Hybrid Shuttle Bus Testing and Demonstration: ARBOC "Spirit of Mobility"

September 3, 2014

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EXECUTIVE SUMMARY

This report presents the evaluation of two ARBOC Specialty Vehicles "Spirit of Mobility" gasoline hybrid shuttle buses in revenue service for a municipal fleet (City of Tracy, California) over six months. Each bus, built on a GMC 4500 chassis, was outfitted with an ultracapacitor hybrid system which provides boost during acceleration events while recapturing energy during braking events. A baseline was established by disengaging the system on one of the buses throughout the duration of the test. The two vehicles traveled a total of 31,900 miles, consumed 5,070 gallons of fuel during 2,878 hours of operation and carried an estimated 42,000 passengers.

The hybrid bus was evaluated using several metrics: total fuel economy (MPG), reliability and maintenance costs, and operator and manager surveys. In addition, the effect of different routes and drivers was evaluated. The emissions from the hybrid and the baseline were evaluated during a two-day on-road emissions test, which measured the criteria pollutant emissions and fuel economy.

Fuel Economy Results

Over the course of the demonstration, the hybrid bus operated at 6.62 MPG averaged over two routes, 13.2% greater than the non-hybrid, which operated at an average of 5.85 MPG. During the first month of the test, in which driver training was freshest and the weather was cooler (less demand for A/C), the hybrid operated at 8.34 MPG, an improvement of 28.1% over the non-hybrid performance in the same month. The hybrid reduced fuel consumption and emissions as well, results are highlighted in Table ES-1 below.

Table ES-1: Fuel and Carbon Dioxide Savings from the Hybrid During the 6-mo Demonstration

Parameter	Value
Vehicle-miles traveled (mi)	17,467
Fuel consumed (gallons)	2,566
Fuel avoided (gallons)[a]	2,942
Total fuel saved (gallons)	375
CO_2 saved (lbs.)	7,371

[a] The amount of fuel that *would have been* used if the vehicle were a non-hybrid

Over the six months of operation, the hybrid vehicle traveled 17,467 miles when in revenue service on Routes A and B and consumed 2,566 gallons. However, if the hybrid had been replaced by a non-hybrid it would have consumed 2,942 gallons. In total, the hybrid vehicle saved 375 gallons and eliminated 7,371 lbs. of CO2 during the demonstration period.

Fuel economy was also evaluated during an on-road emissions test through a carbon balance calculation. The hybrid fuel economy was higher on the two-day test, both in terms of absolute MPG and also percent improvement over the non-hybrid. Fuel economy results for the two-day emissions test are shown in Table ES-2.

Table ES-2: Fuel Economy Results From Fuel Economy and Emissions Test

	Route A	Route B	Combined
Hybrid Fuel Economy (MPG)	8.68	7.26	7.97
Non-Hybrid Fuel Economy (MPG)	6.97	6.15	6.56
% Improvement	24.5%	18.0%	21.4%

Over the duration of the on-road emissions test, combined over both routes, the non-hybrid vehicle operated at 6.56 MPG while the hybrid vehicle operated at 7.97 MPG, an improvement of 21.4%. Performance varied by route, with higher fuel economy and greater percentage improvement seen on Route A than on Route B.

Fuel economy results were higher in the two-day test than in the six-month demonstration. This differential can be partially explained by the more controlled environment during the two-day test, with no A/C load and nearly half the amount of idling as in the six-month demonstration. The performance of the hybrid in the two-day test closely mirrored the results from the first month of testing, in which drivers had just received an on-road training session and lower temperatures decreased the A/C load. These results indicate that higher fuel economy and hybrid benefits are achievable if the vehicles are driven with a focus on efficiency.

Criteria Pollutant Emissions

As part of the emissions test, the tailpipe pollutants were quantified for each vehicle. Table ES- 3 below summarizes the emissions measurements in grams per mile (g/mi) by vehicle and route. Emissions were quantified for Nitrogen Oxides (NOx) and Carbon Monoxide (CO). Both Particulate Matter (PM) and Hydrocarbons (HC) were found to be below detectable limits.

Table ES- 3: Criteria Pollutant Emissions[a] (g/mi)

	Route A		Route B		Combined	
Bus	NOx	CO	NOx	CO	NOx	CO
Hybrid	0.29	2.09	0.24	2.25	0.27	2.17
Non-hybrid	0.35	1.93	0.27	0.97	0.31	1.45
% change	*-18%*	*8%*	*-12%*	*133%*	*-15%*	*50%*

[a] PM and HC found to be below detectable limits.

The hybrid vehicle proved effective in reducing NOx emissions with a reduction of 15% compared to the baseline, while the CO increased 50% compared to the baseline. The additional CO emissions were due to a small number of emission spikes, likely occurring during especially abrupt acceleration events or similar actions. As expected for a model year 2012 gasoline vehicle, the PM and HC emissions were below detectible limits in both the hybrid and non-hybrid buses.

Maintenance and Reliability

Data on maintenance and reliability were supplied by the City of Tracy maintenance contractors. We combined the maintenance work done on the hybrid and non-hybrid vehicles, since both are the same model of bus for a single analysis of maintenance costs. In total, both shuttle buses required $6,830 in maintenance and repairs over the demonstration period, which is equal to $0.16 per mile. The three greatest expenses were in the propulsion system, tires, and periodic maintenance costs.

