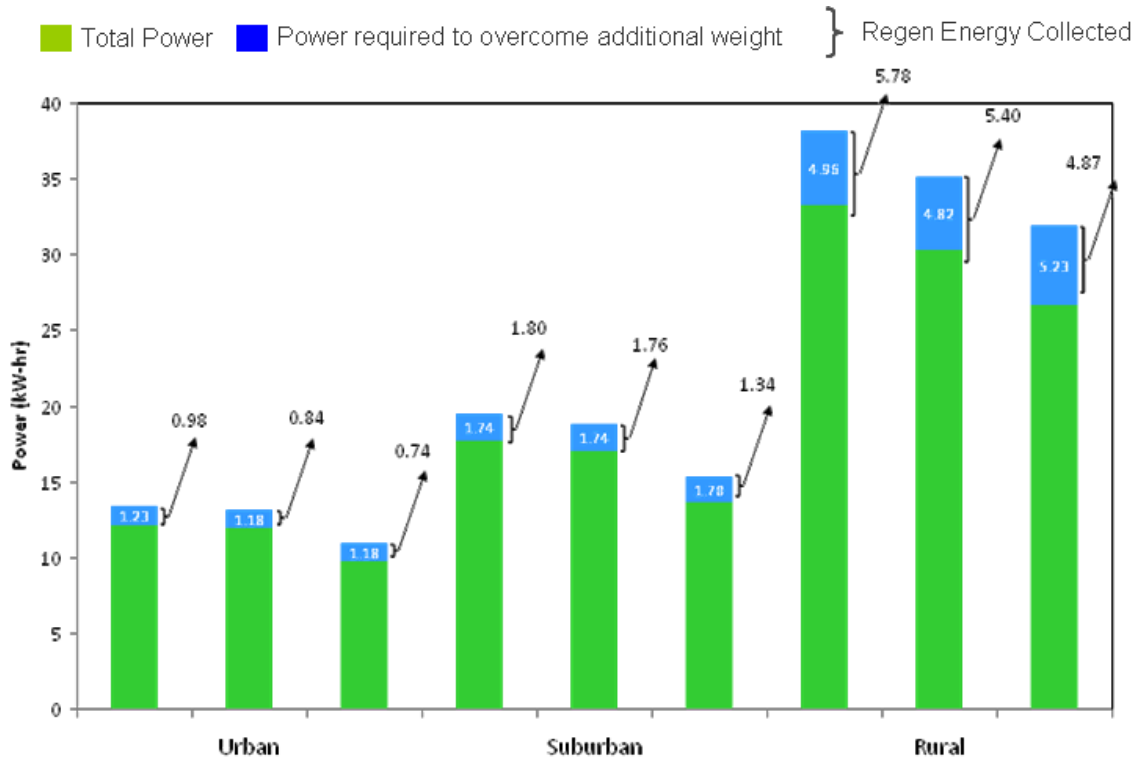


Figure 4-6 Regen Energy Collected vs Power Required to Overcome Weight of Hybrid System, Bus 302

As shown, the estimated energy required to overcome the additional weight of the hybrid system on bus 301 varied from about one half kilowatt-hour for the urban route to 2.25 kw-hr for the rural/hill route. Due to its greater weight, the additional energy required for bus 302 was higher – over one kilowatt-hour on the urban route and almost 5 kw-hr on the rural/hill route.

Bus 301 was able to consistently collect as regen more than twice as much energy as was required to overcome the additional weight of the hybrid system, providing a net energy benefit of approximately one half kilowatt-hour on the urban route and almost two kilowatt-hour on the rural/hill route. This net energy benefit from regen collection was approximately five percent of total cycle energy on all three routes. The net energy benefit of regen offset diesel fuel usage by approximately 0.04 gallons/run on the urban route and 0.15 gallons/run on the rural/hill route.

However, as shown in Figure 4-6, bus 302 generally was not able to collect enough regen energy to offset the estimated additional power required to move the additional weight of the hybrid system installed on the bus.

Figure 4-7 shows, for bus 301, the total energy required to drive each repeat of each test route, along with the amount of regen energy actually collected, and an estimate of the amount of energy that was available for collection as regen. Figure 4-8 shows the same information for bus 302.

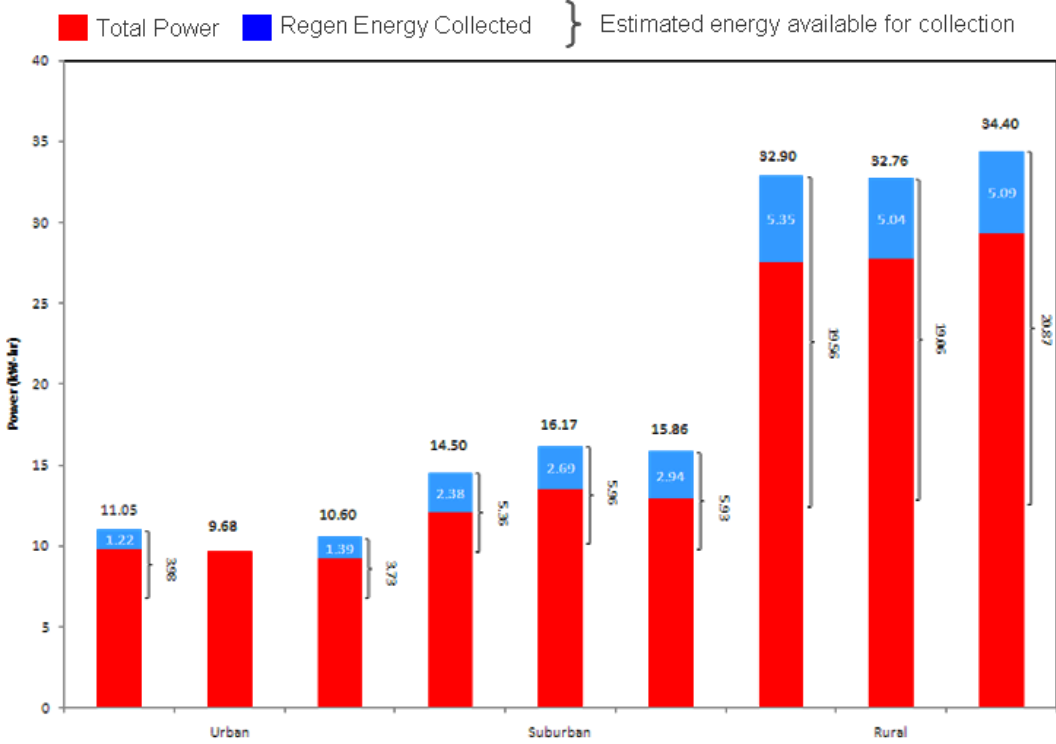


Figure 4-7 Regen Energy Collected vs Estimated Energy Available for Collection, Bus 301

