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Long Beach Transit: Two-Year Evaluation of Gasoline-Electric Hybrid Transit Buses

Technical Report
NREL/TP-540-42226
June 2008

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National Renewable Energy Laboratory

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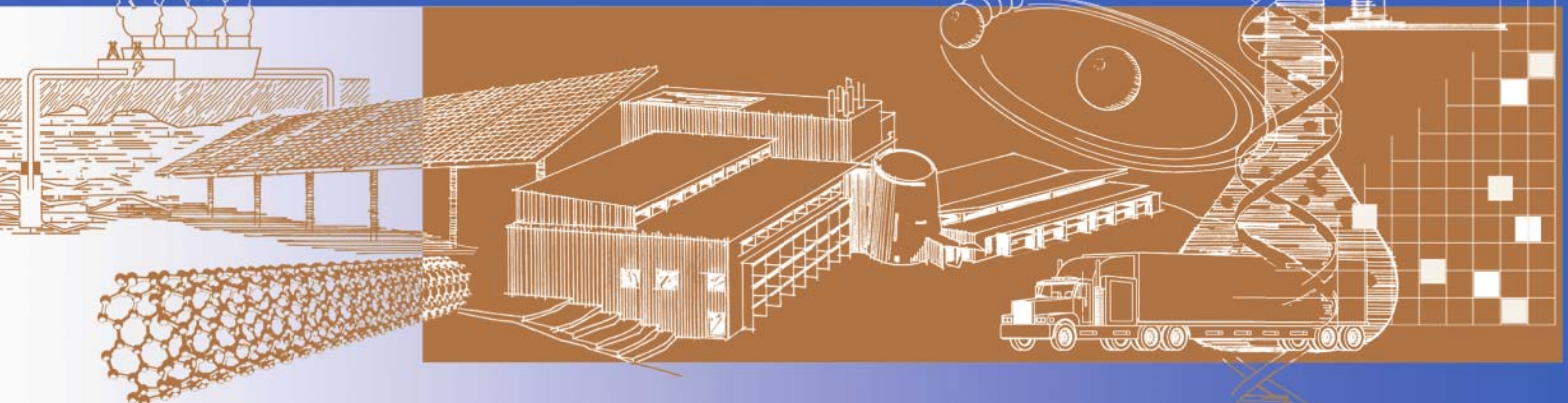

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List of Acronyms

AVTA—Advanced Vehicle Testing Activity
bhp—brake horsepower
CARB—California Air Resources Board
DOE—U.S. Department of Energy
EGR—exhaust gas recirculation
FT&E—Fleet Test and Evaluation (NREL team)
g/bhp-hr—grams per brake horsepower hour
GVWR—gross vehicle weight rating
HVAC—heating, ventilation, and air conditioning
LBT—Long Beach Transit
MBRC—miles between road calls
mph—miles per hour
MY—model year
NO_x—oxides of nitrogen
NREL—National Renewable Energy Laboratory
PM—particulate matter
ppm—parts per million
RC—road call
rpm—revolutions per minute
SCAQMD—South Coast Air Quality Management District
ULSD—ultra-low sulfur diesel
VDC—voltage direct current

Executive Summary

This report is part of a series of evaluations from the U.S. Department of Energy (DOE). DOE, through the National Renewable Energy Laboratory (NREL), has been tracking and evaluating new propulsion systems in transit buses and trucks for more than 10 years using an established and documented evaluation protocol. The DOE/NREL vehicle evaluations are a part of the Advanced Vehicle Testing Activity (AVTA), which supports DOE's Vehicle Technologies Program.

The role of AVTA is to bridge the gap between research and development and commercial availability of advanced vehicle technologies that reduce petroleum use in the U.S. while improving air quality. The main objective of AVTA projects is to provide comprehensive, unbiased evaluations of advanced vehicle technologies in commercial use. Data are collected and analyzed for operation, maintenance, performance, cost, and emissions characteristics of advanced technology fleets and comparable conventional technology fleets operating at the same site. By comparing available advanced and conventional technology vehicles, AVTA evaluations help fleet owners and operators make informed purchasing decisions.

This report focuses on a gasoline-electric hybrid transit bus propulsion system. This propulsion system is an alternative to standard diesel buses and allows for reductions in emissions (usually focused on reductions of particulate matter and oxides of nitrogen) and petroleum use. Gasoline propulsion is an alternative to diesel fuel and hybrid propulsion allows for increased fuel economy, which ultimately results in reduced petroleum use.

Evaluation Design

This report describes the evaluation results for New Flyer low floor buses with new gasoline hybrid propulsion (equipped with ISE Corporation's ThunderVolt Hybrid Drive propulsion system) and older diesel buses at the Long Beach Transit (LBT). These final results represent a 24-month evaluation (July 2005 through June 2007)of these two groups of buses.

The evaluation team selected 10 vehicles from the hybrid group of 47 vehicles and 10 vehicles from the diesel group of 138 vehicles for analysis. The number of vehicles that comprise the study was determined sufficient to provide some degree of statistical significance to the results obtained.

Evaluation Results

The following results and related discussions focus only on selected operating depots and the two study bus groups.

Bus Use and Duty Cycle

LBT operates 228 buses out of two facilities and averages almost 40,000 miles per bus annually for both facilities. The average speed of the 40-ft bus fleet is 13.8 miles per hour (mph) with an average of 8 stops per mile. LBT currently has forty-seven 40-ft hybrid gasoline-electric buses. The hybrid study group had a usage rate of 31,875 miles per month (38,250 miles per bus annually) —2.4% lower than that of the diesel study group buses. This small difference is not statistically significant and makes the two groups ideal for comparison.

Fuel Economy and Fuel Costs

On a volumetric basis, the 24-month average fuel economy for the hybrid buses is 3.35 miles per gallon (mpg)—4.3% lower than that of the diesel buses. This difference is likely due to the lower efficiency of a throttled, spark-ignited engine as well as the lower energy content of a gallon of gasoline versus a gallon of diesel. On an equivalent energy per volume basis, the hybrids had an 8.5% mpg increase. During the evaluation period, gasoline at LBT cost an average of $2.49 per gallon and diesel cost an average of $2.29 per gallon. This lower fuel economy, combined with a higher fuel cost for gasoline, resulted in fuel costs per mile being $.74 per mile for the hybrids as compared to $.65 per mile for the diesels.