Over the life of the demonstration, we encountered two issues with the hybrid drive system. On the hybrid vehicle, an audio alarm on the bus malfunctioned and would not turn off, requiring a new electrical harness. On the baseline non-hybrid vehicle, even though the hybrid system was disengaged, it was damaged due to a defective bearing-and-cup assembly in the hybrid motor when traveling on the freeway.

On average, the vehicles achieved 77% availability during the life of the test: 60% in the non-hybrid and 93% for the hybrid. This value was lower than anticipated due to an extended out-of-service event for the non-hybrid vehicle. Excluding the availability ratings in June and July during which major maintenance events kept the vehicles out of service, the vehicles achieved a combined 86% availability. This highlights their relatively good six-month availability but susceptibility to extended absences from the fleet.

During the demonstration, the hybrid system manufacturer worked with the municipality to upgrade the hybrid drive motor and controller with new technology they had developed. The upgrades improved torque from the system and extended the system life. Tracy also purchased an extended warranty for the hybrid systems, extending it 18 months from the date of purchase.

Driver and manager feedback

The vehicle operators and managers provided feedback on their experiences throughout the demonstration period. Drivers completed surveys at the beginning, middle, and end of the demonstration, in which they compared the hybrid vehicle to the baseline vehicle in terms of 11 performance metrics. The final driver scores are shown below in Table ES-4.

Table ES-4: Driver Survey Scores at End of Demonstration

Performance Metrics		Operational Metrics	
Metric	Score	Metric	Score
Launch from standstill	3.8	Cold start	4.0
Maneuverability	4.0	Inside noise level	4.0
Acceleration	3.6	Reliability	3.2
Deceleration	4.0	Outside noise level	3.6
Overall braking behavior	4.0	In-cab ergonomics	4.0
Productivity	3.6		

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

The hybrid was rated "same" or "better than" the non-hybrid across all metrics. For nine out of 11 metrics, the drivers rated the hybrid better in the middle than the beginning, and at the end compared to the middle, indicating that they grew to appreciate the benefits of the hybrid more as they became more used to operating it.

1. INTRODUCTION

Nationwide, greenhouse gases are becoming a prominent concern, both among the public and within regulatory agencies. At the local, state and federal levels, businesses and public agencies are seeking a better understanding of the sources of greenhouse gas emissions, and are pursuing strategies to reduce their carbon footprint. Within the transit industry, federal and local agencies have focused on new vehicle technologies and alternative fuels as a way to boost fuel economy, reduce operating costs, and reduce greenhouse gas emissions. Many promising technologies have emerged from this focus, including hybrid buses, plug-in electric buses, and fuel cell buses.

While many of these new-technology vehicles have shown benefits in some trials, further in-use testing is needed to better understand their real-world benefits. Transit agencies and OEMs alike are interested in quantifying fuel reductions as they relate to expected values. Additionally, side-by-side comparisons of hybrid and baseline 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 *CALSTART Hybrid Electric Bus Evaluation Project* compares the performance of a hybrid-electric shuttle bus ("the hybrid") against an equivalent baseline vehicle ("the non-hybrid") operating in a municipal fleet.

We collected vehicle telemetry data and manual maintenance, fuel, and driver assignment records on both the hybrid and non-hybrid over a period of six months from May to November, 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 in terms of fuel economy, tailpipe emissions, reliability, and driver feedback. We further examined the fuel economy data for specific trends, comparing the fuel economy on different routes and the efficiency achieved by different drivers.

The project provides insights into the types of situations (drive-cycle, schedule, etc.) in which hybrid buses perform best against their conventional counterparts, and the types of situations in which there are few performance benefits. The results of this analysis will help transit operators and hybrid vehicle manufacturers optimize the rollout of these alternative fuel vehicles.

1.1 Project Overview

To conduct this study we partnered with the City of Tracy, as the bus owner and fleet operator. The City of Tracy ("Tracy") is located within the central valley of California and operates the TRACER local bus transit system, serving a population of 85,000 over 20 square miles. In 2012 the TRACER bus service made 110,000 unlinked trips and operated 227,000 vehicle miles, with fifteen vehicles in operation.[1]

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[1] National Transit Database, City of Tracy (TRACER) Agency Profile. 2012. Available at http://www.ntdprogram.gov/ntdprogram/pubs/profiles/2012/agency_profiles/9197.pdf. Accessed on September 3, 2014.

Tracy has a history of alternative-fueled transportation vehicles. Prior to the introduction of the hybrid buses in this study, the entire TRACER fleet operated on natural gas. The introduction of these hybrid buses is part of a strategy to diversify its fleet portfolio while maintaining a clean-fuel vehicle fleet.

Tracy lies in the San Joaquin Valley Air Pollution Control District (SJVAPCD), a regional public health agency which oversees air quality management in eight central valley counties. SJVAPCD has a primary responsibility to meet EPA National Ambient Air Quality Standards (NAAQS). In 2012, the district was designated as “extreme non-attainment” for ozone pollution. In 2013, San Joaquin Valley achieved a milestone in ozone air quality by meeting EPA’s air quality standard through a variety of strategies which included fleet deployment of alternative transportation technologies.[2] However, with EPA 8-hour ozone standards growing more stringent, SJVAPCD must develop plans to meet this standard by reducing ozone levels and emissions of its precursor chemical, nitrogen oxide (NOx). Therefore there is an increasing demand for vehicle technologies that are proven to reduce NOx.