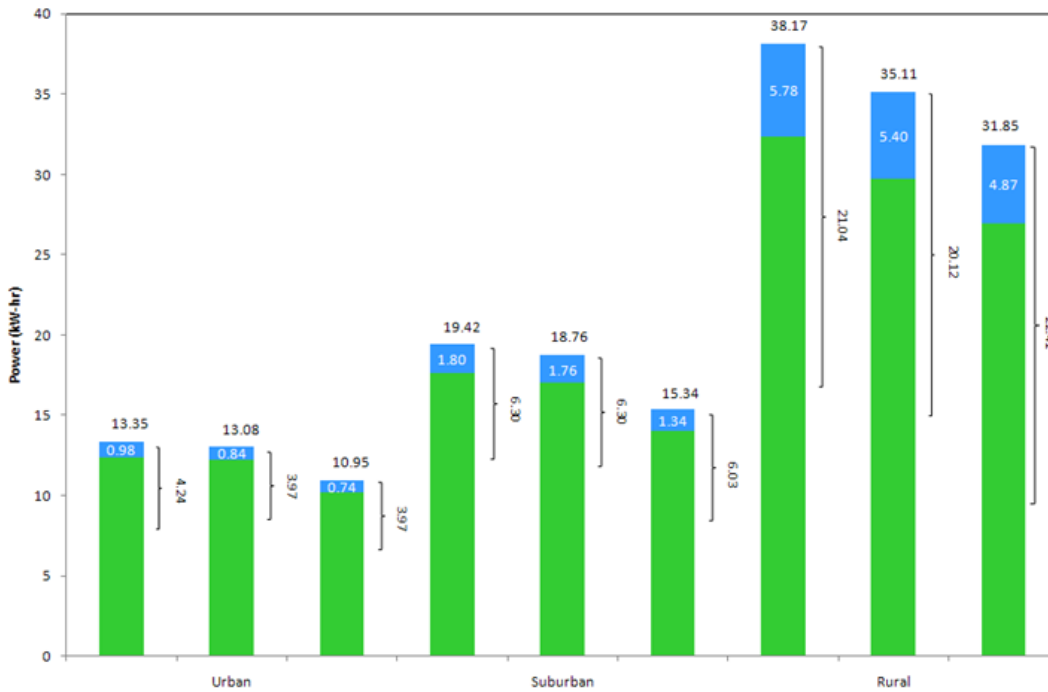


Figure 4-8 Regen Energy Collected vs Estimated Energy Available for Collection, Bus 302

Of the total amount of energy required to drive a school bus over a route, some is required to overcome inertia (accelerate the vehicle, climb grades), some is required to overcome wind resistance (aerodynamic friction), some is required to overcome friction between the roadway and the tires (rolling resistance), and some is required to operate engine/vehicle accessories (alternator, air compressor, engine cooling fan). With a standard diesel school bus most of the inertial energy is dissipated as heat by the braking system when the bus comes to a stop. It is this inertial energy that a hybrid school bus can collect as regen energy; as shown in Figures 4-7 and 4-8 the inertial energy that was theoretically available for collection amounted to approximately one third of total cycle energy for the urban and suburban routes and over half of total cycle energy for the rural/hill route, for both bus 301 and bus 302⁶.

Bus 301 was able to actually capture as regen approximately 25% of this inertial energy on the urban and rural/hill routes and almost 50% on the suburban route. Bus 302 was able to actually capture as regen approximately 23% of this inertial energy on the urban route and 28% on the first two repeats of the suburban and rural/hill routes. On the third repeat of each route the efficiency of regen capture fell off for bus 302 (to 18% on the urban route and approximately 21% on the suburban and rural/hill routes).

As discussed previously, diesel fuel economy for bus 302 fell off significantly on the third repeat of each test route. This was due to reduced “hybrid assist” as the battery pack became depleted over time. Figure 4-9 shows measured diesel fuel economy for bus 302 plotted against accumulated bus miles and battery state-of-charge as the bus operated on the urban route. Figure 4-10 shows the same data for bus 302 operated on the rural/hill route.

As shown, once the battery state-of-charge falls below approximately 40% the hybrid system is programmed to provide less hybrid assist; since the diesel engine is therefore required to provide more power diesel fuel economy drops. The cumulative distance over which bus 302 provided a significant diesel fuel economy benefit compared to diesel bus 300 was approximately 10 miles on the urban route and 22 miles on the rural/hill route.

⁶ For small, rolling hills even conventional vehicles can “recover” much of the inertial energy required to climb a hill, as they pick up speed on the down hill and use their increased inertia to “climb” part of the next grade. The rural/hill test route included a single, steep uphill grade, and a long down hill portion with several stops. For this type of hill the bus operator was required to brake on the down hill portion, which dissipates energy in the braking system; in a conventional vehicle this energy can not then be recovered by using the vehicle’s inertia to “climb” the next grade. For this analysis, we assumed that all of the vertical inertial energy added during the uphill portion of the rural/hill route could be recovered by the hybrid system during down hill braking, which is why “recoverable” energy is a greater proportion of total cycle energy for the rural/hill route than for the other routes. This simplified assumption may somewhat over-state the amount of energy theoretically available for collection as regen on this route.