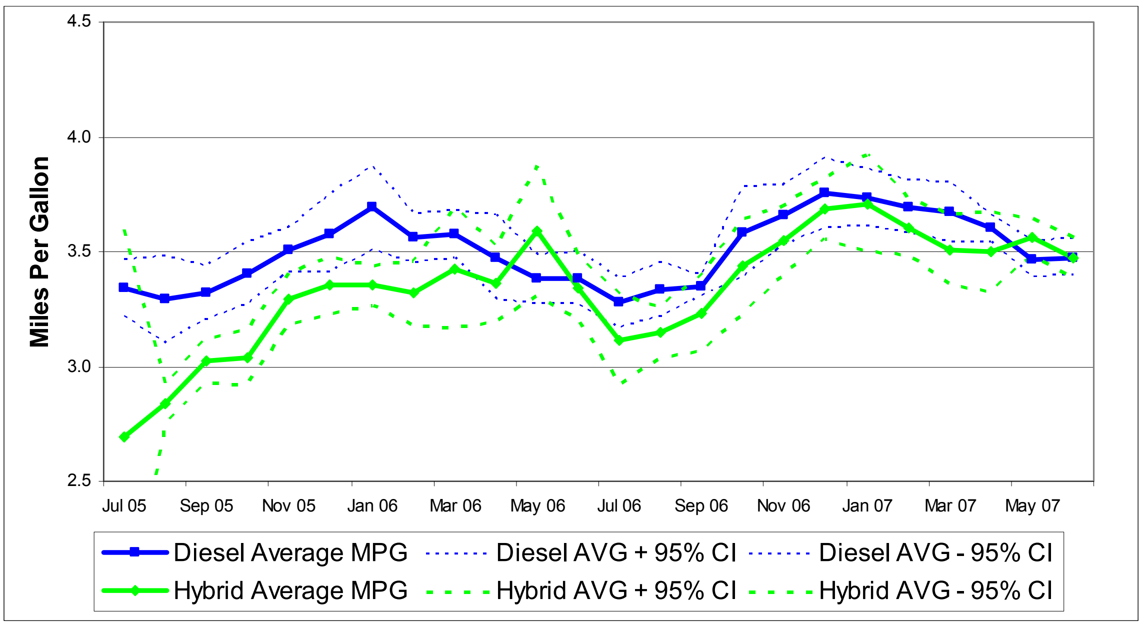

Figure ES-1. Average Monthly Fuel Economy

Maintenance Costs

At the beginning of the evaluation period, the hybrid buses were brand new and remained under warranty for the evaluation period, which accounts for the cost-per-mile difference with the older, out-of-warranty diesel buses. The hybrids cost $.31 per mile to maintain while the diesels cost $.54 per mile. Propulsion related costs were $.08 per mile for the hybrids and $.19 per mile for the diesels.

Brake System Related Maintenance Costs

In general, the brake system maintenance costs are expected to be dramatically lower for hybrid propulsion systems with regenerative braking, which allows use of the electric drive motors to slow a bus, similar to a transmission retarder. The energy from braking is taken into the electric motor and then fed back to the ultra-capacitors. The hybrids had brake system maintenance costs that were about 90% less than that of the diesel buses with no relines to date on the hybrids.

Ultra-Capacitors

LBT chose to use ultra-capacitors for energy storage instead of the traction batteries more commonly used in hybrid transit buses. The ultra-capacitors work well for LBT's duty cycle with frequent stops per mile and slow average speeds and are able to take advantage of the high charge and discharge rates associated with the frequent starts and regenerative braking events. In addition, the ultra-capacitors have a 12-year life expectancy compared to three to six years for batteries. ISE offers a three-year extended warranty on top of their two-year standard warranty for the ultra-capacitors.

During the evaluation period a manufacturing issue was identified; acetonitrile was leaking from some of the ultra-capacitors. ISE corrected the issue with a warranty campaign based on serial numbers of suspect batches of ultra-capacitors.

Road Calls

In this report, a road call (RC) is defined as an on-road failure of an in-service bus, which results in a bus being taken out of service or replaced on-route. RCs are a direct indicator of reliability for transit buses. Miles between RC (MBRC) is a typical industry measurement for RC performance for transit buses. The hybrid buses had 9,000 MBRC compared to the diesel buses with just above 11,000.

For RCs related only to the propulsion system, the hybrid buses are 15,000 MBRC. For comparison, the older diesel buses have MBRC at just above 19,000.

Table of Contents

Overview

Advanced Vehicle Testing Activity

The role of the Advanced Vehicle Testing Activity (AVTA) is to help bridge the gap between research and development (R&D) and commercial availability for advanced vehicle technologies that reduce petroleum use while meeting air quality standards. AVTA supports the Department of Energy's (DOE) Vehicle Technologies Program by examining market factors and customer requirements and evaluating the performance and durability of alternative fuel and advanced technology vehicles in fleet applications. The National Renewable Energy Laboratory's (NREL) Fleet Test and Evaluation (FT&E) team conducts evaluations primarily under support from AVTA, but also under support from other DOE programs focused on nonpetroleum-based and advanced petroleum-based fuels.

The main objective of FT&E projects is to conduct comprehensive, unbiased evaluations of advanced technology vehicles. Data collected and analyzed include the operations, maintenance, performance, cost, and emissions characteristics of advanced technology vehicles and comparable conventional technology in fleets operating at the same site. By comparing available advanced and conventional technology vehicles, FT&E evaluations help fleet owners and operators make informed purchasing decisions. The evaluations also provide valuable data to DOE about the maturity of the technology being assessed.

The FT&E team recently conducted—or is in the process of conducting—several evaluations of advanced propulsion heavy-duty vehicles (see Table 1). For information on these and other evaluations involving advanced technologies or alternative fuels such as biodiesel and Fischer-Tropsch diesel, visit www.nrel.gov/vehiclesandfuels/fleettest.

Table 1. FT&E Heavy-Duty Vehicle Evaluations

Fleet	Location	Vehicle	Technology	Evaluation Status
Metro	St. Louis, MO	GILLIG 40-ft transit bus	Biodiesel blend (B20)	In progress; interim report completed Nov. 2007; final report in June 2008
New York City Transit	Manhattan, Bronx, NY	Orion VII 40-ft transit bus	Series hybrid, BAE Systems HybriDrive propulsion system (diesel), Order of 200 (Gen II); Order of 125 (Gen I);	Completed in Jan. 2008
New York City Transit	Manhattan, Bronx, NY	Orion VII 40-ft transit bus	Series hybrid, BAE Systems HybridDrive propulsion system (diesel), order of 125; DDC S50G CNG engines	Completed in Nov. 2006
Denver RTD	Boulder, CO	GILLIG 40-ft transit bus	Biodiesel blend (B20)	Completed in Oct. 2006
King County Metro	Seattle, WA	New Flyer 60-ft articulated transit bus	Parallel hybrid, GM–Allison E^P50 System (diesel)	Completed in Dec. 2006
IndyGo	Indianapolis, IN	Ebus 22-ft bus	Series hybrid, Capstone MicroTurbine (diesel)	Completed in 2005
Knoxville Area Transit	Knoxville, TN	Ebus 22-ft bus	Series hybrid, Capstone MicroTurbine (propane)	Completed in 2005
Norcal	San Francisco, CA	Peterbilt/378, Class 8 truck	Cummins Westport ISXG high-pressure, direct- injection, liquefied natural gas (LNG) and diesel	Completed in 2004

Host Site Profile—Long Beach Transit

Long Beach Transit (LBT) operates 228 buses out of two facilities: Anaheim and Larry Jackson, which are located only seven miles apart. The fleet is made up of thirty 30-ft buses, one hundred and eighty-five 40-ft buses, and thirteen articulated buses. LBT services seven cities, transports 28–29 million passengers per year, and averages almost 40,000 miles per bus annually. The average speed of the 40-ft bus fleet is 13.8 miles per hour (mph) with an average of eight stops per mile. LBT currently has forty-seven 40-ft hybrid gasoline-electric buses that arrived in June through August of 2005. The transit authority has taken delivery of 15 more in the third quarter of 2007 and has requested an additional 25 for 2008.

Because LBT operates in the South Coast Air Quality Management District (SCAQMD), SCAQMD regulations prevented LBT from purchasing new diesel buses after 2002. As in other California transit districts, the primary path toward reducing oxides of nitrogen (NOx) and particulate matter (PM) emissions had been using buses powered by natural gas. LBT conducted an overall cost analysis, though, that led the agency to try the new hybrid gasoline-electric buses instead. Like natural gas, gasoline was qualified as an alternative fuel for transit buses by the California Air Resources Board (CARB).