During the six month demonstration period, we measured fuel consumption and other performance parameters of both the hybrid and non-hybrid. In addition, we employed an expert subcontractor to conduct on-road emissions testing at the end of the demonstration period. We also monitored the maintenance of both vehicles and conducted driver and manager surveys to obtain user acceptance data from a variety of sources.

Upon completion of the testing period, we analyzed the data to quantify the benefits of the hybrid system and discover insights into optimal scenarios for its use. Using this data, we performed a set of analyses to answer questions about the benefits of these hybrid buses in several categories:

Overall Fuel Economy
Fuel economy of the hybrid vehicle was compared to that of the non-hybrid vehicle. Results were determined both for the controlled two-day test and the uncontrolled six-month demonstration, with an analysis of any discrepancies.

Criteria Pollutant Emissions
An expert subcontractor measured tailpipe emissions as part of a two-day test, determining any emission reductions between vehicle platforms.

Comparison of Routes
During both tests, the vehicles operated on two different routes, producing different levels of benefits for both fuel economy and tailpipe emissions. We compared the benefits on each route to measure any differences, and analyze the route structures to understand the causes of these differences.

Maintenance and Reliability Analysis
Through service logs and conversations with fleet and maintenance managers, we established a comprehensive picture of the maintenance required by these vehicles during the six-month demonstration period. Due to the identical on-board equipment of the two shuttle buses, the final analysis in this section combined their service events and costs to provide a case study of the bus platform and the hybrid system.

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[2] San Joaquin Valley Air Pollution Control District, “Report to the Community 2013-2014 Edition, available at http://www.valleyair.org/2013-14-AnnualReport.pdf. Accessed on September 3, 2014.

Driver and Manager Feedback
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 from prior topic areas.

1.2 Project Team

CALSTART managed and executed this project and had primary responsibility for data collection, analysis and the final report. The data collection process included data logger installation, remote data download, in-house post processing analysis, subcontracting the emissions testing and the final report. In addition, CALSTART coordinated the teamwork among project partners.

The City of Tracy operates the TRACER bus system, a fleet of 15 buses that provide local service on six routes. The hybrid electric buses used in this study are an initial step in exploring alternatives to CNG fuel that still have environmental benefits over conventional diesel buses. Tracy provided access to vehicles for installation, emission testing and uninstallation, as well as to drivers for vehicle-based surveys. In addition, Tracy's contracted maintenance staff provided data on maintenance costs and service records.

Crosspoint Kinetics is a key supplier of hybrid drive systems for the transit and truck industry. The company's systems provide regenerative braking and electric power capabilities that can be outfitted on existing trucks and buses, boosting their fuel economy without significantly modifying the drivetrain systems. The ARBOC/Crosspoint Kinetics hybrid shuttle buses were the focus of this test project. The company's main roles were in coordinating their hybrid data collection process with CALSTART, participating in biweekly calls and recording in-kind contributions to the project.

2. DESCRIPTION OF VEHICLES AND ROUTES

This section provides background information on the test vehicles and their assigned routes. The shuttle buses are described in detail, highlighting the configuration of the hybrid system. The assigned routes were selected from current fixed routes in the TRACER system. Manual data from the City of Tracy included driver schedules and vehicle rotation, providing the necessary inputs to determine driver performance and the impacts of different route characteristics.

2.1 Vehicle Selection

The City of Tracy operates four ARBOC shuttle buses outfitted with Crosspoint Kinetics hybrid drivetrains, two of which were selected for this project. The hybrid systems are installed as a new OEM vehicle component and connect with the drivetrain between the transmission and the axles. This placement allows the system to be engaged or disengaged without affecting the operation of the engine or transmission, in effect transitioning the bus between a hybrid and conventional vehicle. For the purpose of this test, one vehicle operated with the hybrid system engaged, while the other remained in conventional mode throughout the duration of the demonstration period. By eliminating differences in the test vehicle and baseline vehicle due to different chassis or engine manufacturers, our results isolate the effect of the hybrid system on overall vehicle performance.

Description of Shuttle Buses

The vehicles used for this test are 26' cutaway shuttle buses with capacity for 19 seated passengers. The ARBOC Specialty Vehicles are differentiated by their focus on passenger accessibility, especially for elderly and wheelchair passengers. These low-floor ARBOC models (see Figure 2-1) are termed the "Spirit of Mobility" and are specially designed to exceed Americans with Disabilities Act (ADA) requirements, in part with electronically-controlled wheelchair ramps.

Figure 2-1: The ARBOC "Spirit of Mobility" Shuttle Bus with Crosspoint Kinetics hybrid system

This ARBOC bus, model year 2012, is built on a GMC 4500 chassis with a 191 inch wheel base. The vehicle is powered by 6.0L GM Vortec V8 gasoline engine (engine family CGMXE06.0585[3]) producing 342 horsepower and 373 lb-ft of torque. The schematic in Figure 2-2 shows the vehicle and cabin layout.

