Monterey-Salinas Transit Hybrid Shuttle Bus Testing and Demonstration

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EXECUTIVE SUMMARY

This report presents the evaluation of two buses in revenue service at Monterey-Salinas Transit (MST) over six months. In the test, a hybrid bus, an International diesel bus with an Eaton hybrid-electric drivetrain, was evaluated along with a conventional bus, a Ford E450 cutaway gasoline shuttle bus. The findings from this extensive demo are presented here.

Over the course of the six month demonstration, the vehicles traveled a total of 103,616 miles over 3,506 hours of revenue service. We recorded data on all vehicle operations using engine loggers on a second-by-second basis, as well as through manual mileage and fuel logs. This was supplemented by maintenance records and driver and manager interviews in some cases.

The two vehicles in this demo program are a diesel-electric hybrid manufactured by Navistar International Trucks and a gasoline E-450 shuttle bus manufactured by Ford Motor Company. The vehicles are of different size: the hybrid is 25,500 GVWR and the E-450 is 14,500 GVWR. Therefore, a direct comparison of the performance of the two vehicles should not be inferred. Properties of the two test vehicles are shown in table ES-1.

Table ES-1: Details of Demonstration Vehicles

Vehicle	Hybrid	Ford E-450
Manufacturer	International	Ford
Model	IC Bus HC	E450
Model Year	2013	2008
GVWR (lbs.)	25,500	14,500
Fuel Type	Diesel	Gasoline

While these two vehicles are different in terms of GVWR, fuel type and model year, they were chosen because the Ford E-450 is the baseline choice that MST would use if the hybrid were not available. In addition, this choice enables an analysis of several MST routes to better understand route properties.

The performance of the hybrid and E-450 buses were evaluated using several metrics: total fuel economy in miles per gallon (MPG), reliability and maintenance costs, and user acceptance. Finally, data such as GPS positioning and speed enabled a comprehensive route analysis of the Monterey-Salinas Transit (MST) system. The findings from this analysis provide insights about which routes are best suited to the hybrid bus, and which will provide the greatest fuel economy and savings.

Fuel economy

Throughout the demonstration, we tracked the distance traveled and fuel consumed for each bus. The hybrid vehicle results were calculated using electronic data recorders, while the E-450 results are calculated using manual distance and fuel reports. Findings are shown in Table ES-2 below.

Table ES-2: Fuel economy results during 6-month demonstration

Vehicle	Hybrid	Ford E-450
Miles Traveled	30,150	36,928
Fuel Consumed (gal)	4,045	5,133
Fuel Economy (mpg)	7.5[a]	7.2[a]
Data source	Electronic engine data	Manual logs

[a] Hybrid fuel economy is measured as miles per gallon of diesel. E-450 fuel economy is measured as miles per gallon of gasoline.

The hybrid bus operated at an average of 7.5MPG (miles per gallon of diesel), calculated from engine data measured from the data collection equipment. E-450 averaged 7.2 MPG (miles per gallon of gasoline). Because the vehicles are different vehicle class and different fuel types, the MPG results should not be directly compared.

In addition to the overall MPG, a snapshot of hybrid fuel consumption on two well-traveled routes, Routes 1 and 24, was generated to compare performance on these nearly-opposite route types. Results are shown below in Table ES-3.

Table ES-3: Hybrid fuel economy results by route

Route	Hybrid Fuel Economy (MPG)[a]	Average Speed (MPH)	Gallons/ Hour
Route 1	7.1	16.8	1.6
Route 24	7.3	26.6	2.7

[a] Hybrid fuel economy is measured as miles per gallon of diesel.

Further route analysis shows that Route 24 to be much more rural with high-speed travel whereas Route 1 was the most urban route in this test with stop and go traffic; the fuel economy results however are relatively similar. This indicates that the efficiencies from the hybrid system overcome fuel economy penalties that the vehicle would otherwise incur in stop-and-go traffic.

In performing the fuel economy analysis on the hybrid vehicle, we found an inconsistency in the distance reported by the hub odometer in that vehicle and what our data loggers were reporting based on engine output. Based on prior experience, we proceeded with the analysis relying on the engine data. However, the discrepancy between engine outputs and hub odometer should be examined further.

Route Analysis

In order to assess which MST bus routes may be best suited to the hybrid vehicle, we developed attributes of nine routes served by the hybrid bus and the E-450. We collected speed and GPS data from the E-450 as it traveled on seven routes throughout the Monterey and Salinas areas. Using these data, plus data from the two hybrid routes, each route was characterized in order to evaluate if a hybrid would be a good fit for these routes. Routes were characterized by average stops per mile, average speed and speed distribution. The route relationships are shown in Figure ES-1.

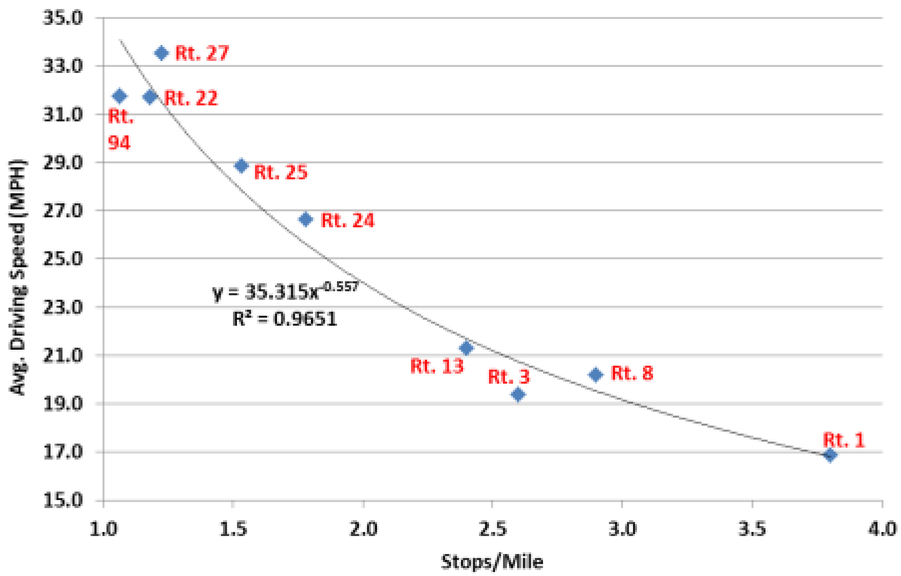

Figure ES-1: Route characterization relationship plot

Figure ES-1 shows the relationship between driving speed and stops per mile across the nine routes. We observe an inverse-root relationship between these two metrics with a handful of routes falling very close to the trend line. Since we know the fuel economy generated on Routes 1 and 24 was approximately 7.2MPG (miles per gallon of diesel), it would follow that a similar fuel economy could be generated on Routes 3 and 22, which also fall very near the trend line.

Further study of the nine routes led to a speed bin analysis which confirms travel patterns between routes. Time spent at six different speed ranges was quantified for each route, with percentage of total time displayed in Figure ES-2 below.

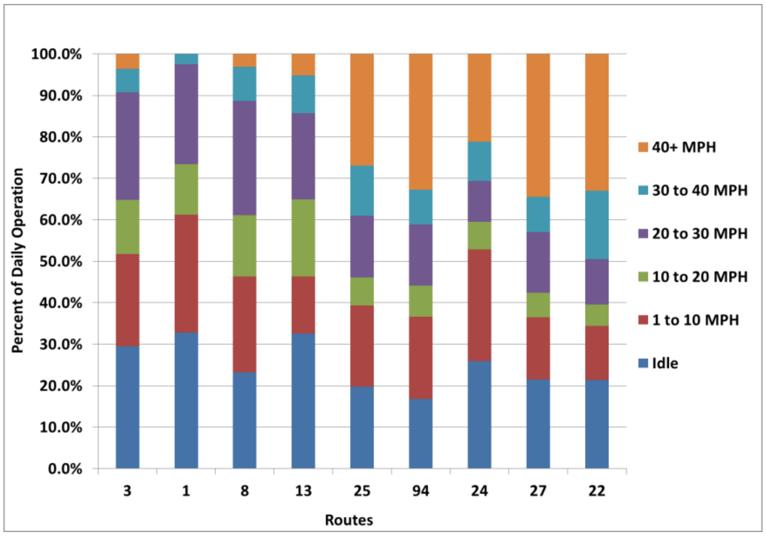

Figure ES-2: Route speed bin analysis

Idle time (shown in blue at the bottom of the chart) is comparable between routes but high-speed travel (shown in orange at the top of the chart) is a strong differentiation between rural and urban routes. All routes spend nearly 20% or more of their engine-on time at idle. Urban routes (3 thru 13 on the left) spend less than 6% of their time above 40MPH, and 20% to 30% between 20 and 30MPH, indicative of lower-speed stop-and-go travel. Rural routes (25 thru 22 on the right) spend nearly 30% or more of their engine-on time at or above 40MPH, indicating significant highway driving.

In addition to the above speed bin analysis, idle events and their duration were analyzed for each route as well. Idling was defined as any engine-on time spent at zero speed, and four ranges were used to categorize such events. From short traffic stops to extended stops, percent of total idle time in each duration bin was quantified with results shown in Figure ES-3 below.

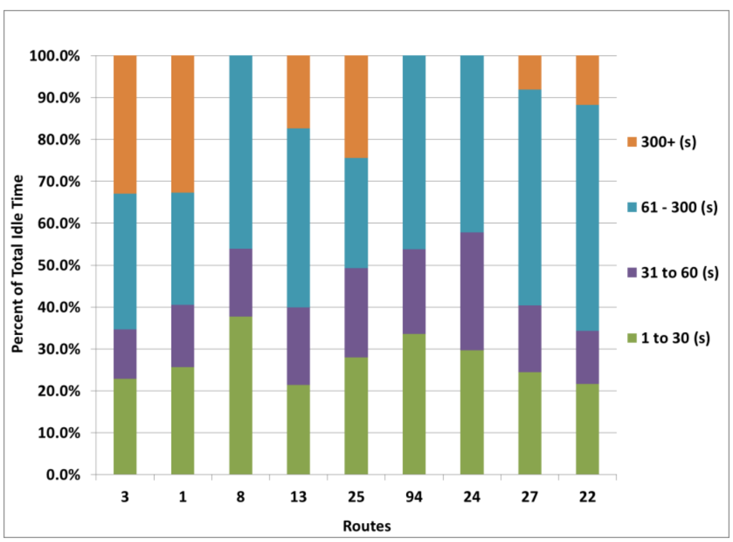

Figure ES-3: Idle event duration by route

Idling events from 1 to 5 minutes long account for over 40% of daily idling on all but three routes, and most of these six routes do not have much idling longer than 5 minutes. This means that the shift changes on these routes are probably accomplished with less than 5 minutes of idle time. The remaining routes (25, 3, and 1) have terminals in very urban locations and are thus more likely to have passengers waiting on the vehicles—necessitating vehicle air conditioning and thus extended idling. Vehicles on these three routes could benefit from some stop-start or engine-off policy or technology to help mitigate wasteful emissions and fuel consumption spent at idle.

Maintenance and reliability

Transit agencies consider expected maintenance costs and vehicle reliability when choosing to invest in a new bus technology. Further, true costs and reliability may not be revealed in a short bus test. In order to better characterize these metrics, we collected and analyzed costs and reliability data for the full duration of the demonstration.

Data on maintenance and reliability were supplied by MV Transportation, the maintenance contractor. In total, the hybrid required $7,286 in maintenance and repairs over the demonstration period, equal to $0.24 per mile, and the E-450 required $4,493 or $0.13 per mile. The hybrid maintenance estimate included parts costs for hybrid-related repairs that were completed under warranty at no cost to MST. Tires and periodic maintenance (PM) costs were among the three greatest expenses on both vehicles.

Over the life of the demonstration, we encountered two issues with the hybrid drive system. The “check hybrid” light came on in the dash, requiring service at the dealership. After testing the Electronic Clutch Actuator speed sensor, the sensor itself was removed from the vehicle and found to be damaged. An additional event occurred in November 2013 when a whistling noise was heard during acceleration events on the hybrid. The diagnosed blown exhaust manifold gasket was repaired at the dealership and involved dismantling much of the front fascia (grill, headlamps, front bumper) of the bus. Excessive shaft play in the vehicle turbo required attention before the vehicle could be put back into service.

On average, the availability of the hybrid vehicle was much lower than the E-450: 55% in the hybrid and 81% for the E-450. This hybrid value was lower than anticipated due to the extended out-of-service events described above. Excluding November, in which the hybrid received the most service work and spent the least amount of time in-service, the vehicle achieved a 61% uptime.

Driver and manager feedback

Drivers, maintenance technicians, and managers interact directly with the vehicles, and often have input that would not otherwise be reflected in the above analyses. We use surveys and interviews to capture these experiences, and include it here to provide more insight into how the vehicles performed during the demonstration. The fleet manager interview was completed by Michael Hernandez, Assistant General Manager/Chief Operating Officer at MST and the maintenance manager interview was completed by Don Parslow, Fleet Manager at MV Transportation. Due to the construction of this study, and for the purpose of this report, Mr. Hernandez is referred to as the “fleet manager” and Mr. Parslow is referred to as the “maintenance manager”.

The hybrid vehicle operators and managers provided feedback on their experiences throughout the demonstration period. Five drivers completed surveys at the beginning and the end of the demonstration, in which they compared the hybrid to the E-450 in terms of 11 performance metrics. Results are shown in Table ES-4 below on a scale from one to five.

Table ES-4: Final driver survey scores for the hybrid bus

Performance Metrics		Operational Metrics	
Metric	**Score**	**Metric**	**Score**
Launch from standstill	1.0	Cold start	2.8
Maneuverability	3.0	Inside noise level	1.8
Acceleration	1.2	Reliability	2.3
Deceleration	2.4	Outside noise level	1.8
Overall braking behavior	3.2	In-cab ergonomics	3.0
Productivity	1.2		

1: Much Worse 2: Somewhat Worse 3: Same 4: Somewhat Better 5: Much Better

The surveys show significant driver dissatisfaction, as shown in nearly all performance metrics near the bottom of the scoring scale including poor ratings for launch from standstill and acceleration. Further, driver feedback was more negative at the end of the demo than in the outset. However, some of the survey trends may be due to driver experiences in this larger vehicle class than specifically due to the hybrid system. The maintenance and fleet managers also provided overall negative feedback, showing dissatisfaction with the required maintenance and vehicle quality.