LBT's cost analysis showed that the hybrids would be more cost-effective than buses powered by natural gas in terms of capital costs for infrastructure, better fuel economy, and savings in maintenance on brake relines and transmission overhauls. In addition, replacing the gasoline engine would be less expensive than overhauling a diesel engine. LBT already had gasoline fueling capability on site, so for the first year of operation the new hybrid gasoline-electric buses used the existing facility. After the first year, LBT spent $1.9 million to upgrade its facilities to update the fuel island at one of the properties with new lines, replace aging fuel tanks, and expand the gasoline capacity for future growth. The second facility required no changes.

Combining a light-duty gasoline engine in a series hybrid heavy-duty application with ultra-capacitors had never been done before. LBT had no official expectations for the hybrids in regards to reliability and durability, but did expect to have some growing pains with the new technology. The hybrids (see Figure 1) were put into service and dispatched the same as the diesel buses with the exception of a few high-speed routes.

Figure 1. Photo of one of LBT's gasoline-electric hybrid transit buses.

Project Design and Data Collection

In this evaluation, the focus is on the hybrids purchased in model year (MY) 2004 and 2005 by LBT and their performance during the first 2 years of service (7/05/05 – 6/07/07). MY 2002 diesel buses are used as a baseline in this evaluation.

Two major interests in hybrid bus operations held by the transit industry are (1) determining energy storage replacement frequency and costs, and (2) quantifying the benefits of regenerative braking, realized in reduced brake system maintenance costs.

Ten hybrid buses and 10 diesel buses (MY 2002) were randomly chosen for this evaluation. The buses were spread evenly between the Anaheim and Larry Jackson depots. The depots both dispatch to all routes that LBT services and the study buses were assigned to routes randomly with the normal fleet of 40-ft buses. The preventive maintenance schedules and maintenance practices are the same at each depot.

Vehicle-specific data for this evaluation were taken from LBT's maintenance and fueling data system. The evaluation period for buses considered in this report began in July 2005 and ended in June 2007.

Data parameters included the following:

- Diesel and gasoline fuel consumption
- Mileage accumulation
- Maintenance records, including work orders, parts costs, and labor hours
- Road call (RC) records.

Vehicle System Descriptions

LBT's hybrid buses are built by New Flyer and use the ISE Corporation's ThunderVolt series Hybrid Drive propulsion system (Figure 2).

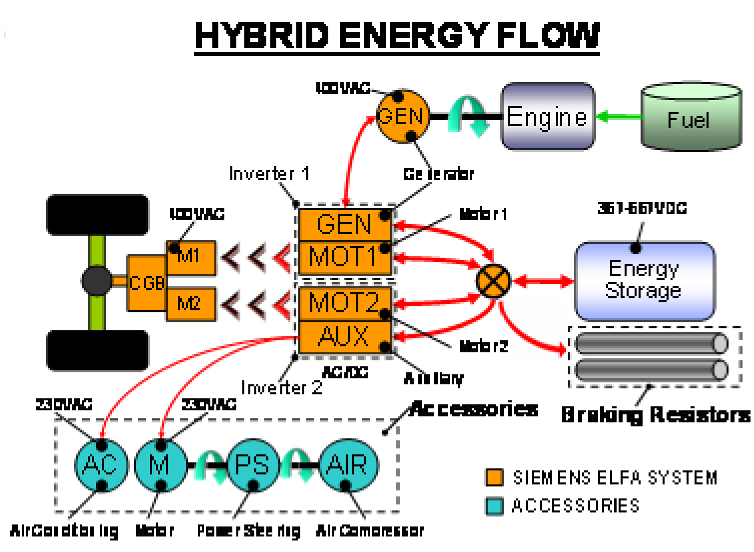

Figure 2. Schematic of ThunderVolt series hybrid drive propulsion system.

In this series hybrid electric system, a Ford 6.8 L Triton V-10 gasoline engine is connected to a generator that produces electricity for the electric drive motor and the ultra-capacitors. The electric motor drives the vehicle and acts as a generator that captures energy during regenerative braking. The electrolytic ultra-capacitors supplied by Maxwell supply additional power during acceleration and hill climbing and store energy recovered during regenerative braking and idling.

Table 2 presents additional details on the hybrid system and Table 3 provides brief descriptions of the vehicle systems.

Table 2. Hybrid Propulsion-Related Systems

Category	Hybrid Bus Description
Manufacturer/integrator	ISE Corporation, ThunderVolt Hybrid Drive propulsion system
Combining Gearbox	2 AC motor input Peak input torque: 2x600 Nm Peak output torque: 4860 Nm Max input speed: 10,000 rpm Ratio: 4.05 Weight: 100kg
Motor	Type: 3-Phase Asynchronous Motor Nominal power: 85 kW Peak power: 150 kW Nominal torque: 220 Nm Peak torque: 530 Nm Rated voltage DC: 650 V Nominal current: 142 A Peak current: 250 A
Generator	Type: Permanent Magnet Sync. Nominal power: 110 kW Peak power: 145 kW Nominal torque: 320 Nm Peak torque: 450 Nm Rated voltage DC: 650 V Rated current: 170 A Weight: 120 kg
Energy storage	Type: Ultra-capacitor, Maxwell Boostcap 2 enclosures, 144 capacitors each, Roof mounted Voltage per enclosure: 360 VDC rated; 403 VDC peak Weight per enclosure: 100 kg
Braking Resistors	Two units in parallel configuration Capacity: 2 x 60kW continuous Capacity: 2 x 70kW max for 15 seconds

Table 3. Vehicle System Descriptions

Bus Specification	Hybrid Gasoline-Electric Buses	Diesel Buses
Bus manufacturer	New Flyer	New Flyer
Bus model	low-floor GE40LF	low-floor D40LF
Model year	2004 and 2005	2002
Length/width/height	40.8 ft/102 in./136 in.	40.8 ft/102 in./110.4 in.
Gross vehicle weight rating (GVWR)/curb weight	40,130/26,800 lb	37,920/26,800 lb
Passenger capacity	38 seated, 19 standing	38 seated, 19 standing
Engine manufacturer and model	Ford 2004 Triton V-10	Cummins ISC (diesel particulate filter equipped)
Rated horsepower	305 bhp @ 4,250 rpm	280 bhp @ 2,100 rpm
Rated torque	405 lb-ft @ 3,250 rpm	900 lb-ft @ 2,100 rpm
Emissions equipment	Ford 3 way catalyst	Johnson-Matthey CRT-2124
Retarder/regenerative braking	Regenerative braking	Engine braking
Air Conditioning Type	Sutrak ACE219 Rear Mount Unit (electric)	Thermo King (engine driven)
Fuel capacity	110 gallons	119 gallons
Bus purchase cost ($)*	462,379	268,051

*Costs listed in the table are actual costs at the time of purchase.

Emissions

Original funding for the gasoline hybrid system was provided by the US DOT/FTA, the State of California, WestStart-CALSTART, Omnitrans, and ISE.

The ThunderVolt gasoline hybrid system was certified by CARB to 0.6g/bHp-hr NOx and 3.7g CO; PM is not measured on gasoline systems; making it a very low emission 40-foot bus drive system. The gasoline hybrid system combines the Siemens ELFA electric drive system with the Ford ULEV rated 6.8 L V10 engine, integrated and controlled by the ISE ThunderCan hybrid control system. Table 4 below compares the emissions certification levels for the Hybrid and Diesel buses. Tailpipe emissions test results are not available for comparison. See http://www.arb.ca.gov/msprog/onroad/cert/cert.php#6 HDE/HDV/MDE for model years 2004 and 2005.