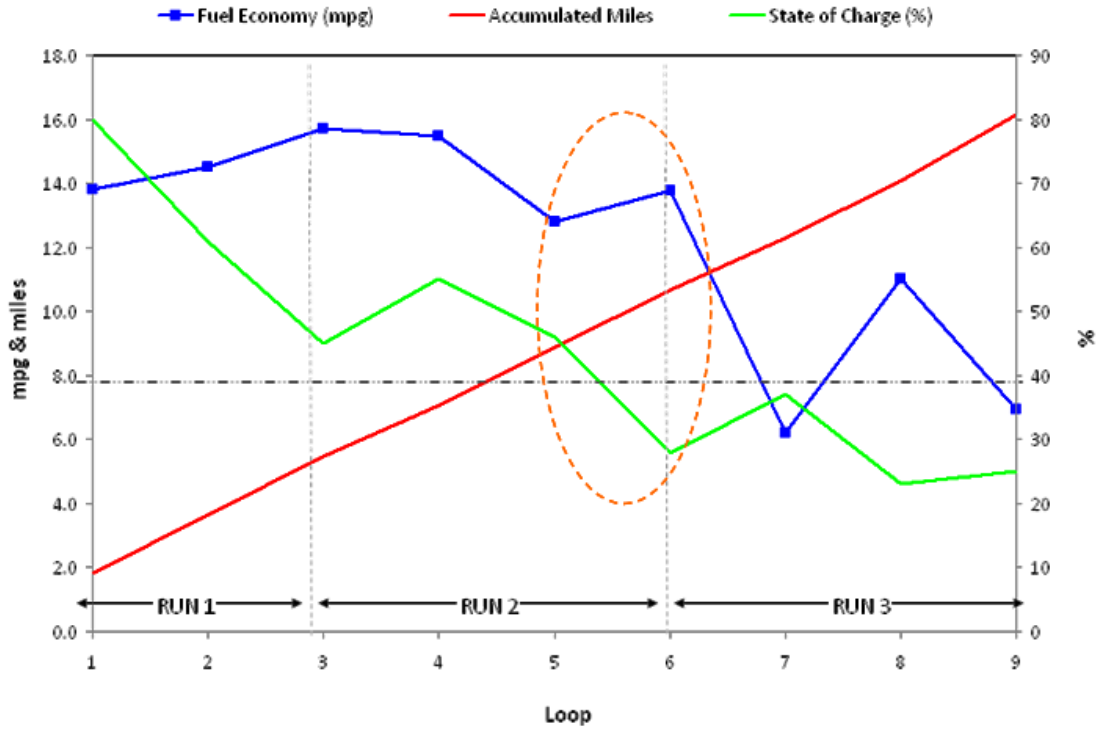


Figure 4-9 Bus 302 Urban Route – Fuel Economy vs % Battery State-of-Charge

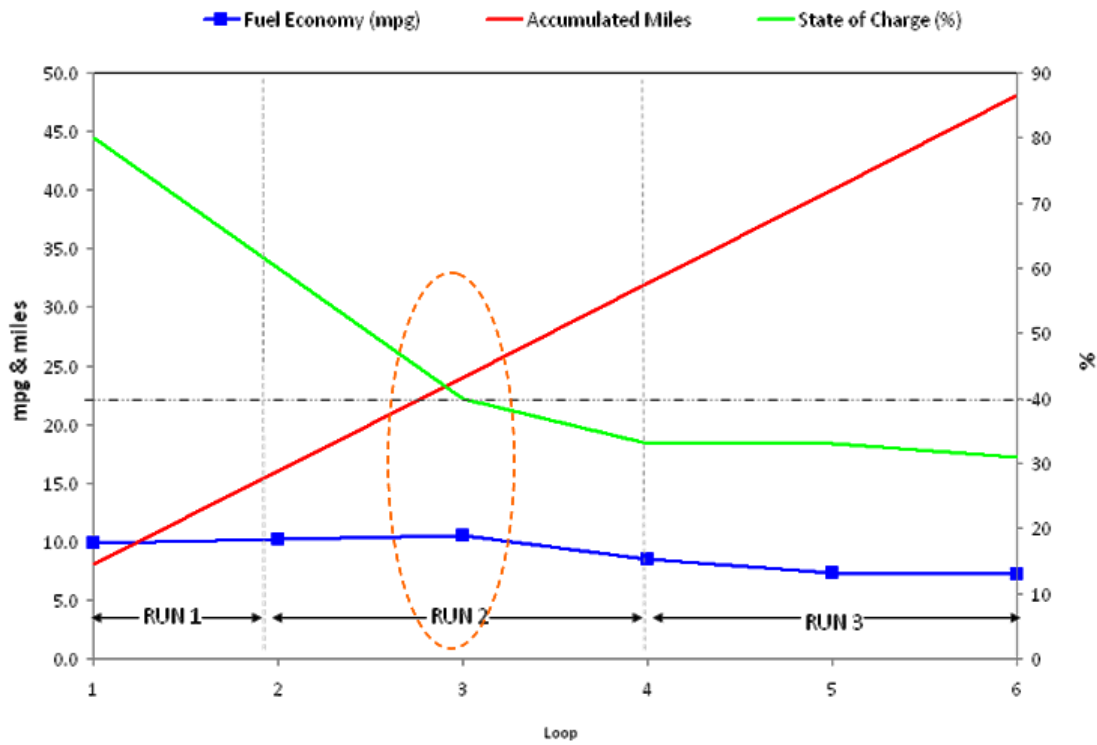


Figure 4-10 Bus 302 Rural/Hill Route – Fuel Economy vs % Battery State-of-Charge

5. Performance Test Results

Bus 300 (diesel) and bus 301 (charge-sustaining hybrid) were tested to determine maximum acceleration rate, and interior and exterior noise levels under several different operating conditions. Due to time constraints bus 302 (charge-depleting hybrid) was not tested.

5.1. Acceleration Testing

Acceleration rates for each bus were measured from zero to approximately 40 mph, and reported as time (seconds) and distance (feet) to reach each speed, in 10 mph increments.

For the testing each bus was loaded to nominal half seated load weight (33 seats x 120 lb per seated passenger = 3,960 lbs) using eighty 50-pound bags of salt.