Summary of findings

This list summarizes the overall takeaways from the study:

- The hybrid bus operated at an average of 7.5MPG. E-450 averaged 7.2 MPG. Because the vehicles are different vehicle class and different fuel types, the MPG results should not be directly compared.
- We found a significant amount of idling during operation, with the idling on three routes (1, 3, or 13) equal to or exceeding 30%. Similarly, on routes 1 and 3, over 30% of idling time was done in stops longer than five minutes. This indicates that an anti-idling policy or engine add-on could be effective to save fuel and costs.
- The mileage of the hybrid bus, as measured on the data loggers, was 25% greater than the mileage as recorded on the vehicle hub odometer. This should be investigated further, as it indicates an issue either with distance reporting from the engine computer or distance reporting from the hub odometer.
- The hybrid bus was more costly to maintain ($0.24 per mile vs. $0.13 per mile) and had significantly lower availability: 55% uptime vs. 81% uptime.
- Drivers expressed dissatisfaction with the hybrid vehicle performance and cabin comfort. The maintenance and fleet managers identified challenges in maintaining the vehicle and the lower than expected build quality.

1. INTRODUCTION

Greenhouse gases, climate change and emissions are becoming a prominent concern, both among the public and at public agencies. In addition, the fuel economy of a transit fleet directly affects fleet operating costs. The transit industry, federal and local agencies have been focusing on new vehicle technologies and alternative fuels as a way to boost fuel economy, reduce operating costs, and reduce emissions. Many promising technologies have emerged, including hybrid buses, plug-in electric buses, and fuel cell buses.

However, while these new vehicle technologies have shown benefits in some trials, few have been road-tested in real world situations and evaluated with rigorous comparative analysis. Transit agencies and OEMs alike are interested in quantifying fuel reductions as they relate to expected values. Additionally, evaluations of fleet vehicles are an effective tool for demonstrating the desired level of performance and reliability. This provides valuable in-use data on component systems and overall maintainability of commercial hybrid vehicles.

The Federal Transit Administration (FTA) is interested in obtaining a better understanding of the performance and reliability of hybrid electric shuttle buses operating in revenue service. The *Monterey-Salinas Transit Hybrid Electric Bus Evaluation Project* evaluated the performance of an International diesel hybrid-electric bus and a Ford E-450 gasoline shuttle bus in operation at Monterey-Salinas Transit (MST).

CALSTART collected vehicle engine data, speed and location data, and manual maintenance and fuel records on both the hybrid and E-450 over a period of six months from July through December, 2013. These data were supplemented with surveys and interviews of drivers and agency managers to gain insight on user acceptance from a variety of experience levels and perspectives.

Using this broad data set we evaluated the benefits of the hybrid and E-450 in terms of fuel economy, vehicle usage, reliability, and driver feedback. We further examined a handful of characteristics from the different routes for specific trends, creating a comprehensive route analysis of the MST system.

This study contains the results of both vehicles. We note that the two vehicles are very different and cannot be directly compared (due to size and fuel) in terms of fuel economy.

1.1 Project Overview

MST is a municipal fleet in Monterey County, California that operates 142 vehicles on 60 fixed routes along with paratransit and demand response, with a fleet of 80 buses and 36 demand response vehicles, 18 medium buses and 8 trolleys. MST provides service for 4.4 million trips and 25 million passenger miles annually. They are currently in possession of four International diesel medium buses with a hybrid electric drivetrain system capable of reducing fuel consumption and emissions.

During the six month demonstration period we measured fuel consumption and other performance parameters of both the hybrid and E-450 from data collection equipment installed on the test vehicles. In addition, we monitored the maintenance of both vehicles and conducted driver and manager surveys to obtain user acceptance data.

Upon completion of the six-month demonstration period, we analyzed the data results in order to quantify benefits of the hybrid and discover insights about optimal scenarios for its use. Using these data, we performed a set of analyses to answer questions about the benefits of the hybrid in terms of fuel economy, route characteristics, maintenance, and user acceptance.

Data was collected from multiple sources. We instrumented both vehicles with Isaac Instruments data collection equipment, which included GPS units for location services. The data loggers on both test vehicles were connected to the controller area network (CAN) but the E-450 required a translator device which enabled access to most engine data parameters. We also collected data on maintenance based on service logs and dealership records. We analyzed driver, maintenance and fleet manager impressions using surveys and interviews.

This data set was evaluated to provide insights into vehicle behavior and operating costs. Specifically, the following studies were completed:

Overall HEB Fuel Economy

The primary purpose of this study is to measure the fuel economy of both vehicles over six months of in-use demonstration. We installed data collection equipment on both the hybrid and E-450 to evaluate vehicle telemetry and GPS data, and collected manual records of distance traveled and fuel consumed.

Route Analysis

We recorded detailed telematics data from each bus and analyzed the vehicle location on nine MST routes. The second-by-second data allow us to identify key route characteristics and highlight metrics that indicate ideal hybrid route assignment.

Maintenance Analysis

Through service logs and conversations with the Chief Operating Officer at MST and the maintenance supervisor, we established a comprehensive picture of the maintenance required by these vehicles during the six-month demonstration period. Service logs included both parts and labor costs which were categorized by vehicle system type for further analysis.

User Acceptance

We used surveys at strategic points during the demonstration period to evaluate driver experiences with the hybrid. Additional data were collected from interviews with fleet and maintenance managers. The first-hand experiences of these individuals provided valuable insight into bus operation, and supplemented the quantitative results.

The analysis and results for each of these categories is presented in the chapter below, along with recommendations on further improving fuel economy.

2. CONSTRUCTION OF STUDY

This section provides background information on the test vehicles and their assigned routes. Each bus is described in detail, highlighting the Eaton hybrid drivetrain. For the majority of the study, the vehicles were assigned to routes according to agency scheduling and operational needs; special assignments were provided for this study for small time periods to collect a data on a large number of routes. The routes discussed in this chapter were selected in consultation with MST to establish a comprehensive picture of the Monterey Bay service area without interfering with operational limitations.

2.1 Vehicle selection

The hybrid is an International 32-foot diesel hybrid-electric bus manufactured by Navistar International Trucks and outfitted with an Eaton hybrid powertrain while the conventional-technology vehicle is a gasoline E-450 cutaway shuttle bus manufactured by Ford Motor Company. Specifications are shown in Table 2-1.

Table 2-1: Details of Demonstration Vehicles

Vehicle	Hybrid	Ford E-450
Manufacturer	International	Ford
Model	IC Bus HC	E450
Model Year	2013	2008
GVWR (lbs.)	25,500	14,500
Fuel Type	Diesel	Gasoline

While these two vehicles are different in terms of GVWR, fuel type and model year, they were chosen because the Ford E-450 is the baseline choice that MST would use if the hybrid were not available. In addition, this choice enables an analysis of several MST routes to better understand route properties.

The Eaton system is installed simultaneously with the vehicle build and connects to the driveshaft, replacing the standard transmission. The vehicles are of different size: the hybrid is 25,500 GVWR and the E-450 is 14,500 GVWR. Therefore, a direct comparison of the performance of the two vehicles should not be inferred.

Hybrid Electric Bus

This vehicle was designated a “medium bus” by MST as it was larger than their Ford E450 shuttle buses but smaller than the Gillig 40-foot city buses. Specifications and a schematic diagram of the vehicle are shown in Table 2-2 and Figure 2-1 below.

Table 2-2: Hybrid-Electric Bus specifications

Vehicle System	Manufacturer Detail
Chassis	MY2012 International 32'
Engine	Navistar MaxxForce DT EPA10 7.6L I6 230HP @ 2200 RPM and 660 lb-ft @ 1300 RPM
Drivetrain	Eaton Parallel Hybrid with Regenerative Braking
CAN Interface	J1939

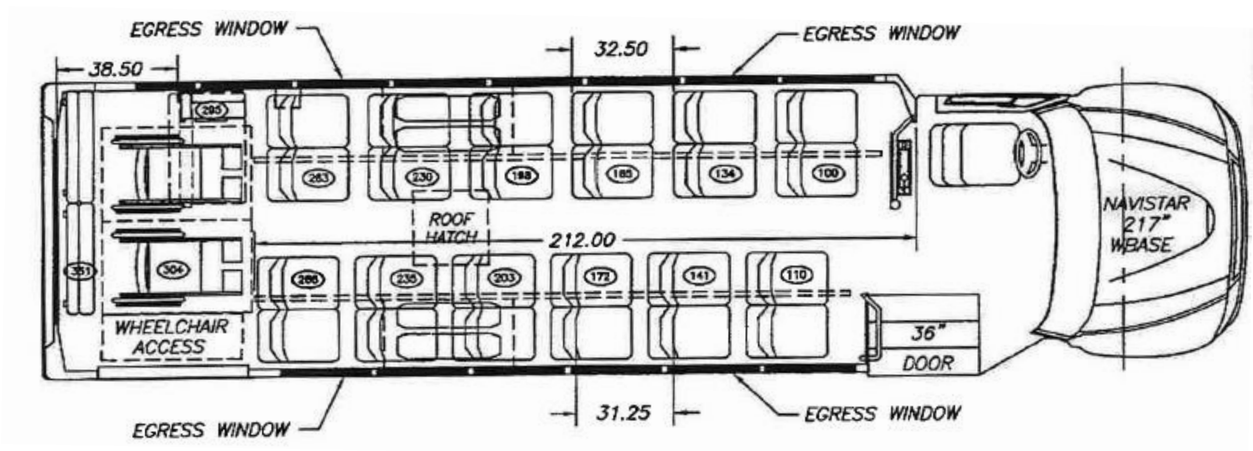

Figure 2-1: Floor-plan schematic of the International 32' medium bus

The vehicle has a 217 inch wheelbase and wheelchair access at the right rear panel. A total of 30 standard seats put this vehicle in between classes currently being employed by MST.

The CAN bus, which is responsible for all engine control systems, proved to be readily accessible on the hybrid with a J1939 port in the vehicle cab. The CAN bus works in tandem with the On-Board Diagnostics (OBD) network, which exports a variety of vehicle telemetry and engine performance parameters.

The Eaton parallel hybrid powertrain replaces the standard vehicle powertrain while maintaining the component layout as shown below in Figure 2-2.

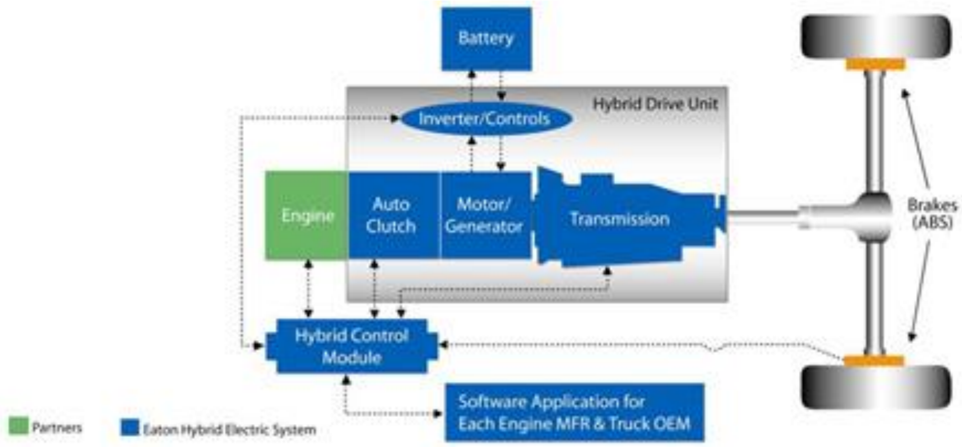

Figure 2-2: A diagram of the hybrid bus undercarriage, showing the Eaton hybrid powertrain system

The system combines torque from the engine and electric motor via the Hybrid Control Module, which dictates the power delivered to the driveshaft. The Lithium-ion batteries are charged via a regenerative braking scheme which allows for energy storage and launch assist. A patented Eaton UltraShift automated manual transmission is responsible for gear selection, which optimizes fuel efficiency regardless of operator. The system can be disengaged for any reason allowing for fully conventional vehicle operation.

Dials on the vehicle dashboard help drivers understand how the hybrid system is operating, and how to optimize their driving; this display is shown in Figure 2-3 below.

Figure 2-3: Eaton hybrid system driver display

The dial on the left shows the battery system State of Charge (SOC), the middle dial shows the action state of the hybrid system—battery charging or launch assist, and the dial on the right shows how well the driver is conserving fuel. The first two dials essentially help the driver understand how to best keep the third dial in the green (better fuel economy) zone by maximizing charging events at low battery SOC and utilizing launch assist at high battery SOC.

Ford E-450

MST maintains a fleet of over 25 Ford E-450 buses parked at the Salinas maintenance facility. General specifications of these vehicles are listed in Table 2-3.

Table 2-3 Ford E-450 shuttle bus specifications

Vehicle System	Manufacturer Detail
Chassis	Ford E450 cutaway
Engine	Ford 5.4L Triton V8 255HP @ 4500 RPM and 350 lb-ft @ 2500 RPM
Drivetrain	Ford Torqshift 5-speed automatic
CAN Interface	OBD-II

The different CAN on this vehicle required an additional J1939 translator device during the evaluation which enabled access to most engine parameters. OBD-II is generally found on smaller commercial vehicles and contains slightly different protocols from the J1939 network employed on the hybrid.

2.2 Route Selection

MST operates a total of 60 fixed and trolley routes, as well as paratransit and demand response. Ridership per route can vary greatly; for example, in February 2013 the most popular route carried nearly 37,000 passengers, while the median route carried less than 3,000 passengers. The following group of routes covers a wide range of service areas in the MST system and represents both urban and rural drive-cycles. Further analysis of these routes allows us to identify key characteristics and highlight metrics that indicate ideal hybrid route assignment. The Monterey Peninsula system map shown in Figure 2-4 below highlights the expanse of territory covered by MST.

Figure 2-4: MST Monterey peninsula system map

MST vehicles travel as far south as King City ,as far north as San Jose, and as far east as Paso Robles, though the majority of routes cover downtown Monterey, Pacific Grove, Sand City, and Carmel. The hybrid operated primarily on Route 24, the Grapevine Express, which travels between Monterey and Carmel Valley Village as shown in the MST route map in Figure 2-5 below.