Table 4. Hybrid and Diesel Bus Emissions Certification

Study Group	NOx (g/bHp-hr)	PM (g/bHp-hr)	CO (g/bHp-hr)
Hybrid	0.6	N/A	3.7
Diesel	4.0	0.05	0.5

Evaluation Results

Bus Use

Table 5 presents the average monthly mileage per bus during the evaluation period for the two groups of buses. The hybrids had a usage rate 2.4% lower than that of the diesel buses. If the July ramp-up is removed from the hybrid group average their usage rate would only be 0.7% lower than the diesels. These small differences are not statistically significant (two-tailed P value = 0.3455) and make the groups ideal for comparison. This monthly mileage is also an indication of both the diesel and hybrid bus reliability. The hybrids were able to provide a similar number of miles of service per month as the conventional diesels operating on similar routes.

Table 5. Average Bus Miles Driven per Month by Study Group

Study Group	Average Miles per Month per Bus
Hybrid	3,188
Diesel	3,266

Figure 3 shows average monthly miles per bus for each bus group with +/- 95% confidence interval lines. Bus average usage did not change significantly during the evaluation period. This chart also shows a quick ramp-up of miles per month for the hybrids as they were implemented into the fleet in July of 2005. After this initial ramp-up, the hybrids were driven a similar number of miles for the rest of the evaluation period.

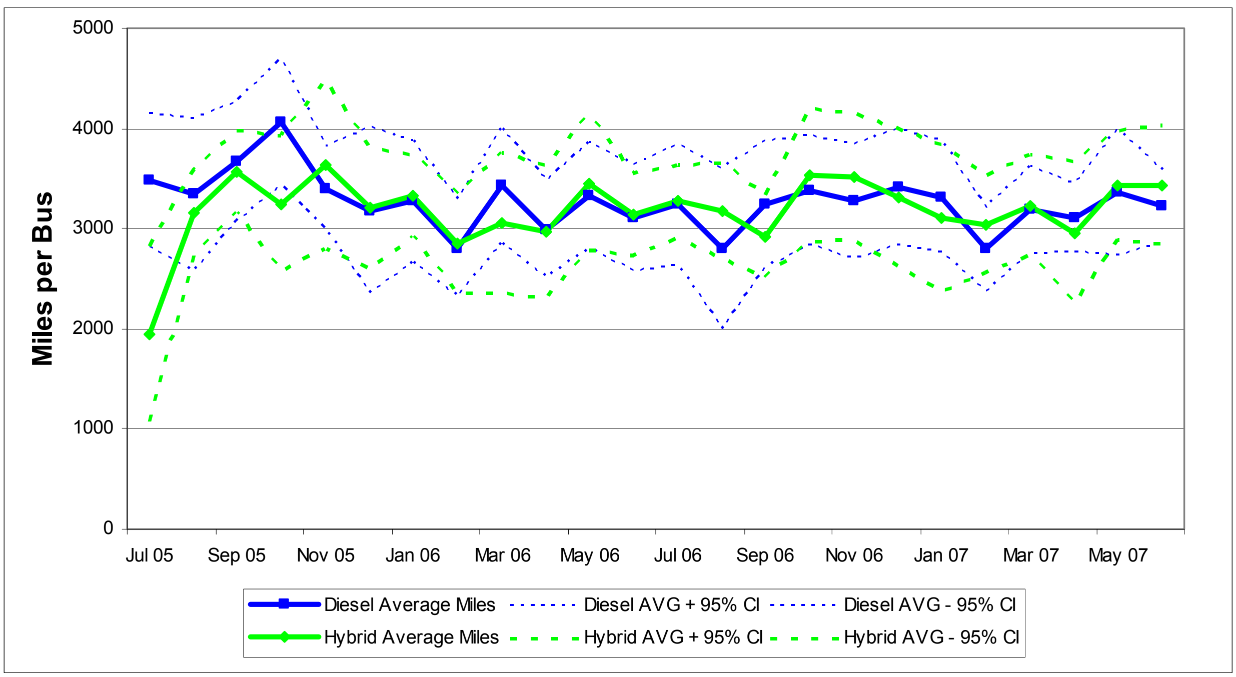

Figure 3. Hybrid gasoline-electric and diesel monthly mileage per bus.

Fuel Economy and Cost

LBT fuels its hybrids with standard California reformulated 87 octane gasoline. During the evaluation period, gasoline at LBT cost an average of $2.49 per gallon. LBT diesel buses use ultra-low sulfur No. 1 diesel fuel at less than 30 parts per million (ppm) sulfur content. This sulfur level was required to be less than 15 ppm by the end of 2006. During the evaluation period, diesel fuel at LBT cost an average of $2.29 per gallon for ultra-low sulfur diesel (ULSD) fuel with sulfur less than 30 ppm.

Table 6 shows the fuel consumption and economy data for each bus in each study group. The 24-month average fuel economy for the hybrid buses is 4.3% lower than that of the diesel buses (two-tailed P value = 0.0001). This statistically significant difference is likely due to the lower efficiency of a throttled, spark-ignited engine and a lower energy content per gallon of fuel. Since California reformulated gasoline has a lower energy content on a per gallon basis than diesel (113,824 Btu/gal vs 128,450 btu/gal), the fuel efficiency of the buses can also be looked at from an energy equivalent basis. Adjusting for this difference in volumetric energy content, the hybrid buses delivered 3.78 miles per diesel gallon equivalent; 8.0 % higher than the diesels (two-tailed P value < 0.0001).

Table 6. Hybrid and Diesel Bus Fuel Use and Economy

Bus	Mileage	Gallons Consumed	Miles per Gallon	Miles per Diesel Gallon Equivalent	Fuel Cost/Gallon ($)	Fuel Cost/Mile ($)
2402	67,167	21,521	3.12	3.52	$2.49	0.80
2404	84,224	26,577	3.17	3.58	$2.49	0.79
2407	96,767	27,909	3.47	3.91	$2.49	0.71
2412	58,127	18,114	3.21	3.62	$2.49	0.78
2414	95,211	27,218	3.50	3.95	$2.49	0.71
2421	60,704	18,713	3.24	3.66	$2.49	0.77
2503	68,352	19,524	3.50	3.95	$2.49	0.70
2512	80,110	23,551	3.40	3.84	$2.49	0.72
2514	71,948	21,139	3.40	3.84	$2.49	0.73
2519	82,389	23,904	3.45	3.89	$2.49	0.72
Hybrid Total	**764,999**	**228,171**	**3.35**	**3.78**	**$2.49**	**0.74**
2202	50,933	14,411	3.53	N/A	$2.29	0.65
2204	88,107	24,799	3.55	N/A	$2.29	0.65
2206	67,684	19,054	3.55	N/A	$2.29	0.64
2208	65,167	18,506	3.52	N/A	$2.29	0.65
2210	72,626	21,171	3.43	N/A	$2.29	0.67
2212	90,865	25,622	3.55	N/A	$2.29	0.65
2216	99,216	27,742	3.58	N/A	$2.29	0.64
2218	91,911	26,499	3.47	N/A	$2.29	0.66
2225	93,363	27,162	3.44	N/A	$2.29	0.67
2226	63,977	18,797	3.40	N/A	$2.29	0.67
Diesel Total	**783,849**	**223,761**	**3.50**	**N/A**	**$2.29**	**0.65**

Figure 4 shows the average monthly mpg for each bus group with +/- 95% confidence interval lines.