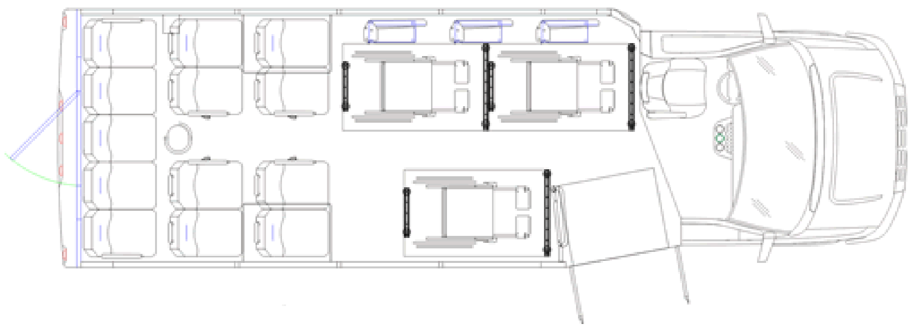

Figure 2-2: The ARBOC "Spirit of Mobility" floor plan

The ARBOC vehicle proved to be a good bus for this test. First, the controller area network (CAN bus) which is responsible for all engine control systems proved to be readily accessible for connection with our data collection equipment. The CAN bus works in tandem with the On-Board Diagnostics (OBD) network, which exports a variety of vehicle telemetry and engine performance parameters. Second, because the cutaway chassis is so common among shuttle bus fleets, lessons from this test can be widely applied to other shuttle buses running on the same chassis.

Description of Hybrid System

The drivetrain is equipped with an ultracapacitor energy storage system, designed and installed by Crosspoint Kinetics. Ultracapacitors store energy in an electric field, rather than in a chemical reaction like batteries, which means they can charge and discharge very quickly. This is an inherent advantage in commercial vehicles deployed on stop-and-go routes, such as shuttle buses.

The Crosspoint Kinetics system provides 10.7 kW of peak power to an integrated electric motor, which supplements the power from the engine to provide torque to the wheels during acceleration. Similarly, the motor and ultracapacitors act as a regenerative braking system during deceleration, capturing energy for the subsequent acceleration event. As a result, the system performance is increased through near-instant boost torque and rapid regenerative charging.

The hybrid system is configured to be engaged between 0 and 30 MPH to provide boost and from 35 to 0 MPH for system recharging. The fully charged system holds 96Wh of energy which can be discharged down to 37Wh in an acceleration event. Crosspoint Kinetics maintains their hybrid drive system highly separate from the rest of the chassis; it is essentially a stand-alone sub-system with no connections to the engine control module or CAN bus. All hybrid system parameters were monitored by a Crosspoint

[3] California Air Resources Board, "Executive Order A-006-1793-1: New Engines for Diesel or Incomplete Medium-Duty Vehicles", available at: http://www.arb.ca.gov/msprog/onroad/cert/mdehdehdv/2012/gm_mdoe_a0061793r1_6d0_0d42_e85.pdf. Accessed on September 3, 2014.

Kinetics controller maintained separately from the standard vehicle architecture. A diagram of the hybrid system is shown in Figure 2-3, with the hybrid components highlighted in green.