The tests were conducted on dry, level ground on a section of road within the Scotia Industrial Park. The available test location was not ideal; there was not a long enough straight section of road to achieve 40 mph consistently, so each bus was required to negotiate a slight curve at speed. This likely affected repeatability of the test runs; both buses exhibited significant variability in acceleration rates from run-to-run.

At the start of each test the bus operator was instructed to quickly push the accelerator pedal all the way to the floor and to hold it there until the bus reached 40 mph, after which the bus was brought back safely to a stop.

For each bus four individual test runs were conducted, two in each direction on the test track. Acceleration data was collected using a Racepak™ G2X data acquisition system (MSD Ignition, www.msddignition.com). This device uses a global positioning system (GPS) signal to determine bus location, speed, and acceleration. Position data is recorded at a frequency of 20 hz.

The results of the acceleration testing are shown in Table 5-1 and in Figures 5-1 and 5-2. As shown, on average hybrid bus 301 accelerated faster than diesel bus 300, achieving 20 mph 0.9 seconds faster and achieving 40 mph 1.9 seconds faster.

Figure 5-2 shows the results for every run of Bus 300. As shown, there was significant run-to-run variability for this bus. The results for Bus 301 show similar run-to-run variability.



Time & Distance to Speed

| Speed (mph) | 300 Seconds | 300 Feet | 301 Seconds | 301 Feet |
|-------------|-------------|----------|-------------|----------|
| 10 | 2.67 | 39 | 2.45 | 36 |
| 20 | 6.64 | 195 | 5.73 | 168 |
| 30 | 12.51 | 550 | 11.10 | 488 |
| 40 | 21.30 | 1,249 | 19.41 | 1,139 |

Table 5-1 Average Time and Distance to Speed (average of four runs)

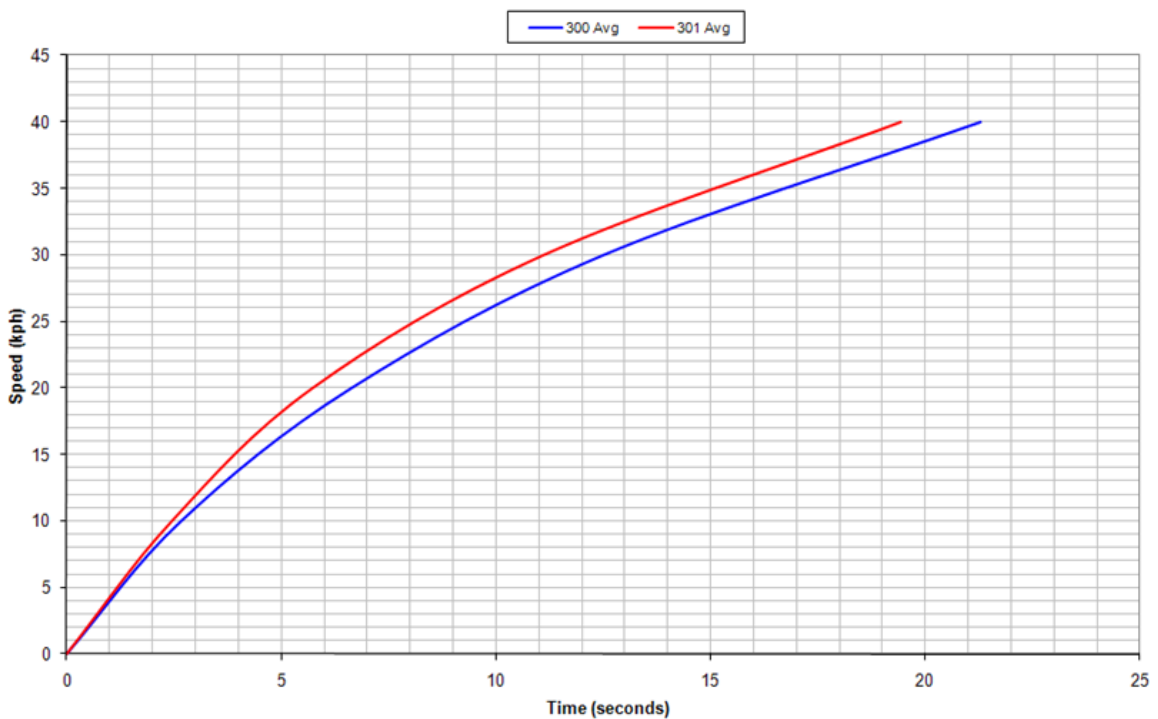


Figure 5-1 Average Acceleration (speed vs time)