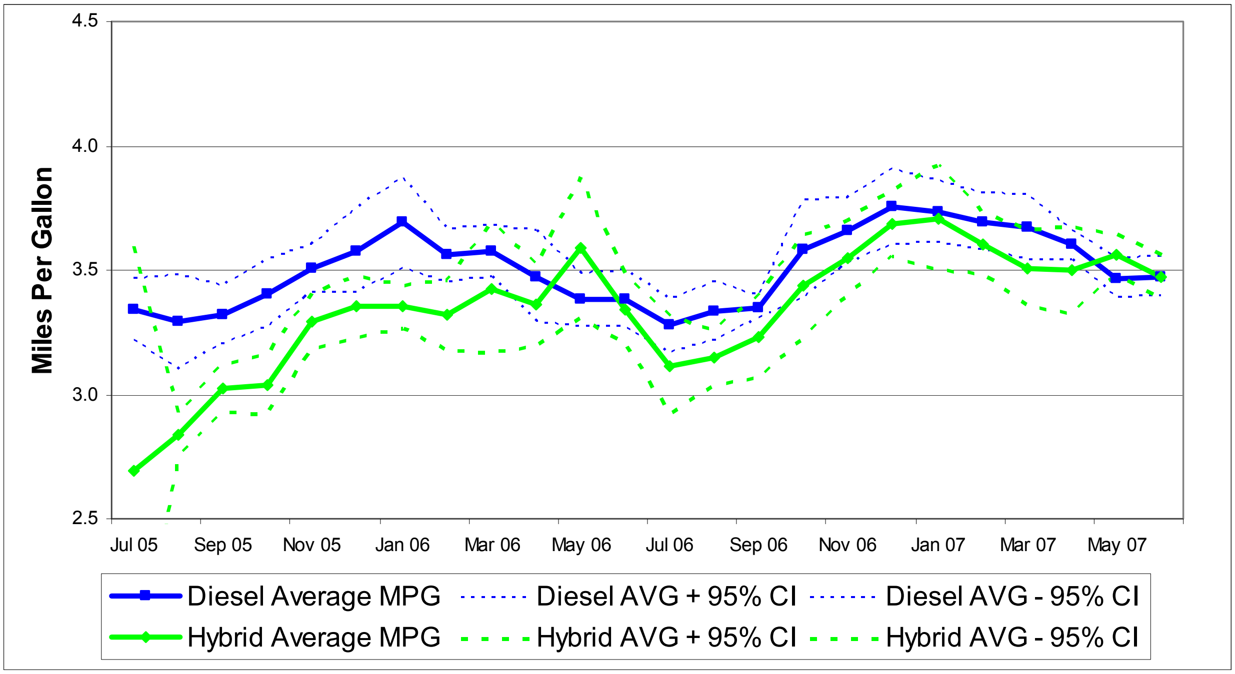

Figure 4. Average monthly fuel economy.

Figure 5 shows the average monthly energy equivalent mpg for each bus group with +/- 95% confidence interval lines.

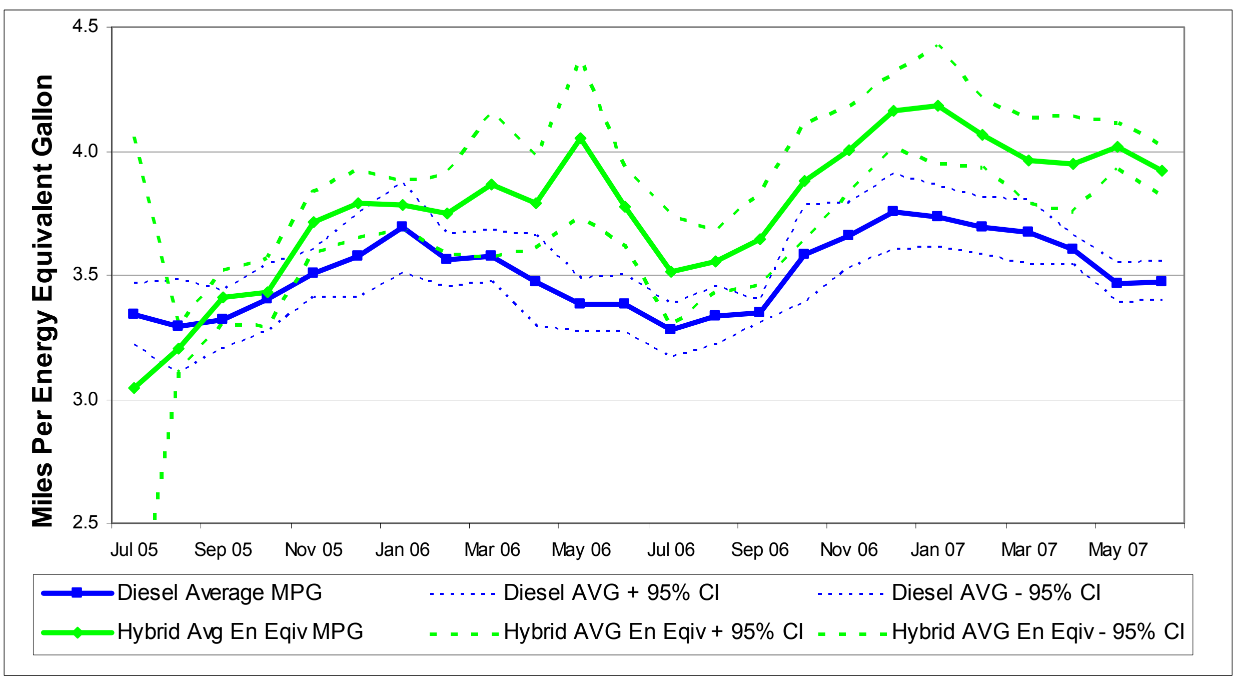

Figure 5. Average monthly energy equivalent fuel economy.

Figures 4 and 5 also showcase the seasonal fluctuation in fuel economy experienced by both hybrid and diesel buses during the 24-month evaluation period. Comparing the summer months of 2006 (June, July, August) to the winter months of 2006-2007 (December, January, February) the diesels had statistically significant 10.2% lower fuel economy in the summer (two-tailed P value = 0.0123) and the hybrids had statistically significant 12.8% lower fuel economy in the summer (two-tailed P value = 0.0259). Much of the summer decrease is caused by an increase in energy consumption for air conditioning; it is not clear why the hybrids experience a greater drop in fuel economy. The hybrids do have electric air conditioning, but this was not isolated as a benefit or detriment to the overall fuel economy.

Maintenance Cost Analysis

This evaluation focuses on bus operations spanning the first two years of the 12-year minimum life of a transit bus. This short evaluation period does not yield enough capital and operating costs to allow us to understand the full 12-year life-cycle cost of the hybrid buses. To gain a complete understanding of costs, we must examine the purchase cost of the buses and the costs for facility modification or addition, warranty, and operations. In addition, we must consider costs for longer term maintenance activities such as engine rebuilds or replacements and ultra-capacitor replacements. Finally, we must look at areas where cost savings can be achieved, as in brake repair. The intent of this evaluation, though, is to capture accurate actual capital and known operations costs associated with the hybrid and diesel vehicles for the time period selected. This analysis is not predictive of maintenance costs assumed by the transit agency beyond the warranty period. ISE's standard propulsion system warranty on these hybrids is two years from the date of purchase and includes the ultra-capacitors. LBT opted to purchase three years of extended propulsion system warranty for the first 27 buses and use the standard two-year warranty for the remaining 20 buses. Some propulsion system components are warranted beyond two years. Hybrid buses in the study group fall into both warranty categories, but all remained under warranty for the entire study period. The exact components and warranty periods, as negotiated by LBT, ISE, and New Flyer, are contractual.