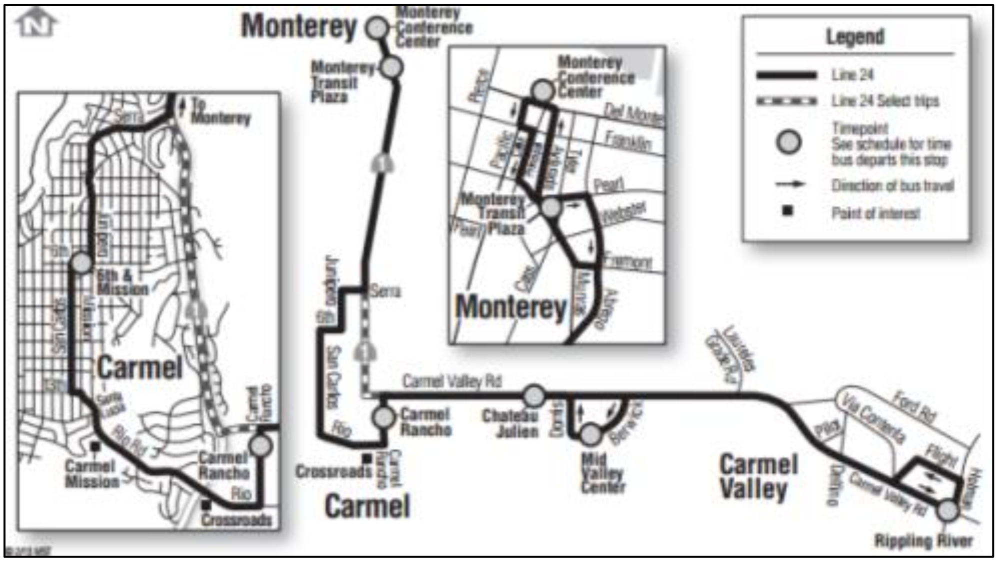

Figure 2-5: Service map for Route 24

Route 24 has 49 fixed stops, and spans 18.9 miles each way, with an average distance between stops of 0.4 miles. This route has significant segments of higher-speed driving, which is generally less efficient for hybrid systems because they do not offer enough opportunity to recharge the system batteries.

The hybrid also ran occasional routes on Route 1 which goes through downtown Monterey into the Pacific Grove neighborhood stopping at the Asilomar Conference Center, Pacific Grove Golf Course, and then returning to the Monterey Transit Plaza, as shown in the MST route map in Figure 2-6 below.

Figure 2-6: Service map for Route 1

This route is 4.6 miles long, with 26 fixed stops and an average distance between stops of 0.2 miles. This is the most urban route in the MST system and therefore provides a good comparison to Route 24 operation.

Unlike the hybrid, the E-450 operated on many MST routes and was not just limited to Routes 1 and 24. Rather, this vehicle was assigned to routes as part of normal operations, though specific days were investigated for further analysis to identify seven more routes that fully characterize the MST system. The following are service maps and brief descriptions of these routes, with specific metrics reported in the performance results chapter.

Route 8 travels through neighborhood streets near the Monterey Regional Airport whereas Route 22 connects downtown Monterey with the southern tip of Big Sur. These two relatively distinct routes were grouped together, with the E-450 often spending half the day on each route; service maps for both routes are shown below in Figure 2-7.

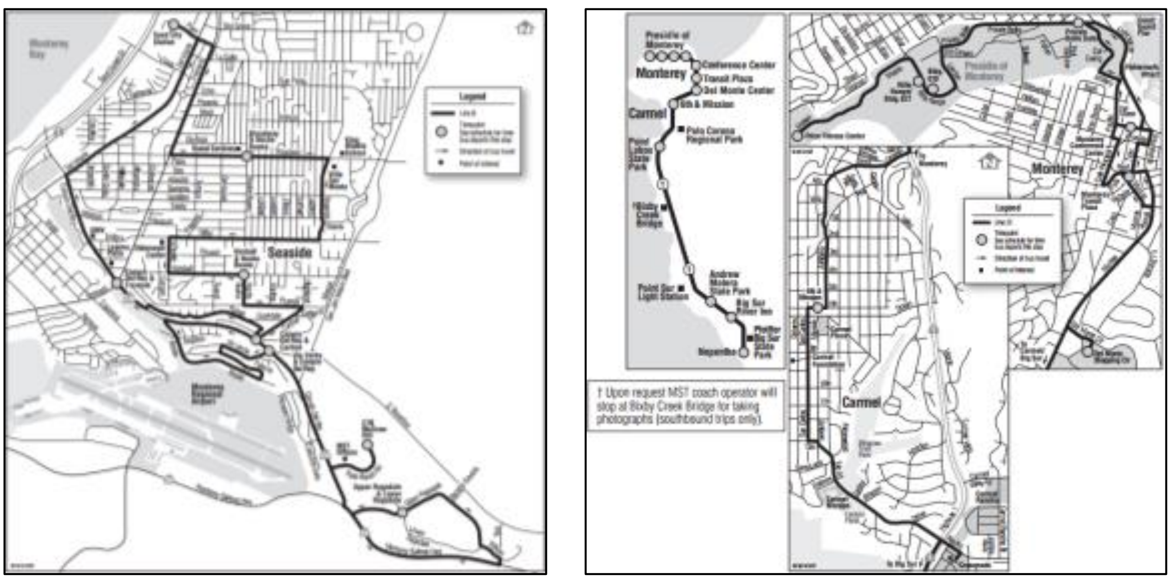

Figure 2-7: Service maps for Routes 8 and 22 (left to right)

Route 8 is approximately 14.7 miles round-trip and Route 22 travels roughly 67 miles to and from the Monterey Transit Plaza and Pfeiffer Big Sur State Park.

Route 3 services the Monterey community hospital (CHOMP) while Line 13 targets the Ryan Ranch area just south-east of the Monterey Regional Airport. These are similar route types, as they include significant higher-speed driving on Highways 1 and 68 as well as low-speed neighborhood driving; service maps for both routes are shown below in Figure 2-8.

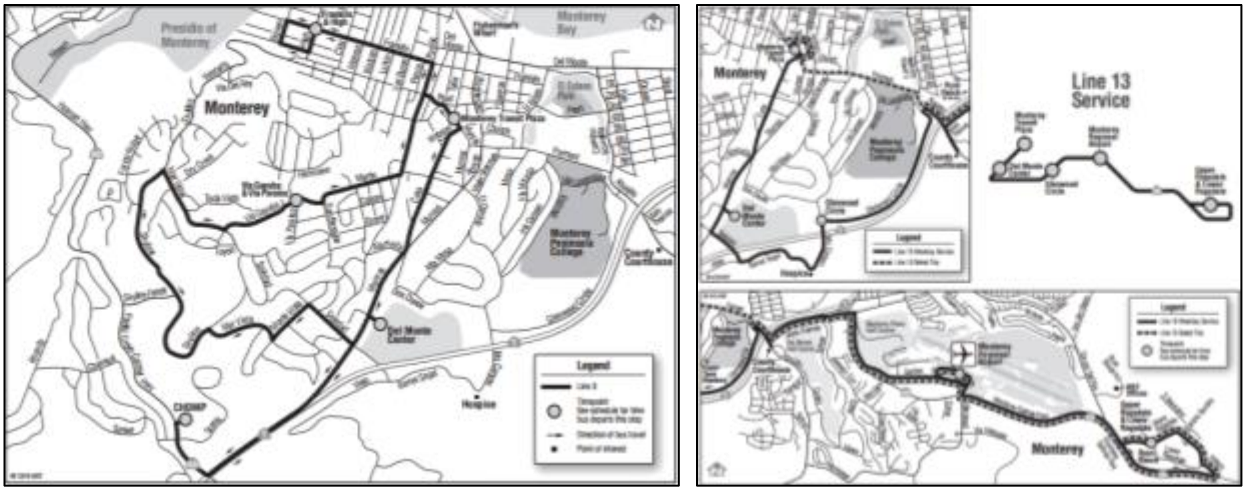

Figure 2-8: Service maps for Routes 3 and 13 (left to right)

Route 3 is approximately 9.3 miles long and Route 13 covers 18.8 miles to and from the Monterey Transit Plaza, servicing the Monterey Regional Airport and Ryan Ranch.

Route 27 connects Marina and Watsonville, which itself has metro connections to Santa Cruz. These two urban centers are approximately 18 miles apart, though there are detours into Castroville which add to the loop mileage, as shown below in Figure 2-9.

Figure 2-9: Service map for Route 27

The average length of Route 27 was 49 miles, and serviced the towns of Marina, Castroville, Moss Landing, and Watsonville along Highway 1 in Monterey Bay.

Route 94 includes both low-speed travel through the highly urbanized center of Carmel and high-speed connection between Carmel, Monterey, Seaside, and Sand City as shown in the service map below in Figure 2-10.

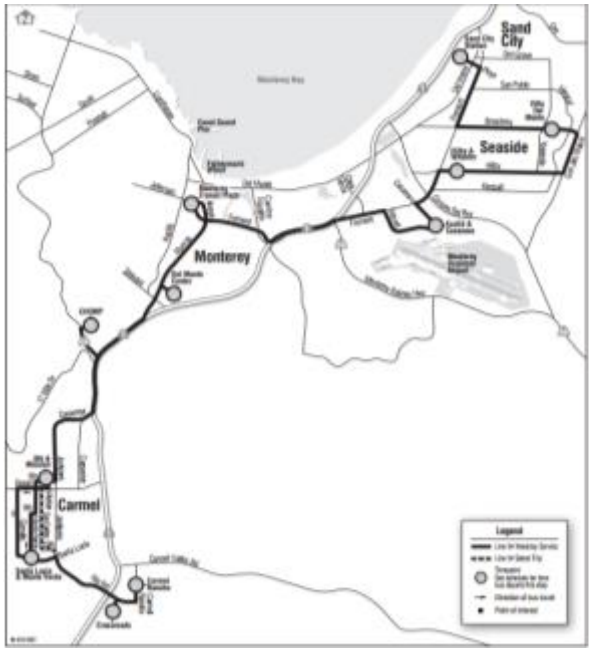

Figure 2-10: Service map for Route 94

The basic form of this loop travels approximately 13 miles to and from Carmel and Monterey. However, some trips extend up to Seaside and Sand City, adding another 12 miles to the loop.

Route 25 meanwhile connects the California State University of Monterey Bay (CSUMB) to downtown Salinas, as shown in the service map in Figure 2-11 below.

Figure 2-11: Service map for Route 25

This route is 22 miles round-trip and includes some urban travel through the CSUMB campus and downtown Salinas as well as high-speed travel connecting the two terminals.

2.3 Service Activities

MST contracts with MV Transportation (MV) in Salinas, CA for maintenance and service delivery. MV Transportation was responsible for performing PM inspections and unplanned maintenance work on these vehicles throughout the duration of the demonstration period. MV also provided CALSTART with all associated documentation for both test vehicles, which was instrumental in establishing the service cost profiles reported in the maintenance chapter. Occasionally the hybrid had to go to a specific dealer in San Martin, CA for work beyond the capability of MV. In the maintenance analysis, vehicle subsystems were examined to look for particularly expensive components or quick fixes.

3. VEHICLE PERFORMANCE RESULTS

In order to assess the performance of the hybrid medium bus in real-world revenue service, we monitored its operation over a period of six months. Additionally, we tracked the E-450 on a variety of routes to better characterize the MST system and identify which routes might be better suited for hybrid vehicle implementation. We collected second-by-second vehicle engine data to examine in each instant how the engine performed. This allows us to answer, in detail, four questions:

- What was the fuel economy of the hybrid vehicle over the duration of the six-month demonstration?
- How does hybrid fuel economy vary between two very different routes?
- How do MST routes differ amongst each other?
- Which routes are more ideal for hybrid implementation?

The testing period was from July 1 to December 31, 2013, during which the two test vehicles combined traveled 103,616 miles over 3,506 hours of operation. The sections below present the methodology used in this study, vehicle usage for the hybrid and E-450, fuel economy findings of the hybrid, route characterization and analysis of vehicle speeds and the effects of idling.

3.1 Methodology

3.1.1 Test Program

We designed a test protocol to measure vehicle performance. During the six-month demonstration period CALSTART monitored vehicle and engine performance using data logging equipment that captured data from the OBD and an additional GPS unit for location services. Two separate vehicles were instrumented for data collection; however the translator device installed on the E-450 could not access any fuel parameters and thus fuel consumption data were only available on the hybrid. The vehicle telemetry data on the E-450 which were made available by this translator device were focused to establish route profiles.

The data capture was designed to operate without manual effort to the extent possible, to reduce burden on the fleet operator. Once the data loggers were installed by CALSTART to collect the engine data, they operated without further intervention, collecting data when the vehicle was turned on and uploading the data via the mobile phone network every two or three days, once the storage buffer was full. We regularly downloaded the engine data from the online server to monitor progress and check for any errors that would require further attention.

Manual records for fuel dispensed were hand-written by drivers whenever they fueled either the hybrid or E-450 at the Salinas yard. The schedule for fueling was irregular, with fueling events occurring every day or two, and at different times of the day. A fuel and mileage log was compiled from this data which was sent daily to CALSTART. In addition, MST provided a monthly report of fuel consumption and miles traveled, which was generated from the same manual fuel records. MV Transportation maintained records on all service activities as part of their business activities. As part of the close-out process, CALSTART collected these records and extracted mileage readings to form the manual mileage log.

Data Collection Equipment

We instrumented both vehicles with Isaac Instruments data collection equipment, which included GPS transceiver and cellular network modem to remotely transmit data to the CALSTART server. The data loggers on both test vehicles were connected to the CAN but the E-450 required a J1939 translator device which enabled access to most engine data parameters. The larger size of the hybrid ensured that it already had a J1939 port connection. These components and their associated cabling are shown below in Figure 3-1.

Figure 3-1: Data collection equipment in vehicle cab

The data collection equipment was capable of obtaining most engine and vehicle messages from the On-Board Diagnostics port, Table 3-1 below presents the main vehicle parameters that were analyzed from the vehicles, though one key hybrid-only parameter is noted.

Table 3-1: Vehicle parameters from data collection equipment used for analysis

Vehicle Parameter	Unit
Engine speed	rev/min
Vehicle speed	km/h
Fuel Rate*	L/h
Accelerator Pedal Position	%
GPS Latitude	°
GPS Longitude	°
GPS Altitude	m

*Available only on the hybrid

We found after the initial installation that the engine control system in the E-450 did not provide data on fuel flow, nor does it provide data on air flow and instantaneous air/fuel ratio, which would have allowed a direct calculation of fuel flow. This data limitation precluded an analysis of E-450's fuel economy based on the engine data.