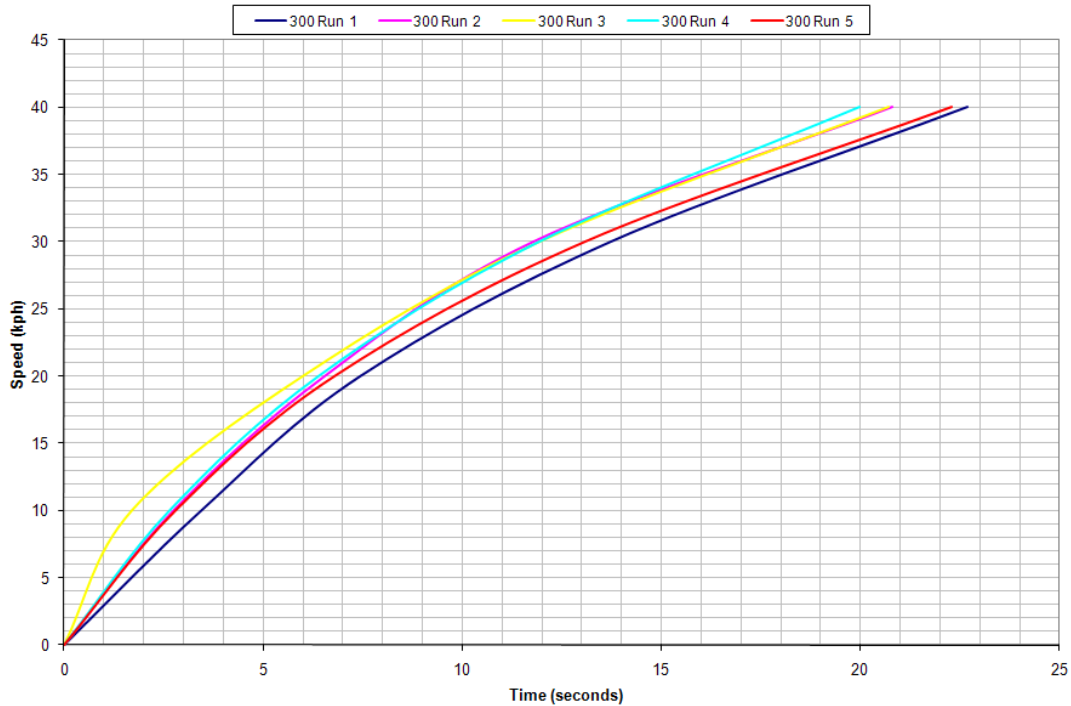


Figure 5-2 Bus 300 Acceleration (speed vs time) for each run

5.2. Noise Testing

Exterior noise testing was conducted in accordance with SAE standard *SAE J366, Exterior Sound level for Heavy Trucks and Buses*. For each bus, peak exterior sound pressure levels (db) were measured at idle and during maximum bus acceleration, with the sound meter located to the side of the bus, fifty feet from the centerline of bus travel. Interior sound pressure levels (db) were measured at idle, during maximum acceleration, and during 20 mph cruise, at each of three points inside the passenger compartment (at driver position, mid-bus, and at the rear of the bus). For interior noise measurements the noise meter was located in the bus aisle at seated passenger head height.

Testing was done in an empty parking lot at the Scotia Industrial Park. There were no buildings or large reflecting surfaces within 300 feet of the bus during testing.

For each condition, three individual tests were conducted. For each test sound pressure data was measured using an Extech Instruments 407738 sound level meter.

The results of the noise testing are shown in Table 5-2. Select results are also shown in Figures 5-3 through 5-6.

As shown, hybrid bus 301 had the same or lower interior sound levels as diesel bus 300 under most test conditions and in most interior locations. Bus 301 interior noise was typically 2 – 8 dB lower; the most significant difference was in rear of the bus during 20 mph cruise. The only exception was at the driver position while idling,

when the measured sound levels in bus 301 were 1.8 dB higher than in bus 300. Hybrid bus 301 also had lower exterior noise than diesel bus 300 while accelerating (1.8 – 2.9 dB lower). While idling exterior noise from bus 301 was 3 dB lower on the curb side but 0.3 dB higher on the street side.

| | | Interior | | | | | | | | |
|--------|-----|----------|-------|--------|-----------|-------|--------|------|-------|--------|
| | | Driver | | | Mid-Coach | | | Rear | | |
| | | Idle | Accel | Cruise | Idle | Accel | Cruise | Idle | Accel | Cruise |
| Diesel | 300 | 50.5 | 70.4 | 64.9 | 46.9 | 66.3 | 62.3 | 46.2 | 68.9 | 65.2 |
| Diesel | 301 | 52.3 | 70.7 | 62.2 | 44.6 | 66.1 | 58.2 | 44.7 | 64.7 | 57.1 |

| | | Exterior - CS | | Exterior - SS | |
|--------|-----|---------------|------|---------------|------|
| | | Accel | Idle | Accel | Idle |
| Diesel | 300 | 73.6 | 55.0 | 73.6 | 54.9 |
| Diesel | 301 | 70.7 | 52.0 | 71.8 | 55.2 |

Table 5-2 Average Noise Readings (dB)