The hybrid buses are new enough that much of the maintenance is done under warranty. All maintenance for the ISE hybrid drive was done on site by ISE mechanics. These maintenance costs are not included in the maintenance cost analysis in this section. Not accounting for warranty repairs in the evaluation of total maintenance cost does offer an incomplete picture of total maintenance cost. Even with warranty costs absent, however, this analysis reflects the actual cost to the transit agency during the time period selected.

The FT&E team collected the maintenance costs in the same way for each study group. The duty cycle and maintenance practices are the same for both diesel and hybrid study groups. All work orders and parts information available were collected for the study buses. The maintenance analysis discussions include only maintenance data from the evaluation period on the study group buses.

Two major interests in hybrid bus operations held by the transit industry are (1) determining energy storage replacement frequency and costs, and (2) quantifying the benefits of regenerative braking. In addition, the benefits of regenerative braking, realized in reduced maintenance costs, are evaluated using data from the hybrid buses. Diesel buses are used as a baseline in this evaluation.

Total Maintenance Costs

This cost category includes the costs of parts and hourly labor costs of $50 per hour, and does not include warranty costs. Cost per mile is calculated as follows:

Cost per mile = ((labor hours * 50) + parts cost)/mileage

The labor rate has been artificially set at a constant rate of $50 per hour so that other analysts can change this rate to one more similar to their own. This rate does not directly reflect LBT's current hourly mechanic rate.

Table 7 shows total and propulsion related maintenance costs for the two study groups. The total maintenance cost per mile was 42% less for the hybrid buses than for the diesel buses. At the beginning of the evaluation period, the hybrid buses were brand new and remained under warranty for the evaluation period, which accounts for the cost-per-mile difference with the older, out-of-warranty diesel buses.

Table 7. Hybrid and Diesel Bus Total & Propulsion Maintenance Costs

Study Group	Miles	Parts Cost	Labor Hours	Cost per Mile ($/mile)
Hybrid	764,999	$56,664	3,646	0.3124
Hybrid Propulsion-Related	764,999	$15,050	8,96	0.0782
Diesel	783,849	$137,287	5,707	0.5392
Diesel Propulsion-Related	783,849	$62,508	1,739	0.1906

Propulsion-Related Maintenance Costs

The propulsion-related vehicle systems include the exhaust; fuel; engine, nonlighting electrical (general electrical, charging, cranking, and ignition); electric propulsion; and transmission systems. The ultra-capacitors are discussed in the next section of this report. Table 8 summarizes the cost comparisons between the study groups.

Table 8. Summary of Propulsion-Related Maintenance Cost Comparisons

Vehicle System	Hybrid ($/mile)	Diesel ($/mile)
Exhaust system	0.0059	0.0220
Fuel system	0.0051	0.0193
Engine	0.0392	0.0844
Non-lighting electrical	0.0176	0.0267
Transmission	N/A	0.0382
Total propulsion-related	**0.0782**	**0.1906**

Figure 6 shows the cumulative average total and propulsion-related maintenance cost per mile for the study buses. Figure 7 shows the monthly average total and propulsion-related maintenance cost per mile for the study buses.

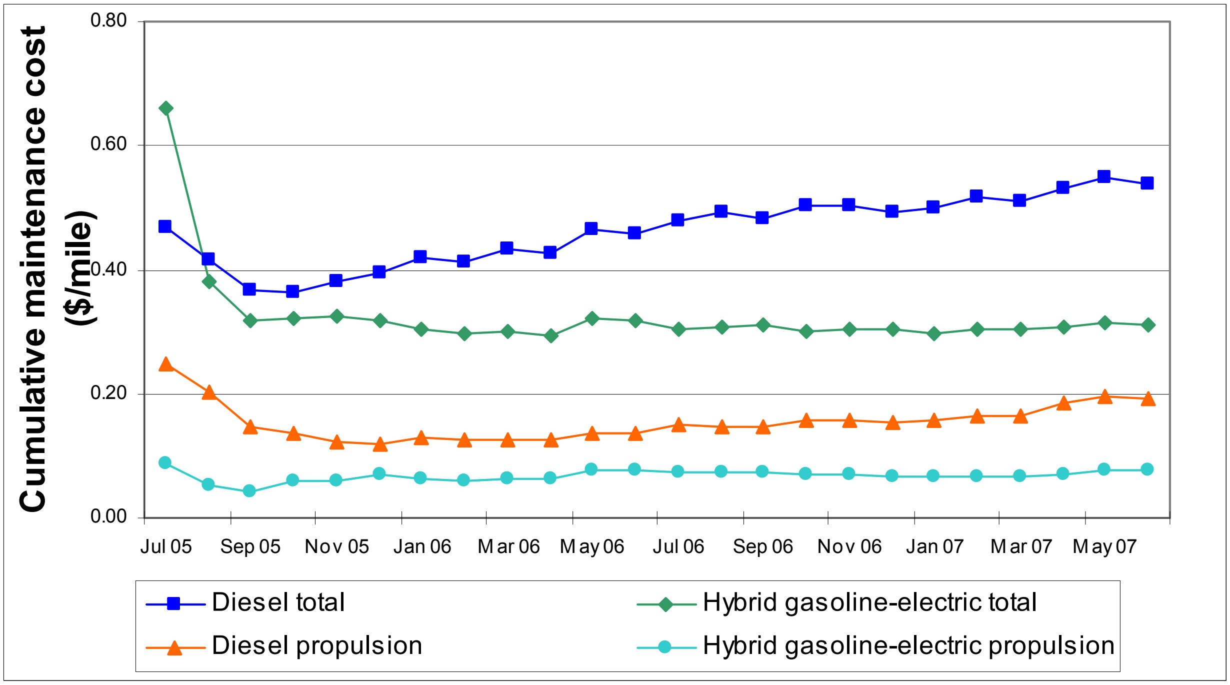

Figure 6. Cumulative total and propulsion-related maintenance costs.