Manual Fuel Logs

As a secondary and backup source for fuel consumption, we collected manual records of the amount of fuel dispensed to each vehicle over the six-month period. MST uses a hand-written fuel dispensing system which relies solely on driver inputs at vehicle fueling events. The monthly mileage and fuel consumption values reported by MST for these vehicles are listed as a comparison to the engine data to highlight any distinctions in these high-level numbers. The hybrid vehicle was equipped with a hub odometer, whereas the E-450 was equipped with a standard odometer. A hub odometer is installed on one of the vehicle wheels and calculates mileage based on wheel revolutions. These designs usually generate readings comparable to standard odometers but are fairly delicate and susceptible to uneven road surfaces, additionally they can be more difficult to physically read than an in-cab odometer. These distinctions may result in measurement inaccuracies; in fact, we found our mileage measurements diverged significantly across the different data sources. The distinction between mileage reported from the engine data and these two other sources (hub odometer, in-dash odometer) will be discussed further.

3.1.2 Data Analysis

Engine data were received as text files containing values for 27 parameters related to vehicle function. As the data was recorded at one record per second, we received approximately 80,000 records daily or 12.8 million over the course of the project. At the completion of the project, these records were uploaded to a MySQL database where the extraneous information was stripped away and the remaining fields were processed for further calculations. For example, date and timestamps stored as text were converted to date fields and time fields to enable further processing.

We found anomalies in the data stream of the E-450 which required manual clean-up after loading all the raw data into the database. For example, when the data logger first initializes after the vehicle is turned on, there is a period of several seconds where all data fields are recorded at their maximum value. These fields are easy to locate, both because the values are unrealistically high (e.g., RPM values far in excess of the capabilities of the engine), and the values are exactly consistent between records. All of these records were marked as “pegged” and discarded from the analysis.

Vehicle distance was calculated using the instantaneous vehicle speed recorded each second. We calculated the distance traveled during that one-second period – distance traveled equals speed times duration of segment. To calculate the distance traveled over any given time period, we summed the distance traveled for each second within that period.

In order to evaluate the fuel economy on the hybrid, the fuel rate parameter was converted to provide per-second fuel consumption by the engine. By summing this fuel flow per second over a given time period and dividing into the corresponding mileage, we obtain the fuel economy value. This data collection and analysis methodology has been used in a several prior CALSTART projects, including prior Navistar-powered vehicles, and the team has found good accuracy in this approach in prior analyses.

3.2 Review of Demonstration Data

The vehicles were both used extensively over the six-month demonstration period, though the E-450 traveled over twice as many miles as the hybrid. Data on the monthly E-450 usage are shown below in Table 3-2 and hybrid in Table 3-3.

Table 3-2: Monthly usage of the Ford E-450

	Isaac Engine Data			MST Monthly Report	
Month	**Mileage (mi)**	**Engine Hours (h)**	**Fuel (Gal)**	**Mileage (mi)**	**Fuel (Gal)**
July	7,057	345.9	n/a	7,548	1068
August	5,717	273.6	n/a	6,148	843
September	5,684	292.1	n/a	5,671	779
October	6,188	359.5	n/a	6,532	931
November	5,555	299.7	n/a	5,454	752
December	5,400	275.8	n/a	5,575	760
Overall	35,603	1,846.7	n/a	36,928	5133

Table 3-3: Monthly usage of the hybrid vehicle

	Isaac Engine Data			MST Monthly Report	
Month	**Mileage (mi)**	**Engine Hours (h)**	**Fuel (Gal)**	**Mileage (mi)**	**Fuel (Gal)**
July	7,449	366	974	6,487	1,135
August	4,984	239	662	3,895	711
September	4,288	213	583	3,125	583
October	5,588	287	766	4,121	831
November	2,416	121	330	1,946	326
December	5,425	264	730	4,581	843
Overall	30,150	1,492	4,045	24,155	4,429

The tables above show that there are some inconsistencies in the data sets when comparing the Isaac engine data to the manually reported data. These inconsistencies and data gaps affect the following findings for vehicle fuel economy.

In the case of the E-450, the mileage as measured by the data loggers is consistent with the data from the manual logs, within an expected error range. Total measured through the engine is 35,603 miles for the duration of the test, a difference of 3.7% from the data from the manual logs, of 36,928 miles; monthly figures varied from 0 to 8% between the two sources. This difference is consistent with expectations for the Isaac system. When recording J1939 data, the Isaac Instruments equipment is known to include a built-in error of 5 to 10%.[1]

On the E-450 we were unable to capture electric fuel consumption data, due to unexpected technical limitations with the on-board computer. Fuel flow was not reported for the vehicle. To compensate, we attempted calculations that inferred fuel use from a combination of engine parameters, however these results did not appear reliable enough without pre-test calibration.

As a result we rely on the manually recorded data for calculating E-450 fuel economy.

On the hybrid vehicle, we were able to capture distance and fuel flow electronically and have a full comparison against the manually collected data on the hybrid. However, as shown in the table above, the electronic data diverged greatly from the manual data. Over the course of the six month demonstration, the mileage on the data loggers is 25% greater than the mileage reported manually. Fuel measurements are off by approximately 10%. The reasons for this divergence aren't clear, but we see some potential explanations.

Distance is measured through a hub odometer (hubdometer), which tracks wheel rotation instead of engine revolutions over time. In either case, the engine or the hubdometer is programmed to assume the vehicle's wheel size is a certain value. If the assumed wheel size is incorrect, the measurements from either source will be incorrect.

Based on this uncertainty, and without further data on which measurement is more correct, we choose to use the engine data logger measurements in order to remain consistent with past work. The engine data logger should mirror the vehicle engine odometer (as opposed to the hubdometer). Similarly, we choose to use data logger fuel use over manual records of fuel consumed, although the impact of this decision is smaller because the difference between engine data fuel use and manual measurements is smaller.

We recommend an additional validation of the hubdometer, in which the vehicle is driven a large distance (such as to the dealership), and the hubdometer measurement is checked before and after the trip. The distance of the trip can be easily measured through online mapping sites. This would provide confidence in the hub odometer, or identify a problem.

3.3 Fuel Economy Results

When fuel economy is averaged over the entire testing period, the hybrid bus operated at 7.5 MPG (miles per gallon of diesel), and the E-450 at 7.2 MPG (miles per gallon of gasoline). A summary of fuel economy is presented in Table 3-4.

[1] Michael P. Lammert, Kevin Walkowicz, Adam Duran and Petr Sindler, "Measured Laboratory and In-Use Fuel Economy Published Observed over Targeted Drive Cycles for Comparable Hybrid and Conventional Package Delivery Vehicles," National Renewable Energy Laboratory, Pub. 9/24/12, Available at (http://www.nrel.gov/docs/fy13osti/55673.pdf)

Table 3-4 Fuel Economy of Hybrid and Ford E-450

	Hybrid			E-450		
Month	**Miles Traveled**	**Fuel (Gal)**	**Fuel Economy (MPG)[a]**	**Mileage (mi)**	**Fuel (Gal)**	**Fuel Economy (MPG)[a]**
July	7,449	974	7.6	7,548	1068	7.1
August	4,984	662	7.5	6,148	843	7.3
September	4,288	583	7.4	5,671	779	7.3
October	5,588	766	7.3	6,532	931	7.0
November	2,416	330	7.3	5,454	752	7.3
December	5,425	730	7.4	5,575	760	7.3
Overall	30,150	4,045	7.5	36,928	5133	7.2
Data source	Engine	Engine	Engine	Manual	Manual	Manual

[a] Hybrid fuel economy is measured as miles per gallon of diesel. E-450 is measured as miles per gallon of gasoline.

While the fuel economy benefit appears small in total magnitude, it is notable that the hybrid remains more efficient than the E-450, despite the size difference of 25,500 lbs. vs. 14,500 lbs. GVWR. The hybrid bus' hybrid-electric system improves overall efficiency to compensate for the increased load from the much larger vehicle. With a greater weight and larger passenger capacity, a bus of that size would be expected to have much lower fuel economy than the smaller E-450.

To gain a better understanding of fuel economy, we take a closer look at how the hybrid bus performs on two separate routes. This comparison provides further insights into how the hybrid is performing. Stepping back from the individual vehicles, we perform a comprehensive evaluation of 11 MST routes to examine how average speed and number of stops could impact fuel economy. Lastly, we look at trends in idling time to identify where the vehicles are idling excessively and how that could impact the results. These analyses are presented below.

3.3.1 Hybrid Route Fuel Economy Comparison

In order to evaluate the hybrid fuel economy on routes 1 and 24, we isolated data on two days of data for each route. This data set provided the basis for analysis of ideal hybrid route assignment. On each day the GPS trace was analyzed to ensure only revenue service data was calculated into the mileage, fuel consumption, and engine hours. We cut out any vehicle time before or after the vehicle entered service. The results for this comparison on Routes 1 and 24 are shown below in Table 3-5.

Table 3-5: Hybrid fuel economy comparison by route

Route	Mileage (mi)	Engine Hours (h)	Stops/ Mile	Avg. Driving Speed (MPH)	Fuel Economy (MPG)	Gallons/ Hour
Route 1	144.2	12.7	3.8	16.8	7.1	1.6
Route 24	181.8	9.2	1.8	26.6	7.3	2.7

[a] Hybrid fuel economy is measured as miles per gallon of diesel.

These two routes are nearly opposites, as shown in the service maps in Figure 2-5 and Figure 2-6. The hybrid on Route 24 is 10MPH faster than on Route 1, and consumes over a full gallon more of diesel per hour of engine-on time (including idling). Meanwhile, the hybrid stops over twice as often per mile on Route 1 than on Route 24, allowing for more hybrid system regeneration and boost. This calculation involved counting the number of stop events at which speed decreased from greater than zero to zero, and included both traffic and passenger stops, providing an in-depth view of vehicle travel. Fuel economy is 2.5% higher on Route 24 than on Route 1, possibly due to inherent engine efficiencies at higher speeds, though it is unclear whether a difference of only 10MPH allows for such engine efficiency gains.

The findings from Table 3-5 give us a range of stops per mile and average driving speeds that might result in approximately 7.2MPG (miles per gallon of diesel) in hybrid fuel economy. In the next section, we'll investigate the interrelatedness of stops per mile and average driving speed, with the ultimate distinction between routes likely coming down to gallons of fuel consumed per hour. When traveling at higher speeds vehicles will always use more fuel because the engine is working harder, so hybrid implementation optimizations must keep this in mind.

Given the differences in the routes, it is notable that the fuel economy from the hybrid is so consistent across the two. Without electronic data on the E-450, we cannot perform the same analysis on the E-450 for comparison. It is possible that the benefits of the hybrid help to counter the losses in conventional vehicles from stop and start driving.

3.4 Route Characterization and Analysis

A total of nine MST routes were investigated as part of this project, including the two routes analyzed in the previous section and seven traveled by the E-450. This analysis helps to better characterize the MST system and identify which routes might be better suited for hybrid vehicles. In each case, at least three full loops (from the start of the route to the end of the route, and returning to the starting point) of each route was extracted from the data set, and GPS data were plotted in Google Earth to determine exact moments when the test vehicle was driving along one of the routes in question; the associated data for those portions of the day were categorized for that particular route. In Figure 3-2 below we see the Monterey Transit Plaza highlighted with the red arrow, where Route 13 begins its loop, and the repetition of Route 13 followed by Route 3 for the entire day, a total of 166 miles.

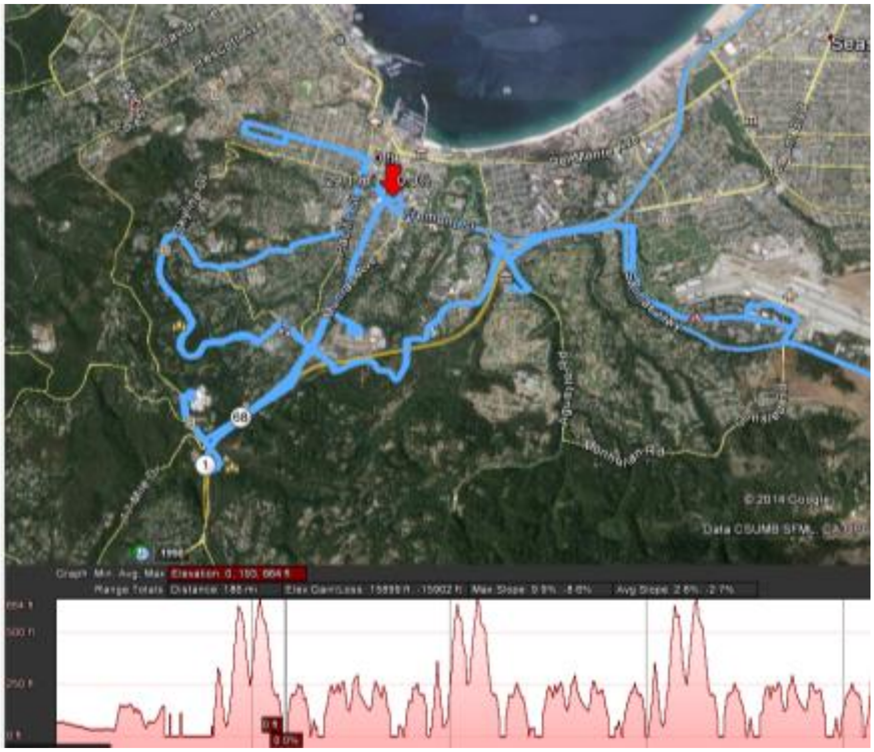

Figure 3-2: Partial GPS trace for Routes 13 and 3

All route data is summarized in Table 3-6 below. The table includes total route length, total distance traveled, and number of vehicle stops. Stops are defined as any deceleration down to zero speed, and include both stops to pick up passengers and stops in traffic. Engine hours include idle time, average driving speed discounts any periods of idling. All route data with the exception of Routes 1 and 24 came from the hybrid; high level results are shown below.

Table 3-6: Route characteristics summary

Route	Vehicle	Route Length (mi)	Total Test Mileage (mi)	Engine Hours (h)	Stops/ Mile	Avg. Driving Speed (MPH)
1	Hybrid	10.4	144.1	12.7	3.8	16.8
3	E-450	9.3	56.5	4.2	2.6	19.4
8	E-450	14.7	44.2	2.9	2.9	20.2
13	E-450	18.8	89.1	6.2	2.4	21.3
22	E-450	67.6	215.1	9.3	1.2	31.7
24	Hybrid	36.0	181.8	9.2	1.8	26.6
25	E-450	22.0	197.7	9.1	1.5	28.9
27	E-450	49.0	158.9	6.2	1.2	33.5
94	E-450	25.0*	192.3	7.3	1.1	31.8

*Some loops are truncated at 13 miles; others include an additional 12 mile loop

Clearly there was more data on some routes than others; Routes 8 and 3 were all less than 60 miles and 4.5 hours of operational data. The individual route lengths varied from just over 9 miles to just under 68 miles, though Route 94 included an optional 12 mile loop, often increasing its loop length from 13 to 25 miles. As mentioned in the route discussion in Section 2.2, Routes 1 and 3 are the most urban whereas

Routes 22 and 27 have significant high-speed rural travel, which follows the route-length trend shown in Table 3-6.The best way to visualize the interrelated nature of the stops per mile and average driving speed is in Figure 3-3 below, which highlights the unique relationship of these two characteristics.