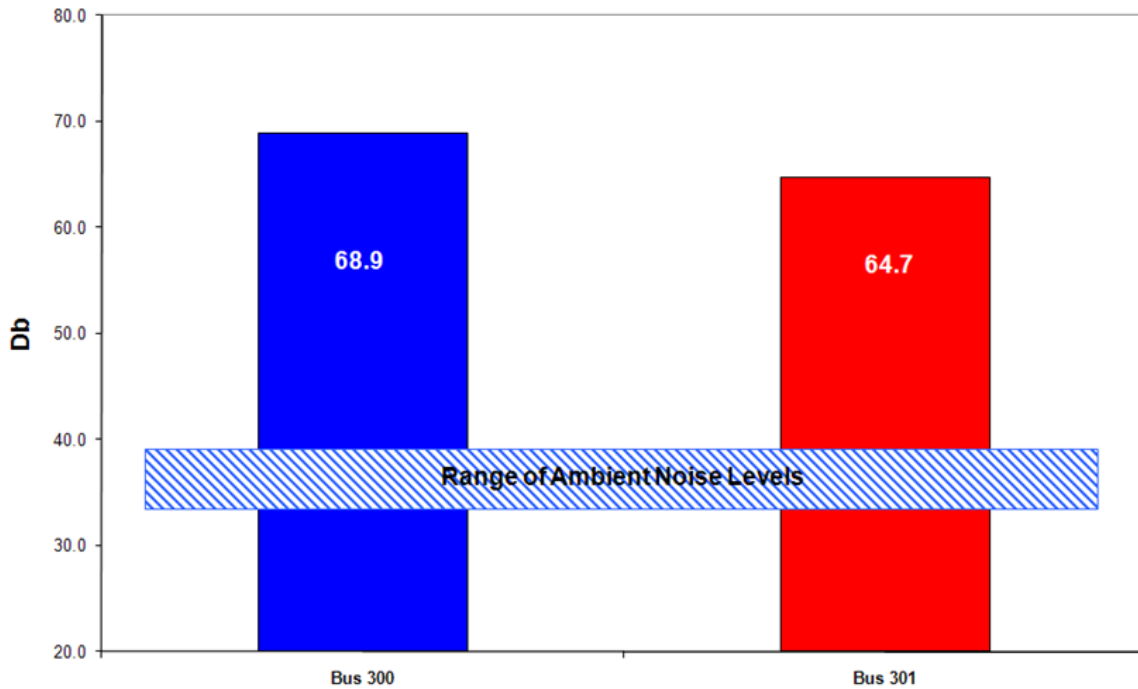


Figure 5-3 Interior Noise – Acceleration Back of Coach

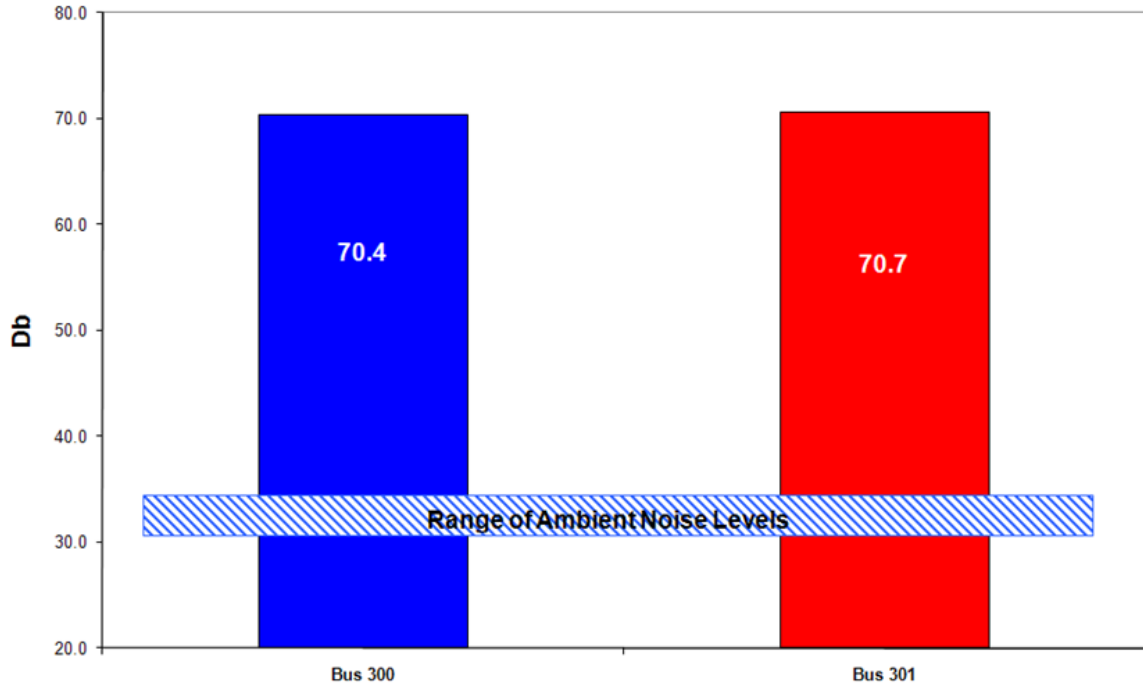


Figure 5-4 Interior Noise – Acceleration Front of Coach

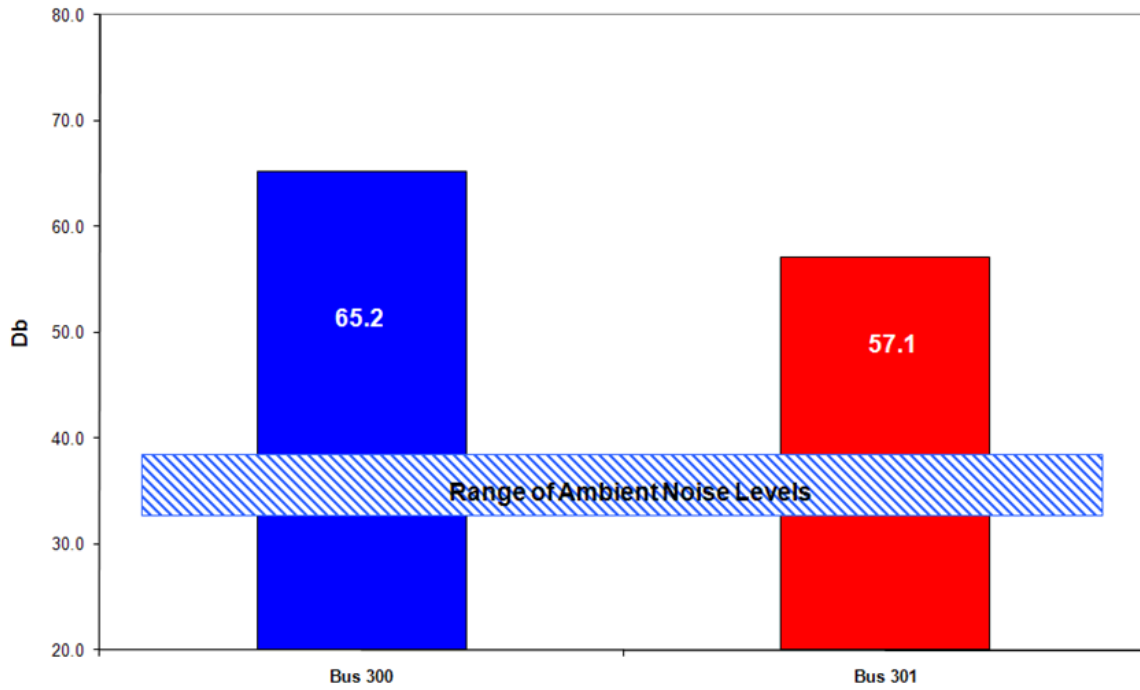


Figure 5-5 Interior Noise – 20 mph Cruise Back of Coach

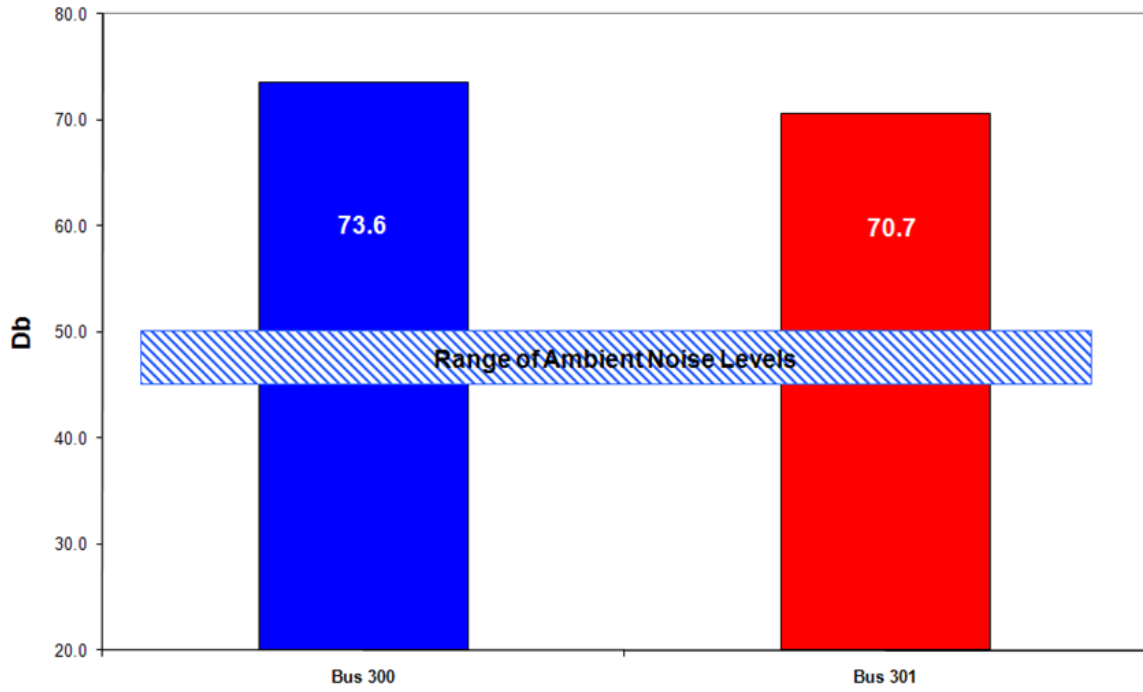


Figure 5-6 Exterior Noise – Acceleration, Curb Side