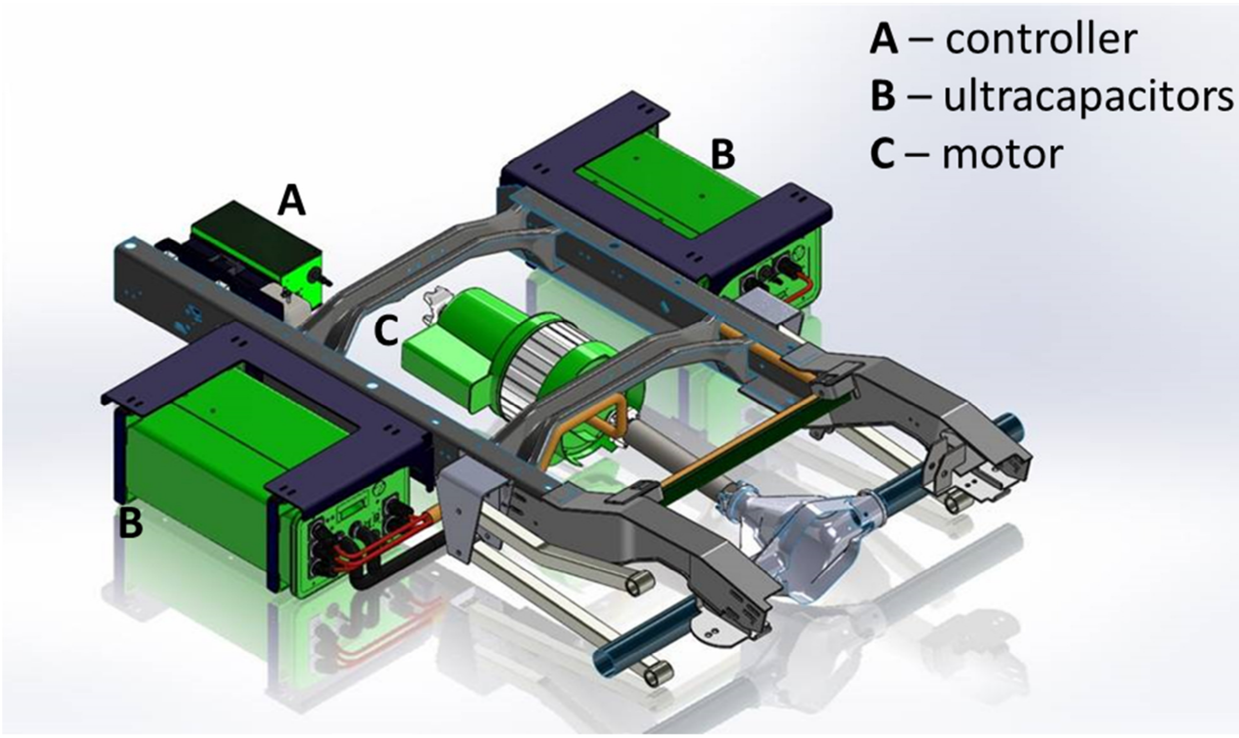

Figure 2-3: Hybrid Undercarriage (motor, ultracapacitors, and controller in green)

As seen in this figure, the hybrid drive system attaches directly to the drive shaft, and is seated well away from the engine compartment between the frame rails of the chassis. Its fully sealed componentry are easily distinguishable and highly accessible for maintenance and other personnel during service.

2.2 Examination of System Functionality

The following charts were generated from engine data and demonstrate how the hybrid system functions; providing boost to the vehicle when the driver requests it and recharging whenever the accelerator pedal is released. The Crosspoint Kinetics system discharges and recharges very quickly, though it should be noted that the pattern shown below in Figure 2-4 is not an ideal system usage because the acceleration events depicted were not sustained long enough to fully deplete the ultracapacitor storage.

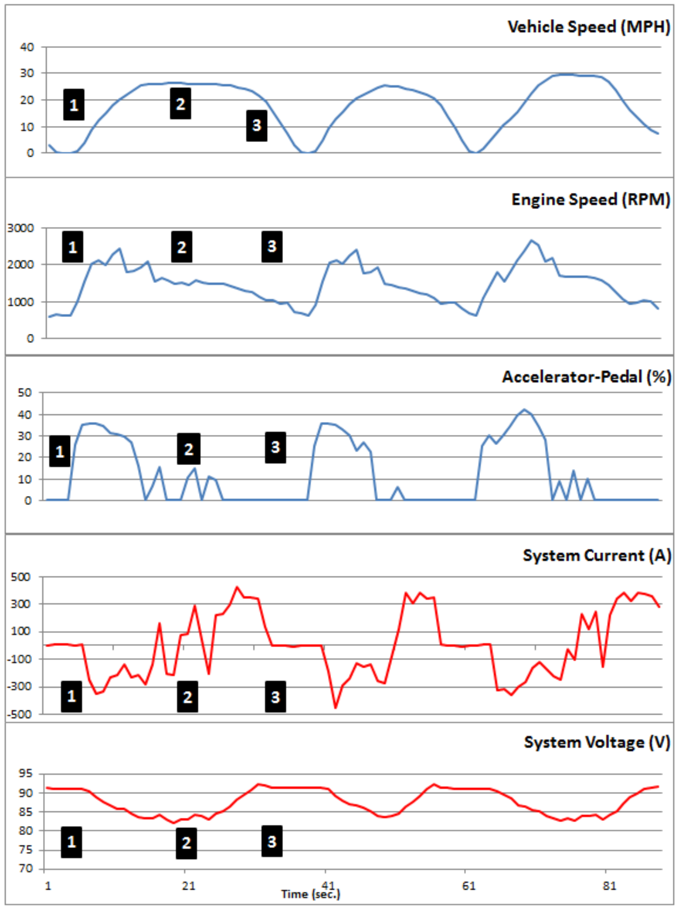

Figure 2-4: Engine and Ultracapacitor Systems During Start and Stop

Phase 1: The driver depresses the accelerator pedal, which, along with engine speed, increase slightly ahead of vehicle speed. The system current, which had been level at 0A, immediately becomes negative—indicating boost is being provided. System voltage, which had been level slightly below the maximum value of 91V, begins to decrease as well.

Phase 2: The driver maintains the accelerator pedal around the 8% threshold, which allows the system to start recharging. System current crosses the x-axis, indicating regenerative braking activity for approximately 5-10 seconds. System voltage begins increasing from 83V to the "full" value of 91V during the 5-10 seconds of regenerative braking.

Phase 3: As the vehicle continues to slow down, the driver fully releases the accelerator pedal but the system current remains at 0A because the system voltage is already at its full value of 91V.

The pattern of phases 1-3 is then repeated twice more.

The above figure indicates that average acceleration events of 0-20 MPH will not fully discharge the ultracapacitors, and that only extended acceleration can deplete the system. This is important because it means that drivers should always be able to take advantage of boost opportunities when starting from 0 MPH after a sustained braking event. Since the Crosspoint Kinetics system does not use the brake pedal to engage regeneration, drivers should maintaining accelerator pedal position below the 8 % threshold as often as possible while coasting to increase opportunities for recharging the system. This ensures that boost will be available to the drivers whenever they can accelerate, effectively reducing engine load and improving fuel economy.