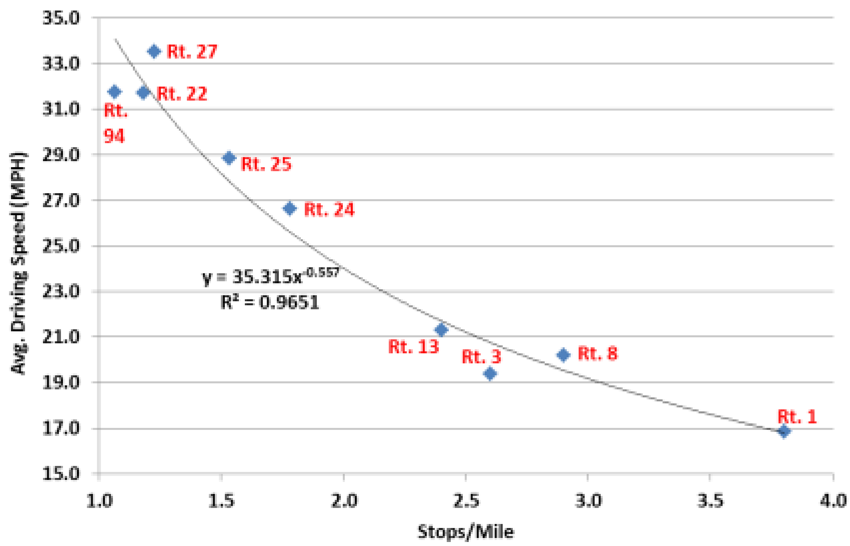

Figure 3-3: Route characterization plot

Clearly shown above are the increased average driving speeds and decreased stops per mile on Routes 22, 27 and 94. These three routes represent the extremes in rural or highway driving with little to no urban stop-and-go operation. The roughly inverse-root relationship between the two variables continues towards the middle third of the curve in Figure 3-3 wherein Route 24 maintains a somewhat elevated average driving speed but begins to increase in stops per mile. At the other end of the spectrum, Route 1 has a very low average driving speed but exceedingly high stops per mile, as discussed in the previous section.

Figure 3-3 provides a visual range for the tested routes that might result in comparable fuel economy to that seen on Routes 1 and 24. Any routes that lie near the parabolic trend line, such as routes 8, 13, and 22 are shown to have the same inverse-root relationship as Routes 1 and 24. If an identical hybrid were to be driven on these additional routes it is possible that our data collection equipment would register fuel economy near 7.20MPG (miles per gallon of diesel).

3.4.1 Route Speed Analysis

In order to assess which MST bus routes may be best suited to the hybrid vehicle, we developed attributes of nine routes served by the hybrid bus and the E-450. Vehicle speed is both a route characteristic and, as discussed previously, an important variable that affects fuel economy. All nine routes were analyzed using vehicle speed distribution bins, wherein each bin represents the percentage of engine-on time that the vehicle spent in that range. The results of this analysis are shown in Table 3-7.

Table 3-7: In-depth speed analysis by route

Route	Idle	1 to 10 MPH	10 to 20 MPH	20 to 30 MPH	30 to 40 MPH	40+ MPH
1	32.8%	28.5%	12.2%	24.1%	2.5%	0.0%
3	29.5%	22.2%	13.0%	26.0%	5.6%	3.6%
8	23.3%	23.1%	14.7%	27.6%	8.2%	3.1%
13	32.5%	13.9%	18.6%	20.7%	9.1%	5.2%
22	21.3%	13.0%	5.3%	11.0%	16.4%	33.0%
24	25.9%	26.9%	6.6%	9.9%	9.4%	21.2%
25	19.7%	19.6%	6.7%	14.9%	12.0%	27.0%
27	21.5%	15.0%	5.9%	14.7%	8.5%	34.4%
94	16.8%	19.8%	7.5%	14.8%	8.3%	32.8%

As described in Chapter 2, due to its mainly urban travel Route 1 had the highest daily percentage of idling, at nearly 33%, whereas Route 94 had the lowest percentage of idling and nearly the second-most time spent at or above 40 MPH. The nine routes can all be visually inspected in Figure 3-4 below.

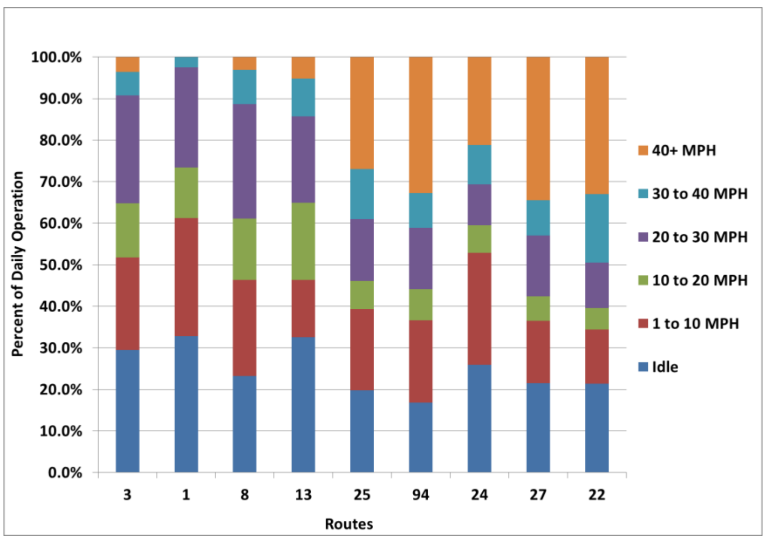

Figure 3-4: In-depth speed analysis chart

All routes spend nearly 20% or more of their engine-on time at idle, while there is a noticeable split in the figure above between the more rural routes (25 thru 22 on the right) and the more urban ones (3 thru 13 on the left). The urban routes spend less than 6% of their time above 40MPH, and 20% to 30% between 20 and 30MPH, indicative of lower-speed stop-and-go travel. Routes 25 thru 22 meanwhile spend nearly 30% or more of their engine-on time at or above 40MPH, indicating significant highway driving. Route 24 is slightly lower at 21.2%, mainly due to somewhat elevated time spent from 1 to 10MPH traveling through the urban center of Carmel Valley Village.

3.4.2 Route Idling Analysis

The amount of idling seen on each route was quantified in two forms of daily averages, the idling per hour and idling per mile. These are two very relatable metrics that demonstrate how active (or inactive) route operation can be over a long stretch of time or a short distance; results are shown below in Table 3-8.

Table 3-8: Route idling summary

Route	Idling per Hour (min)	Idling per Mile (min)
1	19.7	1.7
3	17.7	1.3
8	14.0	0.9
13	19.5	1.4
22	12.8	0.6
24	15.6	0.8
25	11.8	0.5
27	12.9	0.5
94	10.1	0.4

As expected, the two idling columns have a direct relationship; as one increases so does the other. However there are a few exceptions to this rule in Table 3-8, namely Route 8 which has a slightly lower idling per hour value than Route 24 while idling 0.1 minutes more per mile.

We take a closer look at the idling events themselves by defining specific idling durations, the data and visualization are shown below in Table 3-9 and Figure 3-5.

Table 3-9: In-depth idling analysis by route

Route	1 to 30 (s)	31 to 60 (s)	61 - 300 (s)	300+ (s)
1	25.6%	14.9%	26.8%	32.7%
3	22.9%	11.8%	32.4%	32.9%
8	37.7%	16.3%	46.0%	0.0%
13	21.4%	18.5%	42.7%	17.4%
22	21.6%	12.7%	53.9%	11.7%
24	29.6%	28.1%	42.2%	0.0%
25	27.9%	21.3%	26.3%	24.4%
27	24.4%	16.0%	51.5%	8.0%
94	33.6%	20.3%	46.2%	0.0%

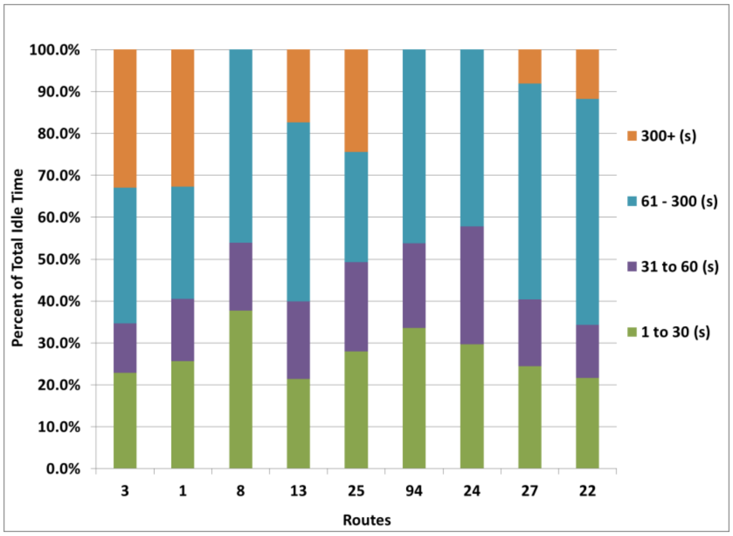

Figure 3-5: In-depth idling analysis chart

Our experiences and conversations with MST staff helped shape the idle duration bins used in this analysis. The first bin from 1 to 30 seconds includes short traffic and passenger stops and appears roughly equivalent between all the routes, with a few outliers in Routes 8 and 94. The second bin from 31 to 60 seconds represents the few extended traffic stops and more likely passenger stops, which generally take longer than a traffic stop. The third bin from 1 to 5 minutes will likely only include extended passenger stops and some shift changes wherein the vehicle idles at route terminals. The last bin categorizes all idle events greater than the five minute anti-idle regulation, and is most useful in identifying those routes which could benefit from stop-start or engine-off policies and technologies.

Most interestingly, idling events from one to five minutes long account for over 40% of daily idling on Routes 8, 13, 22, 27, 94, and 24. Shift changes often result in longer-duration idling events, though we see from Figure 3-5 that five of these six routes do not have much idling longer than five minutes, meaning that the shift changes on their routes are probably accomplished with less than five minutes of idle time. Routes 25, 3, and 1 meanwhile have terminals in very urban locations and are thus more likely to have passengers waiting on the vehicles for the routes to begin—necessitating vehicle air conditioning and thus extended idling. Vehicles on these three routes could benefit from some stop-start or engine-off policy or technology to help mitigate wasteful emissions and fuel consumption spent at idle.

3.5 Conclusions

We installed data collection equipment to record engine data from two test vehicles, and received monthly usage reports from MST to corroborate and compare our findings over the demonstration period. Below are conclusions from the performance evaluation:

- The hybrid bus operated at an average of 7.5MPG (miles per gallon of diesel). E-450 averaged 7.2 MPG (miles per gallon of gasoline). Because the vehicles are different vehicle class and different fuel types, the MPG results should not be directly compared.
- The MST monthly report numbers for mileage differ by 25% from the mileage collected by the data logger. This may indicate a problem with the hub odometer from the hybrid vehicle. This should be verified with test of the hub mileage before and after a long trip.

- Ultimately, Route 1 and Route 24 gave similar fuel economy values, around 7.2MPG, (miles per gallon of diesel) though the stops per mile and average driving speeds were vastly different between the two routes.
- The inverse-root relationship shown between stops per mile and average driving speed indicated that Routes 8, 13, and 22 might also result in a fuel economy of 7.2MPG (miles per gallon of diesel).
- The more urban routes spend a greater percentage of their idling on longer-duration events, perhaps a result of the necessity for vehicle comfort systems tied to higher ridership.
- Several of the routes had significant idling times (up to 30% of engine-on time) and a significant number of long-idle events (30% of idling occurring in events five minutes or longer). The cause of these should be investigated further, and an idling engine-off policy or equipment should be considered.

4. SERVICE AND RELIABILITY FINDINGS

Transit agencies consider expected maintenance costs and vehicle reliability when choosing to invest in a new bus technology. Further, true costs and reliability may not be revealed in a short bus test. In order to better characterize these metrics, we collected and analyzed costs and reliability data for the full duration of the demonstration.

A large component of total vehicle lifecycle cost is the ongoing cost of maintenance activities, both regular servicing and repairs when a component fails. This study's six month demonstration period offered an opportunity to measure and quantify the maintenance cost of the test vehicles. The six-month duration is too short to capture rare events that may occur every two or three years, or mid-life replacements with large costs, so the findings in this chapter should be considered a low bound for total maintenance costs over the lifetime of the vehicle.

Data were collected from service logs and maintenance logs, which contained labor hours expended in service activities as well as all part costs. We organized maintenance and service events on three levels: first, total costs per month, second, costs broken down by major system category, and third, work performed on the hybrid system itself. In addition, the availability of the two buses is measured and reported. These findings are presented below.

4.1 Methodology

The hybrid and E-450 buses were serviced by MV Transportation in Salinas, CA. MV performed PM checks at regular intervals for basic maintenance tasks – change oil, check brake pads, check tire wear, and similar tasks. Between PM checks, the vehicles were serviced at MV to fix any maintenance issues. The facility maintains a thorough system of electronic and manual records to track the condition of the vehicles, status of repairs, and repair costs. These records were the basis for CALSTART's analysis of the reliability and maintenance costs for the hybrid and E-450 buses.

At the conclusion of the demonstration period, we coordinated with MV to submit electronic (scanned and emailed) copies of the PM and service forms. Service logs for PM inspections (every 45 days/5,000 miles) and unplanned maintenance work were organized by vehicle, date of service, and system type. Occasionally the buses had to go to a specific dealer in San Martin, CA for work beyond the capability of MV. These dealer logs provided parts cost, labor hours, and labor cost with an associated category for each service event, allowing us to organize maintenance data at a high level and by vehicle system.

In addition to service at the MV facility, the hybrid vehicle received two warranty repairs at the dealership. While these repairs were completed at no cost to MST, we are including the repairs in this analysis. This approach is more effective to understand the total maintenance costs for the vehicle without the comprehensive warranty. We collected information from the dealership on the parts cost for both repairs. No information was available from the dealership on labor time or costs.