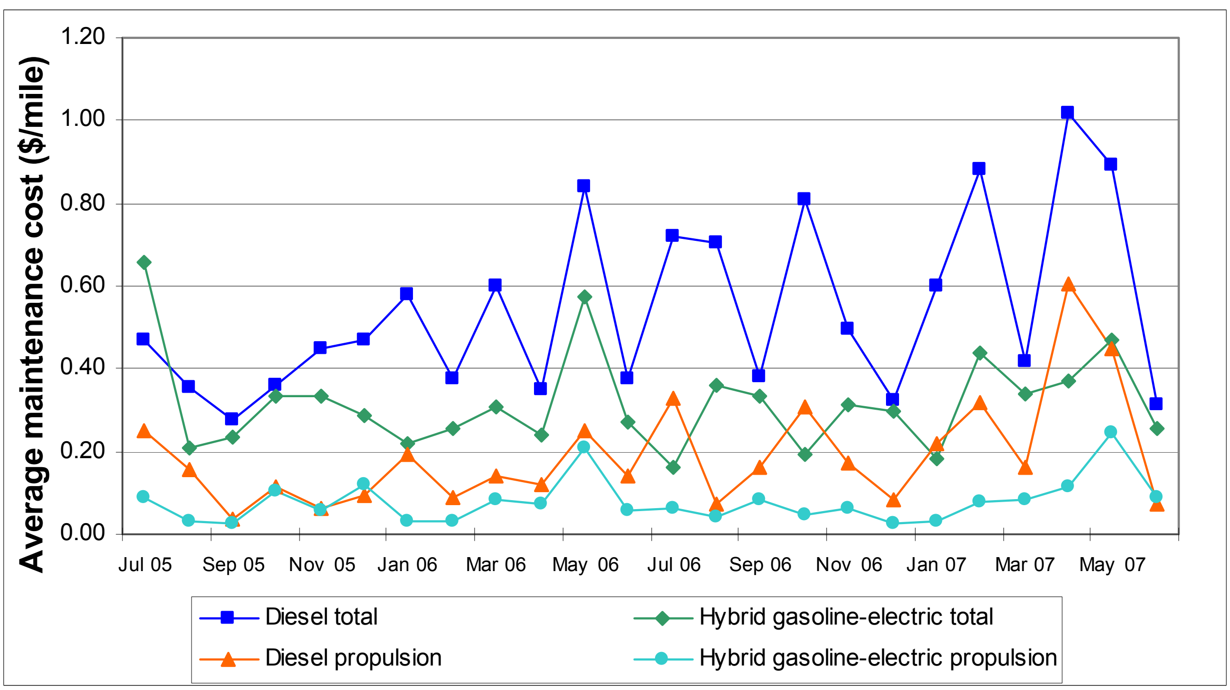

Figure 7. Average monthly total and propulsion-related maintenance costs.

Brakes

In general, the brake system maintenance costs are expected to be dramatically lower for hybrid propulsion systems with regenerative braking, which allows use of the electric drive motors to slow a bus, similar to a transmission retarder. The energy from braking is taken into the electric motor and then fed back to the ultra-capacitors. In addition, the ISE system incorporates additional “braking resistors” to absorb energy when the ultra-capacitors are fully charged. LBT's staff expects diesel buses to undergo a four-wheel brake reline every 35,000 to 40,000 miles on average.

Table 9 shows the maintenance costs for the brake system repairs for the two study groups. During the evaluation period, the 10 hybrid study buses traveled 764,999 miles and required only minimal brake system maintenance such as adjustments for squeaking.

Maintenance costs for the brakes on the baseline diesel buses—which had only slightly higher miles than the hybrids—were 10 times greater than the costs for the hybrids. All 10 buses in the diesel study group had at least a rear brake reline during the evaluation period. Six of the 10 had at least a four wheel reline during the study period, and some of the buses had an additional rear reline.

It is important to note that the diesel buses did not have new brakes at the beginning of the study period. The lower brake system cost assumption, however, is supported by the extent of relines and the longer-than-average miles without a reline for the hybrids during the study period.

Table 9. Brake System Maintenance Costs (July 2005–June 2007)

Study Group	Mileage	Parts Cost ($)	Labor Hours	Cost per Mile ($/mile)
Hybrid	764,999	17.11	55	0.0036
Diesel	783,849	11,192.94	335	0.0356

Figure 8 shows the average time to the first front and rear brake relines on the older diesel buses as compared to the average hybrid bus mileage at the end of the two-year study period. None of the hybrid buses had a reline during the study period. The first relines on the diesel buses occurred before the study period of this report, but are included here to provide an understanding of the brake life comparison. All of the hybrid buses have more miles on them than any diesel bus had by the time of its first rear reline. On average, the hybrid buses have doubled the mileage to first rear brake reline and are approaching the mileage the diesel buses averaged for their first front reline. Assuming the front brakes on the hybrids will last twice as long as the rears, as was the case for the diesels, this data suggests the hybrids will get at least twice the mileage on average between brake relines. From routine inspections, LBT anecdotally suggests they are only half of the way through the brake linings at this point. Measurements were not taken however.

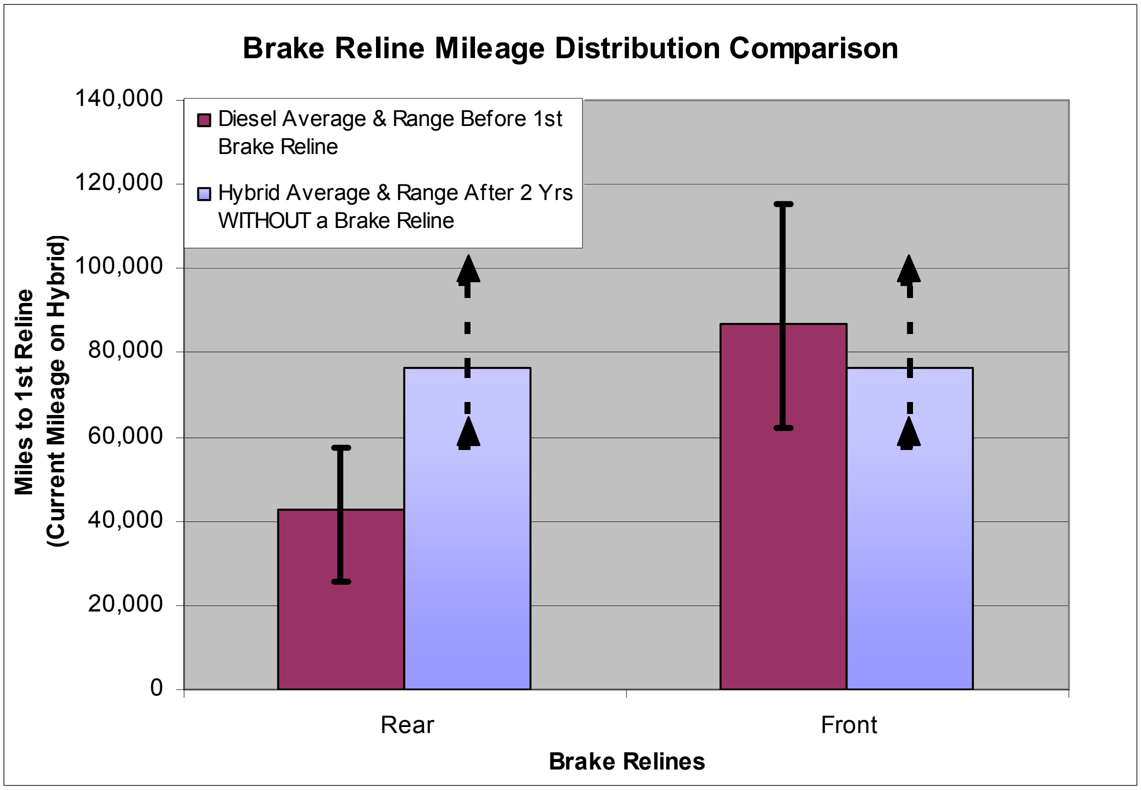

Figure 8. Brake reline mileage distribution comparison.

Ultra-Capacitors

LBT chose to use ultra-capacitors for energy storage instead of the traction batteries more commonly used in hybrid transit buses. The ultra-capacitors work well for LBT's duty cycle with the frequent stops per mile and slow average speeds. In addition, the ultra-capacitors have a 12-year life expectancy compared to three to six years for batteries. ISE has a standard two-year warranty for the ultra-capacitors and offers a three-year extension of the warranty. LBT bought the extended warranty on the first 27 buses, but not the remaining 20.

During the evaluation period a manufacturing issue was identified; acetonitrile was leaking from some of the ultra-capacitors. ISE corrected the issue with a warranty campaign based on serial numbers of suspect batches of ultra-capacitors. The correction sealed them by applying an epoxy coating over the ultra-capacitors. Because this correction was handled as a campaign no cost was incurred to LBT and these repairs do not affect the maintenance analysis section of this report. Two incidents of ultra-capacitor dry cell overheating were attributed to this leakage within the fleet.