2.3 Route Selection

For this test, the hybrid and conventional shuttle buses operated on two fixed routes as part of the TRACER system. There are a total of six routes, two of which were selected for this test and designated as Route A and Route B. Both routes carry between 150 and 200 passengers per day on average and have approximately ten fixed stops with a varying number of additional stops depending on ridership. They are similar in length; Route A is 10 miles long and rouge B is 9.4 miles long. Both routes are shown in Figure 4-5.

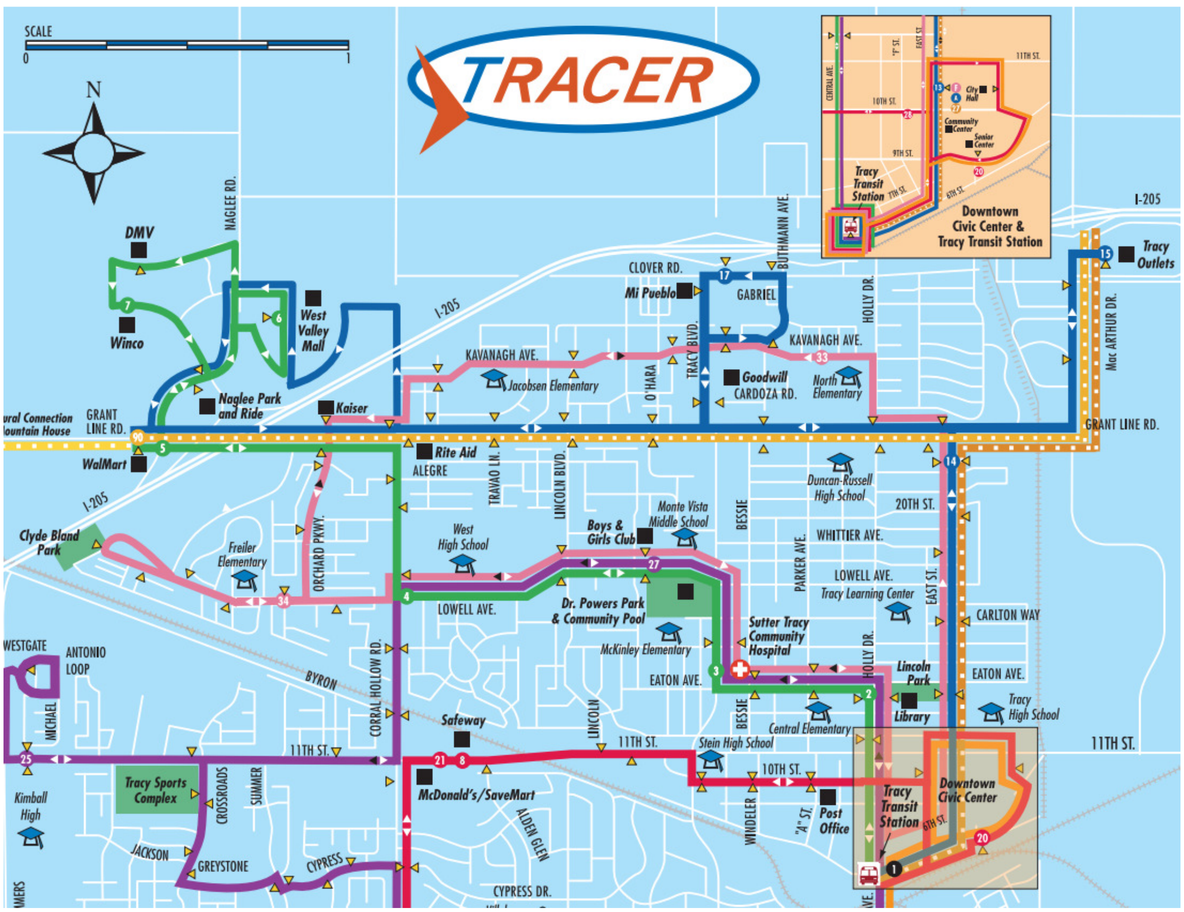

Figure 2-5 Route A (in blue) and Route B (in green) are 10 and 9.4 miles in length, respectively.

The City of Tracy operates buses on these routes from 7am to 7pm, Monday through Friday, and 9am to 5pm on Saturday. There is no service on Sunday. There are two shifts each weekday (AM and PM shift) and one shift on Saturday, with one driver for each shift and different pairs of drivers each day.

2.4 Route Scheduling

The two shuttle buses were dedicated to Routes A and B to the exclusion of other routes. In order to avoid any bias in the data due to route differences, both buses were switched between these two routes on a weekly basis. This variation allowed CALSTART to not only contrast the differences between buses, but also the fuel economy impacts of each route.

The City of Tracy re-assigned a few new drivers to each bus during a shift-bidding process midway through the demonstration period. While over a dozen drivers operated the vehicle during the testing period, a core group of five drivers accounted for 77% of the shifts recorded. For the purposes of a driver analysis, we limited the set of drivers to these five. Names have been anonymized for this report.