Appendix A – Test Routes



Figure A-1 Map of Urban Route

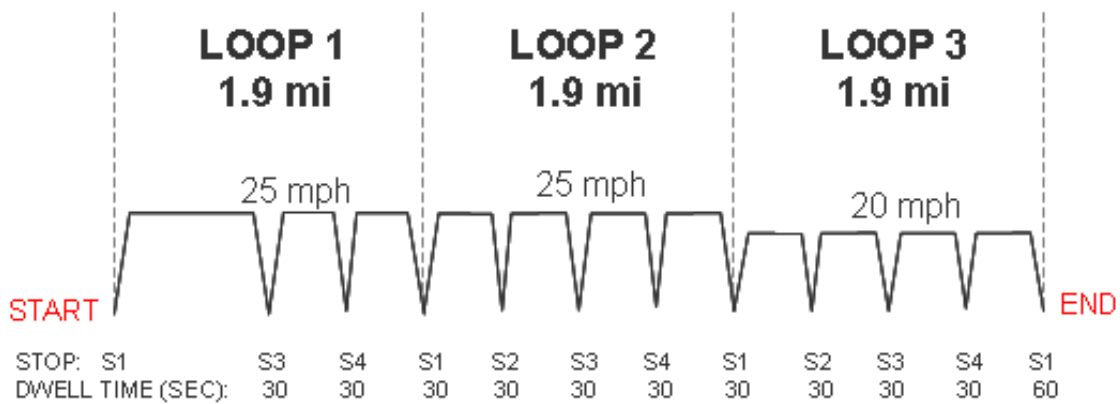


Figure A-2 Urban Route Target Driving Profile

Appendix A – Test Routes



Figure A-3 Map of Suburban Route

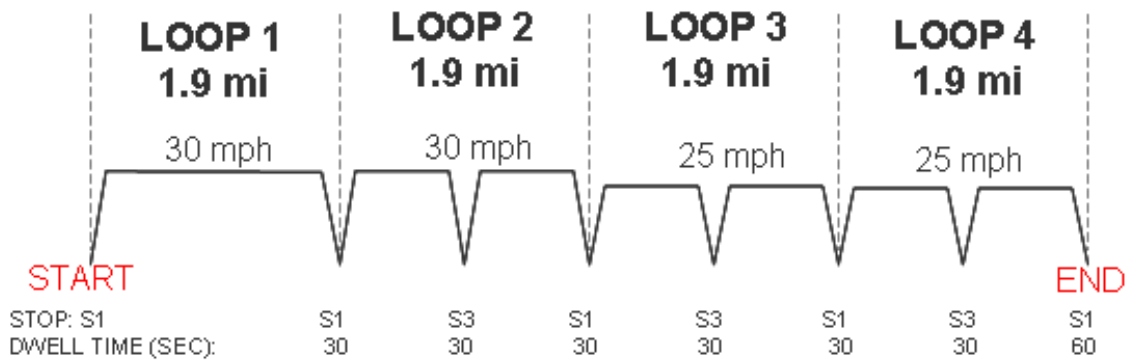


Figure A-4 Suburban Route Target Driving Profile

Appendix A – Test Routes



Figure A-5 Map of Rural/Hill Route