4.2 Total Maintenance costs

Maintenance costs for the buses were tallied for each month of the demonstration period, summing the parts cost, labor hours, and direct labor cost. Wherever commercial labor or parts were used, these costs were also included in the summary. The results for the hybrid and E-450 are displayed below in Table 4-1 and Table 4-2, respectively.

Table 4-1: Hybrid monthly maintenance summary

Month	Mileage (mi)	Parts Cost ($)	Labor Hours (h)	Labor Cost ($)	Total Cost ($)	Cost/Mile ($/mi)
Jul	7448.5	$231.00	18	$382.90	$613.90	$0.08
Aug	4983.8	$0.00	0	$0.00	$0.00	$0.00
Sep	4287.6	$206.89	6	$347.18	$554.07	$0.13
Oct	5588.0	$2,220.68	12	$282.59	$2,503.27	$0.45
Nov	2416.0	$2,403.42	3	$75.34	$2,478.76	$1.03
Dec	5425.8	$860.87	14	$274.68	$1,135.55	$0.21
Total	**30,150**	**$5,922.86**	**53**	**$1,362.69**	**$7,285.55**	**$0.24**

Table 4-2: Ford E-450 monthly maintenance summary

Month	Mileage (mi)	Parts Cost ($)	Labor Hours (h)	Labor Cost ($)	Total Cost ($)	Cost/Mile ($/mi)
Jul	7057.0	$53.05	7	$161.49	$214.54	$0.03
Aug	5717.3	$318.38	11	$269.27	$587.65	$0.10
Sep	5684.1	$24.08	4	$81.00	$105.08	$0.02
Oct	6188.8	$1,168.21	25	$1,715.49	$2,883.70	$0.47
Nov	5555.8	$321.92	8	$198.16	$520.08	$0.09
Dec	5400.1	$51.39	6	$130.02	$181.41	$0.03
Total	35603.1	$1,937.03	62	$2,555.43	$4,492.46	$0.13

Overall, the hybrid cost $0.24 per mile in maintenance cost alone, while the E-450 cost $0.13 per mile over the entirety of the demonstration period. Two hybrid service events in September and November that were covered under warranty contributed to the $2,800 difference in total maintenance cost between these two vehicles.

Along with the $2,800 difference in total costs, the E-450 covered significantly more miles during the demonstration, resulting in its much lower cost per mile. A body shop repair event for the E-450 with over $1,200 in commercial labor is directly responsible for the inflated cost per mile calculation in October.

For the hybrid, a full tire and brake change of over $2,000 (parts only) in October inflated the cost per mile calculation. A comparable amount of miles driven during this month indicate that the vehicle availability did not suffer tremendously from this expensive repair.

4.3 Vehicle System Maintenance Costs

To obtain a greater understanding of which vehicle systems were most costly during the demonstration, each service event was separated by system type, all of which were defined as follows:

- Preventive maintenance inspections (PM)—Labor only for inspections during preventive maintenance
- Tires
- Propulsion-related systems—Repairs for exhaust, fuel, engine, electric motors, traction batteries, and propulsion control, non-lighting electrical, air intake, cooling, transmission, and hydraulics
- Cab, body, and accessories
- Frame, steering, and suspension
- Brakes—Excludes regenerative braking for the hybrids, which is included in propulsion- related systems
- Heating, ventilation, and air conditioning (HVAC)
- Axles, wheels, and drive shaft
- Lighting
- Air System, general.

After categorizing each service event, the total parts and labor cost for each category were summed for both buses; the results are in Table 4-3 below.

Table 4-3: Breakdown of vehicle system maintenance cost per mile

	Hybrid			Ford E-450		
Vehicle System	**Total Cost ($)**	**Cost/Mile ($/mi)**	**Percent**	**Total Cost ($)**	**Cost/Mile ($/mi)**	**Percent**
Propulsion Systems	$2,385.96	$0.08	33%	$250.25	$0.01	6%
Tires	$2,136.59	$0.07	29%	$1,084.55	$0.03	24%
Brakes	$849.05	$0.03	12%	$533.36	$0.01	12%
Cab, Body & Accessories	$244.39	$0.01	3%	$1,690.85	$0.05	38%
Periodic Maintenance	$1,601.29	$0.05	22%	$822.51	$0.02	18%
Lights	$68.27	$0.00	1%	$110.94	$0.00	2%
HVAC	$0.00	$0.00	0%	$0.00	$0.00	0%
Air Systems	$0.00	$0.00	0%	$0.00	$0.00	0%
Axles/Wheels	$0.00	$0.00	0%	$0.00	$0.00	0%
Frame, Steering & Suspension	$0.00	$0.00	0%	$0.00	$0.00	0%
Overall	$7,285.55	$0.24	100%	$4,492.46	$0.13	100%

The percentage column highlights the costliest vehicle systems for each bus throughout the demonstration period. The top five most expensive vehicle systems are highlighted in Table 4-4 below.

Table 4-4: Top 5 Maintenance Cost Categories

Rank	Hybrid	E-450
1	Propulsion Systems	Cab, Body & Accessories
2	Tires	Tires
3	Periodic Maintenance	Periodic Maintenance
4	Brakes	Brakes
5	Cab, Body & Accessories	Propulsion Systems

It is unsurprising that the body and accessories were responsible for most of the repairs on the five year-old conventional bus which had multiple nagging issues that required service as well as a major repair on the windshield. The propulsion system-related repairs on the hybrid were slightly more costly than the tire replacements, due to the parts costs that were covered under the vehicle warranty but included here to reflect total potential operational costs to MST. Tire replacements are not easily comparable between buses due to different configurations, sizes and individual parts costs. The hybrid needed to be fit with tires each costing $350.22, whereas the conventional bus was fit with tires each costing $120.00.

4.4 Unplanned Hybrid System Service Issues

In September 2013 there was a check hybrid light on in the dash of the hybrid, necessitating a diagnosis from the Peterson-CAT dealership. After testing and verifying proper functionality of the power and ground lines to the Electronic Clutch Actuator speed sensor, the sensor itself was removed from the vehicle and found to be damaged. This was likely an issue with the initial build of the vehicle, and was replaced by the Peterson-CAT mechanic upon discovery.

An equally noticeable issue occurred in November 2013 when a whistling noise was heard during acceleration events on the hybrid. An oil-filled and leaking charged air cooler line was repaired, but upon testing and verifying this repair a new noise was heard, which was ultimately diagnosed as a blown exhaust manifold gasket. This repair was very extensive and involved dismantling much of the front fascia of the bus, including some interior components such as the driver’s seat and accelerator pedal, just to gain access to the exhaust manifold. Upon successful completion of the update to the new manifold, another test was run and the vehicle no longer made any extraneous noise. However, an additional problem required attention when excessive shaft play in the vehicle turbo was discovered. The center turbo section was replaced and all charged air components were cleaned and reassembled.

4.5 Preventative maintenance

4.5.1 Tire Wear

Both the hybrid and E-450 demonstrated more rapid tire wear on the rear sets of wheels than on the front set. This could be due to interference from the regenerative braking system on the hybrid and non-equalized weight distribution on either vehicle. In Table 4-5 and Table 4-6 below replacement events are bolded—indicating an increase in tread depth measurement and therefore newer tire.

Table 4-5: Hybrid tire tread depth measurements (1/32 in.)

PM Date	RF[1]	LF	RRO	RRI	LRI	LRO
6/26/2013	**15**	**15**	14	14	14	14
7/19/2013	11	11	**15**	**15**	**15**	**14**
9/6/2013	11	11	12	11	10	12
10/3/2013	8	9	7	4	4	5
11/7/2013	7	6	**12**	**13**	**13**	**13**
12/27/2013	6	4	14	12	12	12

[1]RF = right-front, LF = left-front, RRO = right-rear, outside, RRI = right-rear, inside, LRI = left-rear, inside, LRO = left-rear, outside

This replacement trend on the hybrid was very pronounced; there were no front-tire replacements throughout the six months of testing. The replacement bolded on June 26th, 2013 technically occurred before the demonstration period began. The next front-tire replacement did not occur until early January 2014, in comparison there were two rear-tire replacements during this time period, highlighting the rapidity of rear tire wear on vehicles of this size.

Table 4-6: Ford E-450 tire tread depth measurements (1/32 in.)

PM Date	RF	LF	RRO	RRI	LRI	LRO
7/9/2013	10	10	10	10	10	9
7/30/2013	7	8	7	7	8	7
8/14/2013	6	6	**11**	**11**	**11**	**10**
9/7/2013	**12**	**12**	7	6	7	6
10/3/2013	11	10	5	7	6	4
10/30/2013	9	9	**12**	**12**	**12**	**12**
11/20/2013	8	7	7	8	8	8
12/10/2013	**10**	**11**	8	9	8	7

[1]RF = right-front, LF = left-front, RRO = right-rear, outside, RRI = right-rear, inside, LRI = left-rear, inside, LRO = left-rear, outside

On the E-450 there were four replacement events overall, two rear-tire only replacements and two front-tire only replacements. The duration between front-tire replacements was a full month longer than for the rear tires, echoing the same trend seen on the hybrid. Since the tire specification is different between these two vehicles, a direct comparison is not valid, but we do see that hybrid tire wear is similar to the E-450 and thus a majority of the other fleet vehicles.

4.5.2 Brake Linings

The brake lining measurements listed on the PM forms and reproduced below were meant to demonstrate the lack of distinction between front and rear usage. Hybrid and E-450 measurements at each vehicle PM are given in Table 4-7 and Table 4-8.

Table 4-7: Hybrid brake lining measurement (mm)

PM Date	RF	LF	RR	LR
6/26/2013	14	14	14	14
7/19/2013	16	16	16	16
9/6/2013	14	14	13	13
10/3/2013	13	13	11	12
11/7/2013	12	12	11	11
12/27/2013	12	11	12	12

Table 4-8: Ford E-450 brake lining measurement (mm)

PM Date	RF	LF	RR	LR
7/9/2013	12	12	12	12
7/30/2013	8	8	8	8
8/14/2013	10	10	8	8
9/7/2013	8	8	6	6
10/3/2013	6	6	3	3
10/30/2013	10	10	10	10
11/20/2013	8	8	7 1/2	7 1/2
12/10/2013	8	8	5	5

All vehicle brakes appear to wear at approximately the same rate, which is generally 1-2 mm per month for the hybrid and 2-4 mm per month for the E-450. It appears that new hybrid brake linings are at most 16 mm thick whereas new E-450 brake linings are at most 12 mm thick. Clearly seen in Table 4-8 is the effect of the brake replacement reported on October 9th, which increased the brake lining from 6 mm (front) and 3 mm (rear) to 10 mm at all four corners in the PM measurement taken on October 30th.

4.6 Vehicle Uptime

There was not a specific plan of usage for these vehicles, other than the limited route assignment of the hybrid due to contractual stipulations from funding partners. The calculations of uptime that follow in this section assume that, seven days a week, if a vehicle were available, it was used. For example, given the holidays in December it is possible that the vehicles were never intended to be used every day, yet for this calculation the number of days with data was divided by 31 to obtain an “uptime” of 74%. Therefore the values listed in Table 4-9 are somewhat lower than what the actual uptime may have been.

Table 4-9: Monthly uptime

Month	Hybrid	E-450
Jul	81%	90%
Aug	55%	77%
Sep	47%	73%
Oct	61%	94%
Nov	27%	80%
Dec	61%	74%
Average	**55%**	**81%**

Most notably the E-450 was capable of achieving very high uptime percentages in a few months, whereas the E-450 had many months where uptime fell to 60% or below, with one extreme case in November. This is visually displayed in Figure 4-1 below.

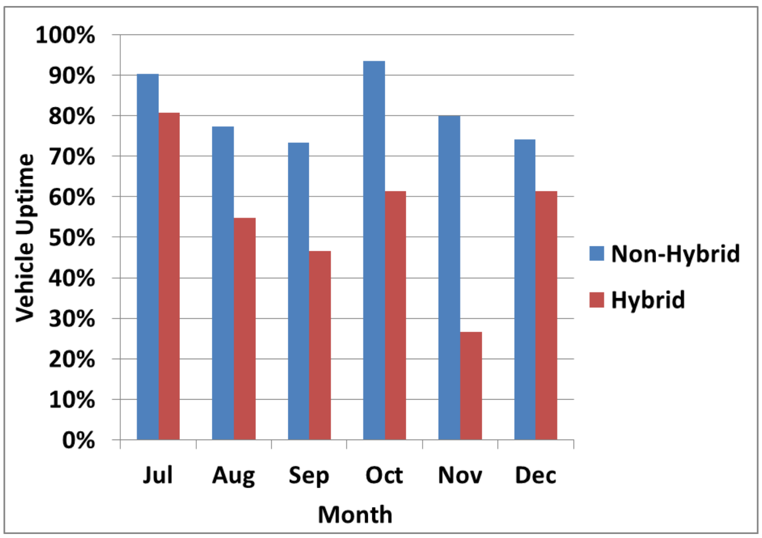

Figure 4-1: Vehicle uptime by month

The first month of the demonstration period was the only one in which hybrid uptime was above 80%, which is indicative of some of the bigger hybrid system-related issues that kept the vehicle out of service over the following months. The propulsion system service event described in Section 4.4 was primarily responsible for the exceedingly low hybrid uptime in November. The lead time on parts and labor forced the bus out of service for a few weeks, while the actual labor itself might have been completed in a few days.

5. DRIVER AND MANAGER FEEDBACK

Drivers and maintenance technicians interact directly with the vehicles, and often have input that would not otherwise be reflected in the above analyses. We use surveys and interviews to capture these experiences, and include it here to provide more insight into how the vehicles performed during the demonstration.

To obtain user acceptance data, three different groups of individuals were targeted with different survey questions and query types. Drivers who operated the hybrid bus were asked to fill out a hard-copy survey at the beginning and upon completion of the demonstration period. This survey (shown in Appendix A) focused on collecting route details, perception of vehicle performance, and possible problem areas associated with the hybrid system. As with many surveys it also allowed drivers to provide suggestions and comments regarding the vehicle.

The maintenance manager was interviewed in person using a similar questionnaire that highlighted his perception of the vehicle performance while providing a ranking of maintenance metrics such as reliability, safety, and design for serviceability. This interview was conducted at the middle and end of the demonstration period to look for any improvement or decay of bus components. The maintenance manager survey is replicated in Appendix B.

The fleet manager was interviewed in person at the end of the demonstration and asked to complete certain sections of the maintenance questionnaire as well. This interview was focused on obtaining a high-level view of how the vehicles fit into the fleet from an operational perspective. Since the hybrids were introduced to the fleet just before the demonstration period began, it seemed appropriate to conduct this interview only at the end once more data and stronger opinions were developed. The fleet manager survey is replicated in Appendix C.