2.5 Service and Maintenance

The City of Tracy contracts with MV Transportation in Stockton, CA for maintenance and service support. MV Transit was responsible for performing Periodic Maintenance 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 buses, which was instrumental in establishing a service cost profile for the shuttle bus. Occasionally the buses were sent to a specific dealer in Sacramento 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. SIX-MONTH DEMONSTRATION: FUEL ECONOMY, ROUTE COMPARISON, AND DRIVER TRENDS

In order to assess the performance of the hybrid shuttle bus in real-world revenue service, we monitored the operation of the hybrid and non-hybrid buses over a period of six months. We tracked data on fuel dispensed, route assignments, and driver shift schedules and 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 is the fuel economy of the hybrid and non-hybrid vehicles, and how much does the hybrid system improve vehicle fuel economy?
- How does fuel economy vary between routes, and how do the benefits of the hybrid vary between routes?
- How does fuel consumption vary between drivers?
- What are the impacts of idling on fuel economy, and how much does fuel economy improve when isolating non-idle fuel economy?

The testing period was from May 1 to October 31, 2013, during which the two buses combined traveled 31,900 miles and consumed 5,070 gallons of fuel. Over 2,878 hours of operation, the vehicles carried an estimated 42,000 passengers. The sections below present the methodology used in this study, the fuel economy findings by vehicle, route and driver, an analysis of vehicle speeds and the effects of idling, as well as a closer examination of how the hybrid system performs during stop-and-go driving.

3.1 Methodology

3.1.1 Test Program

We designed a test protocol to measure vehicle performance in two situations. First, during a 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, one driven exclusively in hybrid mode throughout the test, and one driven exclusively in non-hybrid mode. These vehicles were operated by several different drivers over the testing period, and driven alternately on two different routes.

The vehicle testing and data collection was designed to operate without manual effort to the extent possible, to reduce burden on the participants. 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 and driver shifts were compiled by the City of Tracy and sent to CALSTART every two weeks. Fuel records were directly printed out from the key-card activated fuel tracking system, and driver records were tracked by MV Transportation.

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 the odometer 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 were connected to the OBD network and required a J1939 translator device to receive all the data parameters. 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 many engine and vehicle messages from the OBD, Table 3-1 below presents the main vehicle parameters that were analyzed from each vehicle.

Table 3-1: Relevant Vehicle Parameters from Data Loggers

Vehicle Parameters	Units
Engine speed	rev/min
Vehicle speed	km/hr
Manifold Pressure	kPa
Intake Air Temperature	Kelvin
Accelerator Pedal Position	%
GPS Latitude	°
GPS Longitude	°
GPS Altitude	m

We found after the initial installation that the engine electronic system does not provide data on fuel flow. Instead, we attempted an approach that used the manifold pressure, intake air temperature and engine speed to calculate mass air flow into the engine, then volume air flow into the engine, then volume fuel flow, and finally fuel economy. However, the results from this indirect calculation were considered unreliable – they showed fuel economy fluctuating significantly from month to month, more so than can be expected. For completeness, more information on the calculation methodology is shown in Appendix A.

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. Tracy uses an electronic fuel monitoring system which outputs quantities and specific times of vehicle fueling events. The fuel dispensers require key-card access which ensures that the amount of fuel added to each vehicle is usually quite accurate. The most important fuel log data is highlighted in Table 3-2 below, and a full log can be seen in Appendix B.

Table 3-2: Relevant Parameters from Manual Fuel Log

Fuel Log Parameter	Format
Equipment	Bus ID
Fuel Type	Unleaded
Transmission Date	mm/dd/yyyy
Transmission Time	hh:mm
Posting Date	mm/dd/yyyy
Employee	Employee ID
Site/Pump	Pump ID
Unit Cost	$
Quantity	Gallons
Cost	$

The unit cost of fuel and quantity dispensed combined to form the cost column for each vehicle, which was then summed to create a total fuel cost per vehicle over the two week period. The schedule for fueling was irregular, with fueling events occurring every day or two, and at different times of the day. Because of this, we could not directly determine the vehicle-miles traveled between individual fill-ups, and could not calculate fuel economy on a daily basis. Similarly, fuel consumption could not be directly tied to a specific route (a vehicle may have driven on more than one route between fill-ups) or a specific driver (typically there was more than one driver shift between fill-ups).

Because of this, the fueling data was best used as an aggregate check of fuel consumed on a monthly basis. Even at this level, fluctuations in the fuel economy calculations called into question the accuracy of the manual fuel log.

Manual Driver Shift Logs

In order to compare vehicle performance across drivers and across routes, we collected records from Tracy that documented the route and driver assignments for each vehicle. Typically, each vehicle was rotated between Route A and Route B on a weekly basis, although on some days one of the vehicles may have been out of service or swapped to a different route.

Driver shift logs documented which driver was assigned to each vehicle on a particular day and for a particular shift. During weekdays drivers were scheduled with an AM shift, typically 7 AM to 3 PM, and a PM shift, typically 3 PM to 7 PM. Only one shift was schedule for Saturdays, and the vehicles were out of service on Sundays.

The shift log indicates the time that each shift begins and ends, in the form of a time in/time out time clock, which we used to synchronize the shift assignments with the second-by-second engine data. The most important driver shift log data is highlighted in Table 3-3 below, and a full log can be seen in Appendix C.

Table 3-3: Relevant Parameters from Driver Shift Log

Driver Shift Log Parameter	Format
Date	Day, mm/dd
Employee	Last, First
Route	X
Bus Number	##
First Pick-up	hhmm
Last Drop-off	hhmm
Average Fuel Economy	#.##
First-to-Last Miles	###
Dead-Head Miles	#

The above parameters provided useful driver assignment and operations information for each two week period. We eliminated the trips to and from the depot at the beginning and end of each day, to ensure that our data sets only contained data on revenue service. As a backup to the distance measurements calculated through the engine data loggers, we extracted and tabulated this shift-level mileage. This acted as a useful check on daily distance traveled, and how it compares to the engine loggers.