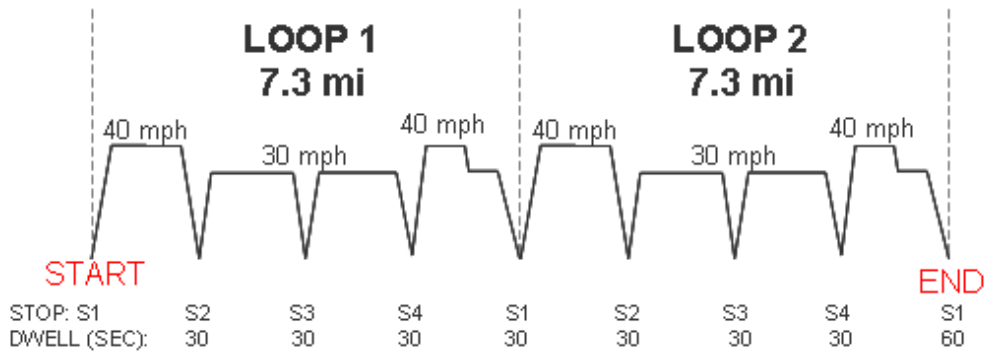


Figure A-6 Rural/Hill Route Target Driving Profile

Appendix A – Test Routes

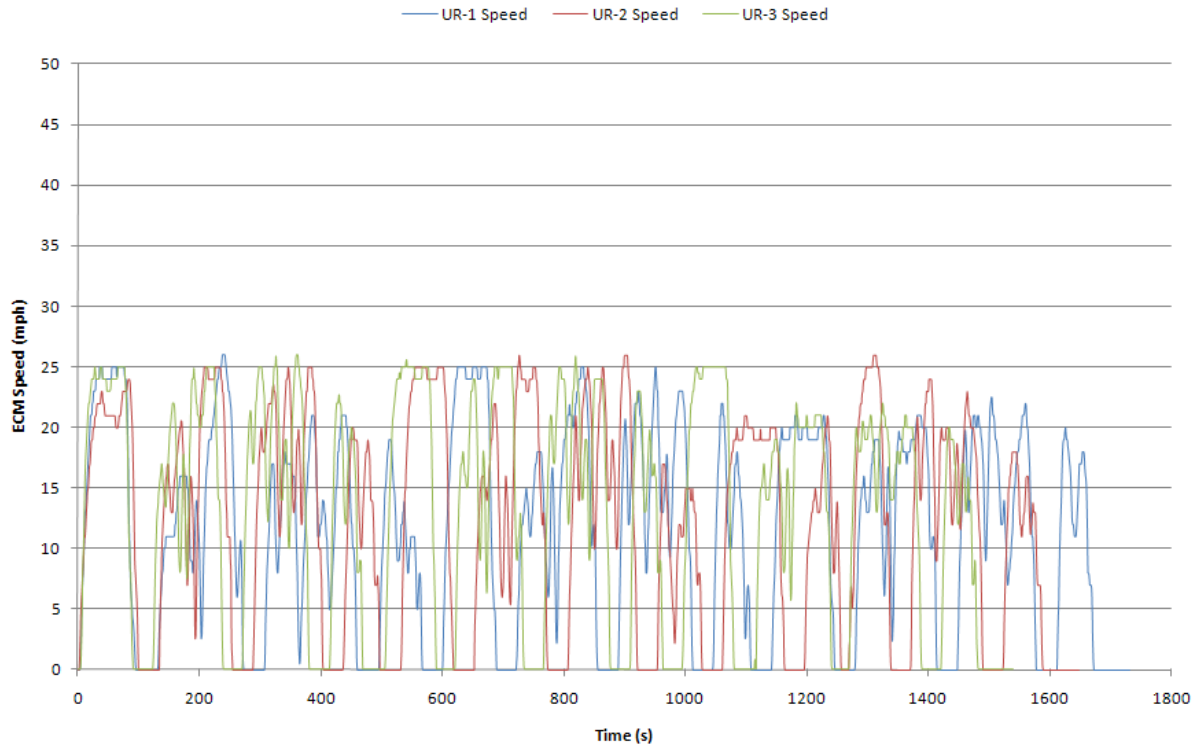


Figure A-8 Example Drive Profiles – Bus 300; three repeats of Urban Route (typical)

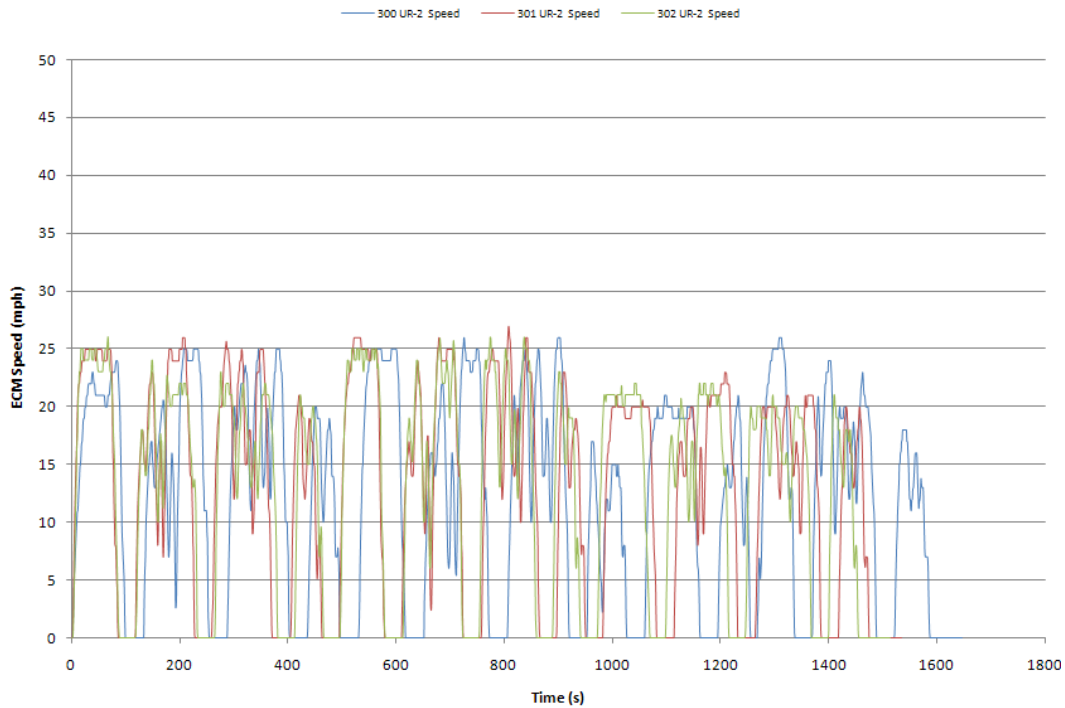


Figure A-9 Example Drive Profiles – Buses 300, 301, and 302; repeat 2 of Urban Route