The fleet manager interview was completed by Michael Hernandez, Assistant General Manager/Chief Operating Officer at MST and the maintenance manager interview was completed by Don Parslow, Fleet Manager at MV Transportation. Due to the construction of this study, and for the purpose of this report, Mr. Hernandez is referred to as the “fleet manager” and Mr. Parslow is referred to as the “maintenance manager”.

5.1 Driver Survey Results

Driver surveys were aimed at establishing performance and operational ratings, along with any additional thoughts regarding the hybrid system that differentiate it from a conventional bus. Due to the subjective nature of driver impressions, a simple, relative rating scheme of “better”, “same” or “worse” was used to compare hybrid truck performance characteristics to those of a conventional shuttle bus. MV was responsible for distributing, coordinating, and collecting completed driver forms. Surveys were distributed via the fleet manager at the middle and end of the demonstration period to as many drivers as possible.

Vehicle Performance

There were six performance metrics to compare to a conventional shuttle bus that drivers ranked on a scale from “*Much Worse*” to “*Much Better*”:

1. **Initial Launch from Standstill**: A major advantage of the hybrid system is in the boost provided from start-up when the engine is most inefficient. This metric aims to capture drivers' perceptions of the effectiveness of the launch with the hybrid system engaged.
2. **Maneuverability at Slow Speeds**: Since most routes travel through neighborhoods it is important to gauge the agility of the vehicle at realistic speeds.
3. **Acceleration**: Comparable to the initial launch, this metric refers to acceleration throughout the power band to gauge boost effectiveness at all speeds.
4. **Coasting/Deceleration**: The hybrid system recharges in certain coasting and all deceleration situations, providing the equivalent of an engine retarder on the vehicle. This metric aims to obtain driver perception on the effectiveness and feel of this new form of coasting in the hybrid.
5. **Overall Braking Behavior**: This metric captures overall braking performance by incorporating brake feel as well as the effectiveness of the new coasting and regenerative braking scheme.
6. **Productivity**: The degree to which the hybridized the system improved the overall speed and service of the bus or slowed things down.

Results from the final round of surveys are shown in Figure 5-1 below and display the combined ratings of all 5 drivers surveyed and indicate their thorough perceptions after significant experience with the vehicle.

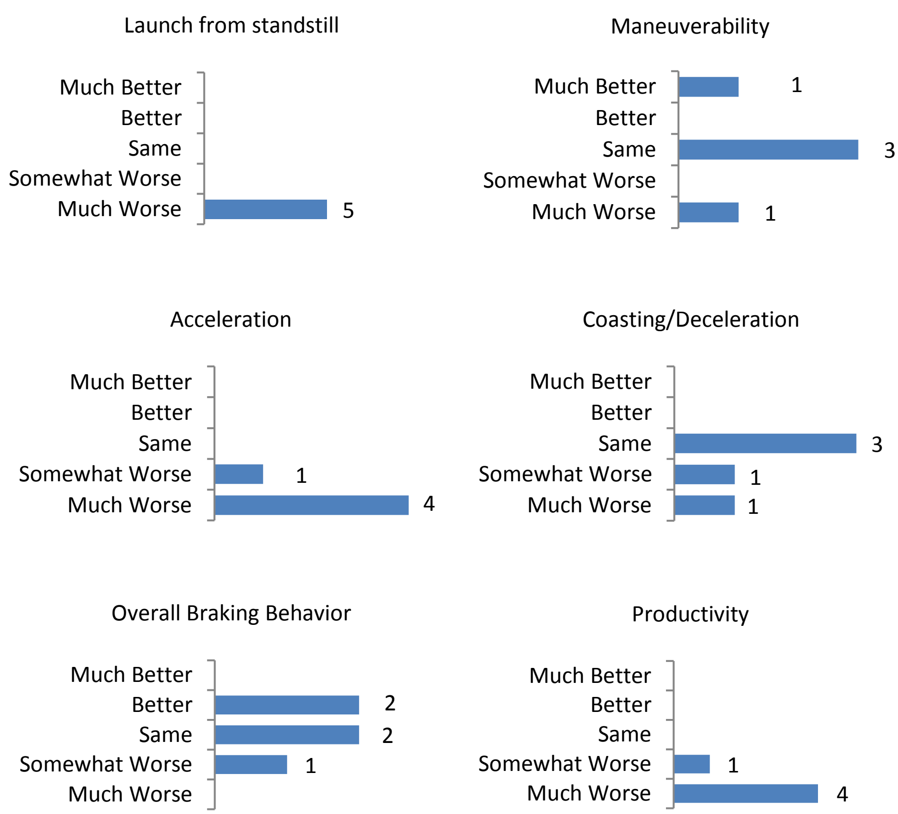

Figure 5-1: Final hybrid performance survey ratings

The ratings depicted in Figure 5-1 above show final perceptions from five hybrid drivers, all of whom had significant experience with the vehicle. Two major issues with this ratings system were that the fleet does not have a conventional vehicle in the same form factor as the hybrid, and most drivers had never professionally driven a diesel powertrain vehicle. The E-450 instrumented in this test is smaller than the hybrid and gasoline-powered, the 40-foot city buses are diesel but a completely different architecture, and the diesel-powered city trolleys are used on totally different routes than the majority of hybrid route assignments. The performance differences between commercial gasoline and diesel-powered vehicles are noticeable and drivers' experiences with the former did not fully prepare them for six months of operation on the latter. At the final round of surveys, the only two categories that rated the same as a comparable vehicle were vehicle maneuverability and overall braking.

We investigated how the driver responses changed from the beginning to the end of the demonstration period. Assigning a quantitative scale from 1 to 5 for "Much Worse" to "Much Better," the average ratings of all driver responses were calculated at each survey event. These trends are shown below in Figure 5-2, where the averaged response to each question is shown for the initial and final surveys.

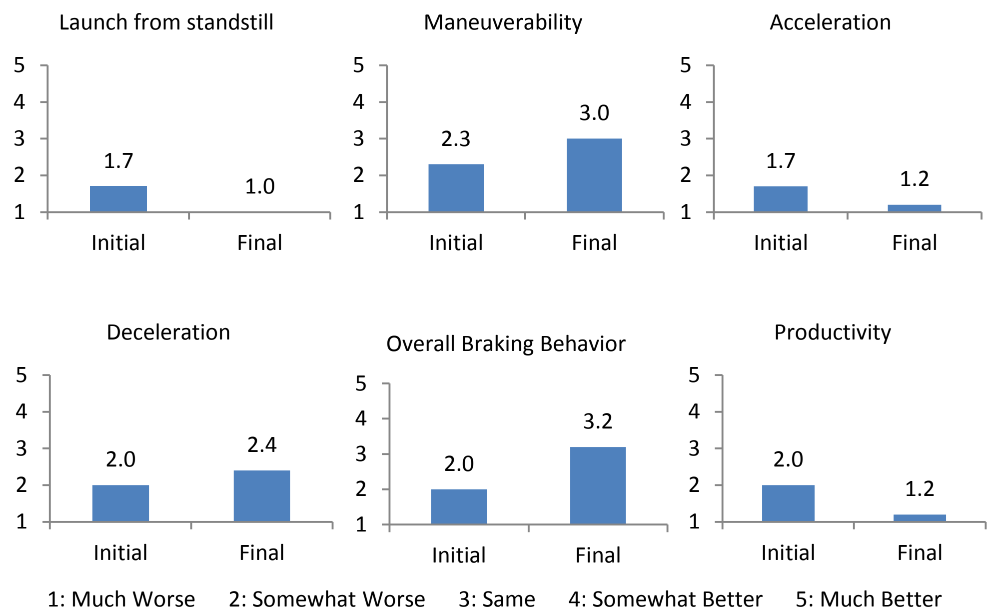

Figure 5-2: Hybrid performance survey historical trends

Driver impressions of the hybrid vehicle diminished over time, as shown in Figure 5-2 above. The slow-speed driving and slowing-down, either specifically from the regenerative braking (coasting/deceleration) or overall braking behavior, actually improved from the beginning of the demonstration period. This could be due to drivers becoming more familiar with these hybrid-specific characteristics, or an increase in slower-speed route assignments.

Operation Metrics

In addition to these performance metrics, drivers rated the vehicles based on their experience with vehicle operation, including:

1. **Cold Start:** This refers to the ability for the vehicle to successfully turn-over for the first time each morning. In some climates extreme cold makes cranking difficult, this metric captures the hardiness of the vehicle.
2. **Reliability:** As new vehicles with advanced systems the reliability rating is imperative to understanding how frequently the buses needed servicing, as well as the fit and finish of interior and exterior componentry.
3. **Inside Noise Level:** This is perceived both by passengers and bus drivers, and can differ dramatically from conventional vehicles.
4. **Outside Noise Level:** Pedestrians and other drivers often make comments to the transit agency regarding elevated noise levels; these may be from the hybrid system itself or from poor integration of the hybrid with standard vehicle systems.
5. **In-Cab Ergonomics:** Since drivers were filling out these surveys, the ergonomics relates most specifically to their cab-space. However some may have responded regarding with the ergonomics of the interior body space in mind as well.

Results from the final operational surveys are displayed in Figure 5-3 below and indicate drivers' thorough perceptions after significant experience with the vehicle.

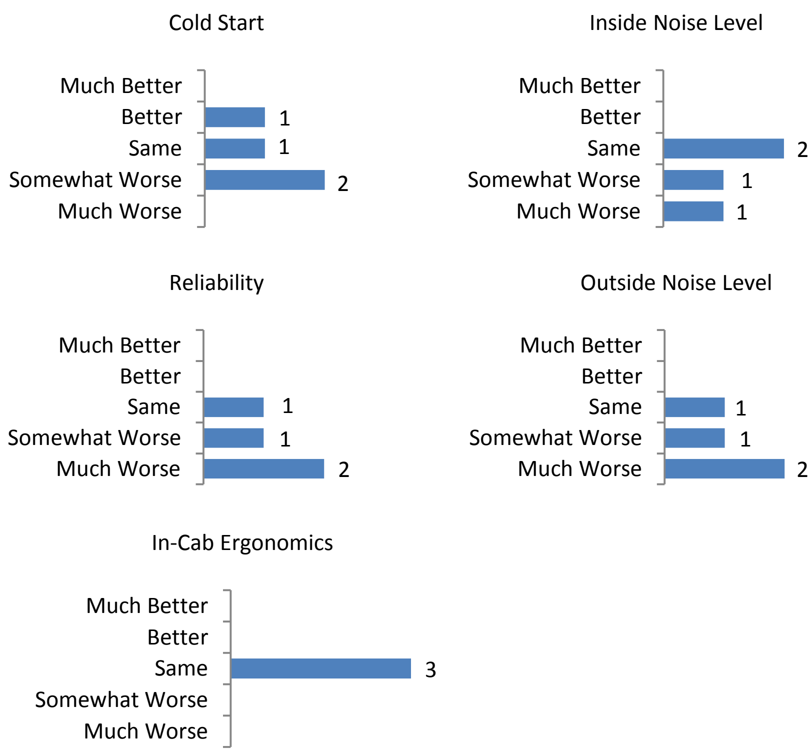

Figure 5-3: Final hybrid operational survey ratings

These operational ratings somewhat mimic their performance counterparts in that drivers provided neutral-to-negative feedback for most metrics. The diesel engine and turbo were noticeably louder than any gasoline counterpart, while the fit and finish of the International chassis was subpar. Numerous complaints from passengers about elevated noise levels, both inside and outside the vehicle as well as diminished reliability from multiple major service events also contributed to the poor ratings.

To analyze any potential trends in the mean rankings from the beginning to the end of the test period, the qualitative scale of "*Much Worse*" to "*Much Better*" was quantified from 1 to 5. The average ratings of all driver responses were calculated at each survey event for all five operational metrics and are displayed below in Figure 5-4 for the initial and final surveys.

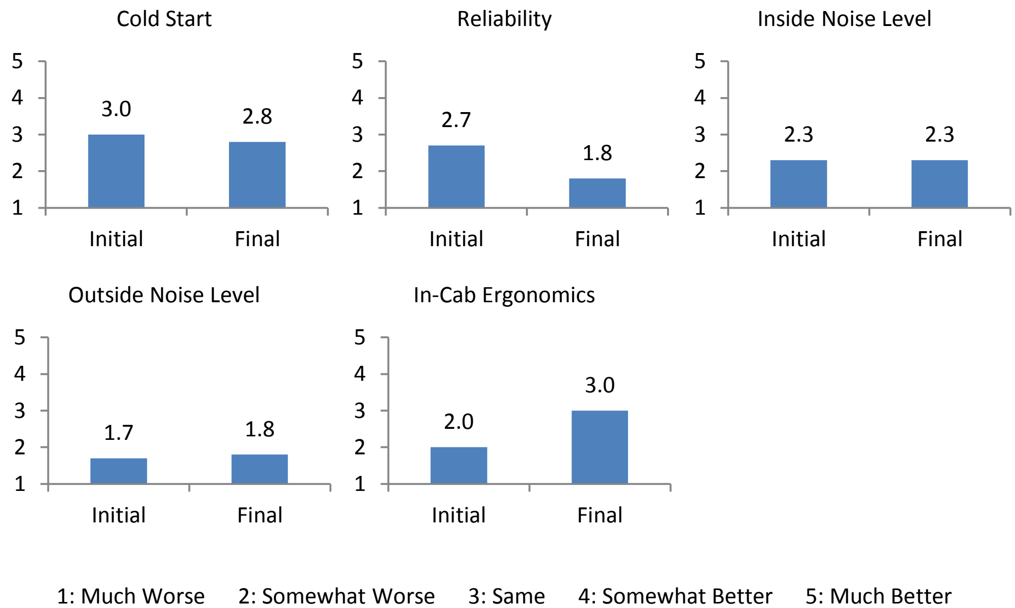

Figure 5-4: Hybrid operational survey historical trends

As shown in Figure 5-4 only the in-cab ergonomics of the hybrid even rated the same as a comparable conventional vehicle, all other operational metrics remained below this threshold throughout the demonstration period. Noise level ratings remained roughly the same, whereas ratings for reliability decreased by 33%. This is most likely due to nagging build quality issues and major repairs that took the vehicle out of service for extended periods of time. Drivers are highly in-tune with vehicle problems that affect proper functionality and passenger comfort, underscoring the importance of this reliability rating.