Figure 9 is a photo of an open ultra-capacitor pack showing the 144 individual cells. Figure 10 shows the installation of the two ultra-capacitor packs on the rear roof of the bus with the ultra-capacitor cooling system in the background.

Figure 9. An Open ultra-capacitor pack.

Figure 10. Two ultra-capacitor packs on the rear roof of the bus.

Road Call Analysis

Figure 11 shows the cumulative average miles between road call (MBRC) for all road calls (RCs) along with those related only to propulsion. MBRC is a good indication of the reliability of a vehicle. Propulsion-related systems include the exhaust; fuel; engine, non-lighting electrical (general electrical, charging, cranking, and ignition); electric propulsion; and transmission systems. Also note that the diesel study group had four months without a propulsion-related RC at the beginning of the study period. This heavily weighted the cumulative average very high, but it is clear the trend is coming back down over time to reflect propulsion MBRC similar to that of the hybrids.

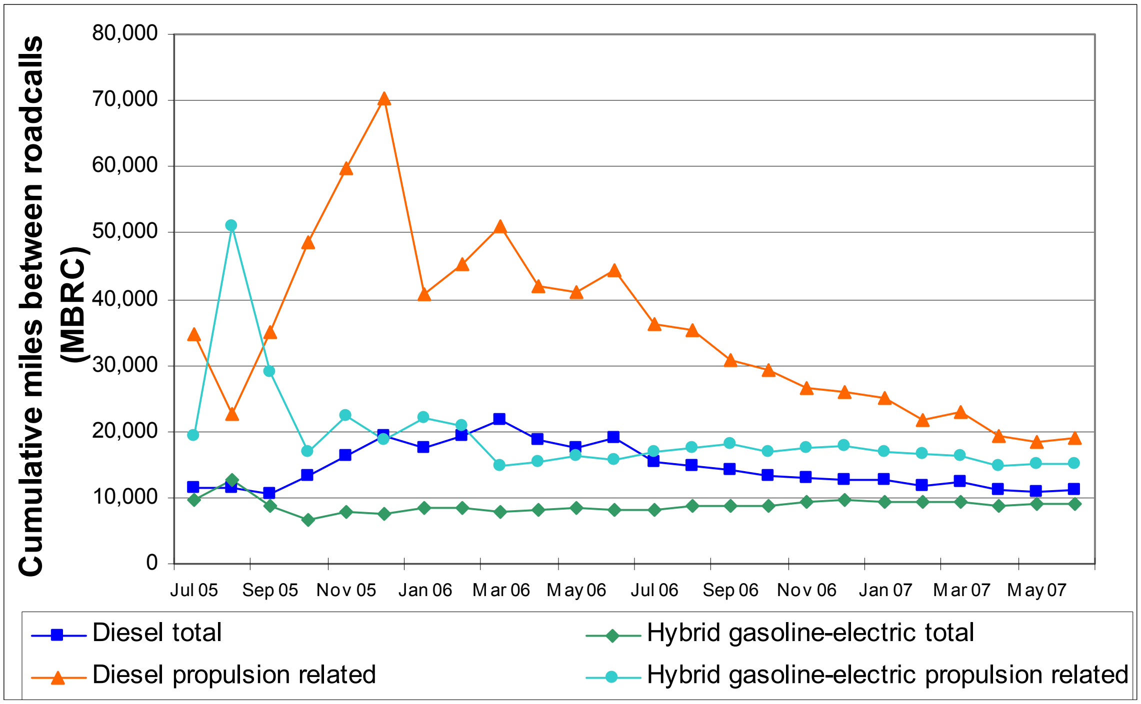

Figure 11. Cumulative miles between road call.

The diesels had 71 road calls during the study period while the hybrids had 85; 20% more. The diesels had 41 propulsion related road calls during the study period while the hybrids had 51; 24% more. LBT's fleet average is about 9,000 total MBRC. LBT had no official expectations for the hybrids because the combination of a light-duty gasoline engine in a series hybrid heavy-duty application with ultra-capacitors had never been done before. LBT's staff has been happy with the MBRC performance of the hybrids, shown in comparison to that of the diesels in Table 10.

Table 10. Cumulative Miles Between Road Call Comparison

Study Group	Miles	Total Road Calls	Total MBRC	Propulsion Road Calls	Propulsion MBRC
Hybrid*	764,999	85	9,000	51	15,000
Diesel	783,849	71	11,040	41	19,118

* hybrid MBRC happened to result in even numbers.

Summary of Costs

Table 11 summarizes fuel and maintenance cost per mile for the two study groups. The average cost per mile for the hybrid buses is 11.7% lower than that of the diesel buses because the hybrids have the majority of their maintenance costs covered under warranty and the diesel buses are not.

Table 11. Summary of Costs per Mile

Bus	Fuel Cost/Mile ($)	Maintenance Cost/Mile ($)	Total Cost/Mile ($)
2402	0.80	0.24	1.04
2404	0.79	0.84	1.63
2407	0.71	0.23	0.94
2412	0.78	0.23	1.01
2414	0.71	0.27	0.97
2421	0.77	0.29	1.06
2503	0.70	0.18	0.88
2512	0.72	0.31	1.03
2514	0.73	0.25	0.98
2519	0.72	0.23	0.96
Hybrid Total	**0.74**	**0.31**	**1.05**
2202	0.65	0.75	1.40
2204	0.65	0.80	1.44
2206	0.64	0.46	1.10
2208	0.65	0.70	1.34
2210	0.67	0.37	1.04
2212	0.65	0.39	1.04
2216	0.64	0.53	1.17
2218	0.66	0.47	1.13
2225	0.67	0.48	1.15
2226	0.67	0.53	1.20
Diesel Total	**0.65**	**0.54**	**1.19**

Status of LBT Hybrid Fleet

LBT has been happy with the performance of the original forty-seven 40-ft hybrid gasoline-electric buses over the first two years of service. The transit authority has taken delivery of 15 more in the third quarter of 2007 and has requested an additional 25 for 2008.

Conclusions

- Monthly miles per bus were essentially the same with the hybrids as with the diesels. This usage rate is one indication of reliability.
- Fuel economy on a mpg basis was 4.3% lower than the diesel buses and fuel costs for gasoline were higher than diesel resulting in a higher fuel cost per mile. On an energy equivalent basis the hybrids had 8.5% better fuel economy than the diesels.
- Maintenance costs were lower on the hybrids, but they are under warranty while the diesel buses are not.
- Brake costs per mile were much lower on the hybrid bus group. The hybrid buses did not experience their first brake relines during the study period so the magnitude of the improvement could not be calculated.
- MBRC was lower for the hybrids than the diesels. This indicates a lower level of reliability.

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Chandler, K.; Clark, N.; Zhen, F.; Wayne, S. (2007). "Hybrid-Electric Transit Bus Performance in North America." Transportation Research Board Annual Meeting 2007. Paper #07-3004.

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This report focuses on a gasoline-electric hybrid transit bus propulsion system. The propulsion system is an alternative to standard diesel buses and allows for reductions in emissions (usually focused on reductions of particulate matter and oxides of nitrogen) and petroleum use. Gasoline propulsion is an alternative to diesel fuel and hybrid propulsion allows for increased fuel economy, which ultimately results in reduced petroleum use.

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hybrid transit bus; Long Beach Transit; ultra-capacitors; diesel bus; LBT

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