5.2 Maintenance Manager Interviews

Interviews were conducted in person at the end of the demonstration period and were always done after completing the maintenance manager evaluation survey. In order to evaluate the serviceability and maintainability of the hybrid, the maintenance manager was asked to provide feedback on various service and maintenance aspects, generally comparing to a similar conventional vehicle. Interviews were roughly 15 to 20 minutes in length and provided an opportunity for interviewees to relay any suggestions or comments related to the vehicle.

The maintenance manager listed a variety of issues observed during the demonstration period, some of which were repaired in-house, others corrected by the Peterson-CAT dealer in San Martin, CA and a few which remained outstanding. In the former category: a fan belt was re-routed, the "Stop-Request" switch was properly installed, hybrid air filters were replaced more frequently and aftermarket brake drums from a different manufacturer were installed . These brake drums replaced inferior models that were part of the original hybrid specification because they were prematurely cracking. The hybrid battery system air filters were fully clogged and being replaced every 5,000 miles, when the dealer specification is every 4 months (approx. 20,000 miles). This is a particularly vexing issue because a clogged air filter causes the battery system to overheat and shut down prematurely to protect itself. An engine clutch issue was first repaired by the Peterson-CAT dealer who then explained to MV how to institute the fix on the other three fleet hybrids. Similarly, an electrical wiring issue on the hybrid would not allow the passenger step to deploy until the vehicle doors were fully open, creating a trip hazard. This was remedied by the bus manufacturer on-site in Salinas who provided the wiring diagram to MV for use on the other three hybrids. Additional repairs performed by the Peterson-Cat dealer included a damaged speed sensor, injection pump and turbo failure. The maintenance manager highlighted the great expense that could come in maintaining these vehicles once they are out of warranty.

Of the issues that remain outstanding, perhaps the most worrisome occurs when downshifting into 2nd gear. Drivers experience a “clunk” that presents as if something ran into the back of the bus. This was an early road test discovery and is generally due to the different gearing inherent in a diesel vehicle, when compared to a gasoline-powered one. While this is not a maintenance-related issue, the manager noted that it is still quite dangerous for drivers and passengers that are not expecting it. Other than an incorrect vehicle decal and the aforementioned inferior brake drums—the cause of which have not been determined—the only major difficulty was hybrid training.

The manager explained that the ideal hybrid training would incorporate five specific arenas, which would provide MV with the knowhow and resources to service the hybrids with the same capabilities as the Peterson-CAT dealership. These categories were:

- Theory of Operation
- Diagnostic Flowcharts
- Specifications
- Electronic Scan
- Parts Supply

All shop personnel should have a good understanding of how the hybrid system works and details on individual components. This would help alleviate some of the managers’ current concerns regarding hard-to-read component labels and a counterintuitive, overcrowded system layout. The flowcharts and electronic scan capability help to diagnose specific issues and provide clear guidelines for repairs. The parts supply network diminishes long lead times and is key in getting vehicles back into service.

5.3 Fleet Manager Interviews

In the same vein as the maintenance manager interview, this discussion with the MST fleet manager began with a vehicle questionnaire focusing on driver acceptance, safety, reliability, overall maintenance issues, and perceived fuel economy improvement. In looking at driver acceptance, maintenance issues, and fuel consumption improvement, the fleet manager essentially summarized the information received from drivers, mechanics, and MV personnel, respectively. Adding safety and reliability to the list speaks to the manager’s capability of comparing the hybrid vehicle to the rest of the fleet.

The fleet manager spoke mainly to the overall acceptance of the hybrids and any weaknesses that needed to be remedied for extended integration. Based on the numerous fit and finish problems, he felt that the quality control on the build process was totally “unsatisfactory for a two-hundred thousand dollar vehicle, with more sloppy workmanship than both larger and smaller vehicles." The manager was also quite worried about the out-of-warranty that might need to be done in the future, and therefore requested as much information as possible about the service work that was done at the Peterson-CAT dealership.

Some of the service issues that arose with the hybrids affected the safety of the vehicles, including the rapid tire and brake drum wear, passenger step deployment lag, and easily-clogged hybrid battery air filter. The manager explained how these issues, along with adding to the expense per mile, alter the image of the vehicle, particularly when a malfunctioning component takes an entire subsystem offline, as was the case with the clogged hybrid battery air filter. Improvements to the vehicle could be made in a quieter, more powerful engine that is better sized for the length of the chassis. Higher build quality would help with reliability on a vehicle that does suit some routes very well, particularly the ones where larger (40-foot) buses bother community members. Finally, the fleet manager mentioned that the 40-foot buses tend to get approximately 5 miles per gallon, and he would hope that the hybrids would be a significant improvement over that statistic.

5.4 Lessons Learned

The hybrid fared poorly in evaluations from drivers, the maintenance manager, and the fleet manager. Of the 11 metrics evaluated in driver surveys drivers rated the hybrid vehicle worse than the E-450 in 10 of the metrics. Further, for the majority of these metrics, the drivers' perceptions did not change or degraded over the six month period.

It's clear there is room here for further driver training and familiarization so they can get the most from the hybrid vehicle. Maintenance time and costs can be improved if additional skills were transferred from the dealership to the MV staff; this investment should be considered depending on MST's future plans for expanding their hybrid fleet. Proper training for both groups would increase efficient driving and serviceability of the vehicle, improving overall acceptance and integration into the fleet.

Improving the perception of the vehicle is also important to the fleet and could be accomplished by upgrading individual components that are currently being replaced far too frequently, namely the brake drums and battery system air filters. Another tool for improving perception could be placing an explanatory placard on the inside and outside of the vehicle to alert users of the increased noise level from the diesel-hybrid propulsion system, which could theoretically lessen the shock for all parties.

6. SUMMARY AND CONCLUSION

This project quantified the fuel economy of a diesel hybrid medium bus in a municipal transit fleet. Two test vehicles, the hybrid and Ford E-450, were instrumented and tested in real-world service for MST. In addition to the hybrid fuel economy study, E-450 telemetry data were analyzed to create a comprehensive route analysis of the MST system. Finally, drivers, maintenance, and fleet managers were interviewed at different points in the project to establish user acceptance data and gauge opinions on the hybrid vehicle. The following are high-level findings of the project:

- Ultimately, Route 1 and Route 24 gave similar fuel economy values, 7.2MPG (miles per gallon of diesel) though the stops per mile and average driving speeds were vastly different between the two routes.
- The inverse-root relationship shown between stops per mile and average driving speed indicated that Route 3 and Route 22 are good fits to produce similar fuel economy results. Other routes would possibly provide worse fuel economy.
- The more urban routes spend a greater percentage of their idling on longer-duration events, perhaps a result of the necessity for vehicle comfort systems tied to higher ridership.
- Tires and PM costs were among the three greatest expenses on both vehicles.
- Suspected build-quality issues during manufacturing, seen both during service events and echoed by the fleet manager, was partially responsible for the below-average reputation of the hybrid.
- The E-450 shuttle bus was five years old but the hybrid was only one year old; many of the problems experienced in the E-450 had more to do with wear-and-tear than inherent design flaws, whereas the hybrid experienced a handful of design-related issues.
- Differences between diesel and gasoline propulsion systems limited drivers’ ability to get comfortable with the hybrid buses, and the driver opinions of hybrid bus performance degraded over time in some metrics.
- The increased noise level from the diesel-hybrid propulsion system needs to be explained to drivers and the public, possibly through a highly-visible explanatory placard located in the vehicle.

7. APPENDICES

Appendix A: Driver Survey

Appendix B: Maintenance Manager Questionnaire

Appendix C: Fleet Manager Questionnaire

7.1 Appendix A: Driver Survey

CALSTART Hybrid Electric Bus Evaluation Project

Bus Driver Operation Evaluation Survey

As part of the hybrid electric shuttle bus (HEB) deployment and testing period we would like to hear your input and evaluation of the HEB. It will help us evaluate the performance of the HEB and identify areas that need improvement. Please take 15 minutes to provide your evaluation of the HEB by answering the following questions. For each question check the box that best fits your rating.

We appreciate your time and assistance with this evaluation. If you have any questions about the content of this survey, please contact Ted Bloch-Rubin at (626) 744-5655 or at tbloch-rubin@calstart.org .

First Name: ____________________

Last Name: ____________________

Work schedule (days, hours): ____________________

Today's Date: ___________________

Please provide a brief description of the route the HEB is operating on:

Average miles / Number of stops / Hours of operation / Type of customers / Traffic / Other

____

____

____

____

____

____

Please provide an overall rating for the driver training:

Very poor	Poor	Good	Very good	Excellent
☐	☐	☐	☐	☐

Comments on the driver training:

____

____

____

____

____

CALSTART Hybrid Electric Bus Evaluation Project

Performance

Property of the HEB compared to a similar conventional bus	Much worse	Somewhat worse	Same	Better	Much better
Initial launch from stand still	☐	☐	☐	☐	☐
Maneuverability at slow speeds	☐	☐	☐	☐	☐
Acceleration	☐	☐	☐	☐	☐
Coasting / Deceleration	☐	☐	☐	☐	☐
Overall braking behavior	☐	☐	☐	☐	☐
Productivity (able to cover routes quicker)	☐	☐	☐	☐	☐

Operation

Property of the HEB compared to a similar conventional truck	Much worse	Somewhat worse	Same	Better	Much better
Cold Start	☐	☐	☐	☐	☐
Reliability	☐	☐	☐	☐	☐
Inside noise level	☐	☐	☐	☐	☐
Outside noise level	☐	☐	☐	☐	☐
In-cab ergonomics (driver interface / if applicable)	☐	☐	☐	☐	☐

CALSTART

CALSTART Hybrid Electric Bus Evaluation Project

Questions

Did you have any customer complaints related to the hybrid system (noise, vibrations, uncomfortable ride…)?

If yes, please explain:____

____

____

____

____

Did you have any issues at low speed (noise, vibrations, system unresponsive…)?

If yes, please explain:____

____

____

____

____

Did you have any issues with the regenerative braking?

If yes, please explain:____

____

____

____

____

Please provide an overall rating of the HEB.

Very poor	Poor	Good	Very good	Excellent
☐	☐	☐	☐	☐

CALSTART Hybrid Electric Bus Evaluation Project

Suggestions and Comments

Please provide suggestions or recommendations of performance areas that need improvement in the HEB.

Please share any additional comments you have concerning the HEB.

(Thank you for your participation!)

7.2 Appendix B: Maintenance Manager Questionnaire

CALSTART Hybrid Electric Bus Evaluation Project

Maintenance Technician Evaluation Survey

As part of the hybrid electric shuttle bus (HEB) deployment and testing period we would like to hear your input and evaluation of the HEB. It will help us evaluate the performance of the HEB and identify areas that need improvement. Please take 10 minutes to provide your evaluation of the HEB by answering the following questions. For each question check the box that best fits your rating.

We appreciate your time and assistance with this evaluation. If you have any questions about the content of this survey, please contact Ted Bloch-Rubin at (626) 744-5655 or at tbloch-rubin@calstart.org.

First Name: ___________________

Last Name: ___________________

Work schedule (days, hours): ___________________

Today's Date: __________________

Performance

Property of the HEB compared to a similar conventional bus	Much worse	Somewhat worse	Same	Better	Much better
Initial launch from stand still	☐	☐	☐	☐	☐
Maneuverability at slow speeds	☐	☐	☐	☐	☐
Acceleration	☐	☐	☐	☐	☐
Coasting / Deceleration	☐	☐	☐	☐	☐
Overall braking behavior	☐	☐	☐	☐	☐
Productivity (able to cover routes quicker)	☐	☐	☐	☐	☐

CALSTART Hybrid Electric Bus Evaluation Project

Operation

Property of the HEB compared to a similar conventional truck	**Much worse**	**Somewhat worse**	**Same**	**Better**	**Much better**
Cold Start	☐	☐	☐	☐	☐
Reliability	☐	☐	☐	☐	☐
Inside noise level	☐	☐	☐	☐	☐
Outside noise level	☐	☐	☐	☐	☐
In-cab ergonomics (driver interface if applicable)	☐	☐	☐	☐	☐

Describe any HEB problems observed during the early part of the demonstration period that were subsequently corrected by the manufacturer:

Maintenance

Please rate the following issues related to HEB maintenance on a scale of 1 to 5, where 1 means unacceptable and 5 means excellent (circle the appropriate number):

	Unacceptable				*Excellent*
❖ Hybrid system and component training:	1	2	3	4	5
❖ Design for Maintainability:	1	2	3	4	5
❖ Design for Serviceability:	1	2	3	4	5
❖ Overall frequency of HEB related problems:	1	2	3	4	5
❖ Ease of repair of HEB related problems:	1	2	3	4	5
❖ HEB system manufacturer support:	1	2	3	4	5

CALSTART Hybrid Electric Bus Evaluation Project

Please provide an overall rating of the HEB.

Very poor	Poor	Good	Very good	Excellent
☐	☐	☐	☐	☐

Suggestions and Comments

Please provide suggestions or recommendations of performance areas that need improvement in the HEB.

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Please share any additional comments you have concerning the HEB.

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(Thank you for your participation!)

7.3 Appendix C: Fleet Manager Questionnaire

CALSTART Hybrid Electric Bus Evaluation Project

Fleet Manager Evaluation Survey

As part of the hybrid electric shuttle bus (HEB) deployment and testing period we would like to hear your input and evaluation of the HEB. It will help us evaluate the performance of the HEB and identify areas that need improvement. Please take 10 minutes to provide your evaluation of the HEB by answering the following questions. For each question check the box that best fits your rating.

We appreciate your time and assistance with this evaluation. If you have any questions about the content of this survey, please contact Ted Bloch-Rubin at (626) 744-5655 or at tbloch-rubin@calstart.org.

First Name: ____________________

Last Name: ____________________

Work schedule (days, hours): ____________________

Today's Date: ___________________

General performance:

Property of the HEB compared to a similar conventional bus	Much worse	Somewhat worse	Same	Better	Much better
Driver Acceptance	☐	☐	☐	☐	☐
Safety	☐	☐	☐	☐	☐
Reliability	☐	☐	☐	☐	☐
Maintenance Issues	☐	☐	☐	☐	☐
Fuel Consumption Improvement	☐	☐	☐	☐	☐

Please provide an overall rating of the HEB:

Very poor	Poor	Good	Very good	Excellent
☐	☐	☐	☐	☐

CALSTART Hybrid Electric Bus Evaluation Project

Suggestions and Comments:

Please provide suggestions or recommendations of performance areas that need improvement in the HEB.

Please share any additional comments you have concerning the HEB.

(Thank you for your participation!)