3.1.2 Data Analysis

Raw data records were received from the data collection equipment 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 (11.5 million records total) 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 which required manual clean-up after loading all the raw data into the database. For example, when the data loggers first initialize 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, and the values are exactly consistent between records. For example, of the 6.7 million data points recorded for the hybrid vehicle, 17,748 data points recorded an engine speed of 8191.88 RPM – clearly an error. 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. Similarly, the speed-based distance measurement allows us to calculate instantaneous fuel economy at any point.

To answer questions about vehicle effectiveness and route impacts, we relied on the fuel logs collected by Tracy as part of their electronic information system. By comparing the dates of fueling events against the route assignment schedule, we "assigned" each fueling event to a specific route, treating the amount of fuel dispensed as fuel consumed on that route. Because the vehicles were assigned to routes on a weekly basis, and the fueling events occurred daily or every other day, there were few circumstances in which either bus drove on both routes between fueling events.

3.2 Summary of Data Collected

A summary of pertinent vehicle and operations data collected for each bus is presented below in Table 3-4. For each bus and route, the table shows the number of driver shifts recorded, the total hours of operation recorded, and the total mileage recorded as part of the six-month demonstration.

Table 3-4: Summary of Data Collected for Each Bus and Route

Bus & Route	Driver Shifts	Operating Time (hrs)	Distance Traveled (mi)
Hybrid bus, Route A	95	562	8,680
Hybrid bus, Route B	129	739	8,787
Hybrid, Total	224	1,300	17,467
Non-hybrid, Route A	82	501	7,772
Non-hybrid, Route B	62	357	4,308
Non-hybrid, Total	144	857	12,080

In total, we recorded vehicle data for 2,157 operating hours and 29,500 vehicle miles. Shifts with fewer than 3.5 hours were discarded from this summary because they did not represent a full morning or afternoon shift. As shown in the summary, the hybrid bus drove approximately 5,000 more miles and completed 80 more shifts than the non-hybrid bus during the demonstration period, due to an out-of-service event on the non-hybrid during June. This is examined more detail in Chapter 5: Service and Reliability Findings.

In order to quantify how Route A differs from Route B in terms of bus operation, we analyzed one driving shift (eight hours of operation) for each bus on each route. Calculated values are shown below in Table 3-5, showing average speed and number of stops.

Table 3-5: Performance Characteristics of Routes A and B

	Route A		Route B	
	Stops/ Mile	Avg. Driving Speed (MPH)	Stops/ Mile	Avg. Driving Speed (MPH)
Hybrid	3.3	20.2	4.4	17.5
Non-Hybrid	3.0	20.4	4.1	17.7

The stops per mile reported above show that the vehicles stopped less often on Route A than on Route B, and that the hybrid generally stopped more frequently than the non-hybrid. This finding includes stops due to traffic (i.e. traffic lights, stop signs), and stops for passengers to board and embark. The data set does not enable us to isolate the number of bus stops from traffic stops, but does reflect an accurate portrayal of how the driver naturally adjusted to traffic along the route. Both routes have ten bus stops along the route.

The average driving speed was calculated as a non-zero average, and shows that both vehicles were driven identically on each route, though Route A was slightly faster than Route B which follows from the less frequent stoppages on Route A.

3.3 Fuel Economy Findings

Table 3-6 below shows the fuel economy data for the hybrid and baseline vehicles over the 6-month demonstration period, as calculated from the engine loggers (mileage) and logs from the fueling system (fuel gal).

Table 3-6: Six Month Fuel Economy of Hybrid and Baseline Vehicles

	Hybrid Bus			Non-Hybrid Bus		
Month	Distance (mi)	Fuel (gal)	Fuel Economy (MPG)	Distance (mi)	Fuel (gal)	Fuel Economy (MPG)
May	2,602	312	8.34	2,705	415	6.51
June	2,908	410	7.09	418	87	4.81
July	3,365	528	6.37	794	194	4.10
August	3,620	619	5.85	2,478	396	6.26
September	3,443	506	6.81	2,790	490	5.69
October	2,961	478	6.20	3,793	635	5.97
Overall	18,899	2,853	6.62	12,978	2,217	5.85

The hybrid vehicle operated with an average efficiency of 6.62 MPG, 13.2% greater than the 5.85 MPG fuel economy achieved by the non-hybrid vehicle. This and subsequent percentage improvements were calculated by dividing the difference in fuel economy between the vehicles by the baseline (non-hybrid) fuel economy value. For both vehicles, the fuel economy was highest in the first month of the test, in which the hybrid achieved 8.34 MPG (the highest result across all vehicles and months). The ambient temperature in Tracy in May is still relatively cool, resulting in decreased air conditioning loads for TRACER fleet vehicles. This reduced accessory load, in addition to the initial hybrid driver training conducted at the beginning of the test, could explain why the fuel economy was so high in the first month of the test.

As a general trend, fuel economy dropped in the June, July and August months while rebounding in the September and October months. This trend follows the change in seasons in the Tracy region; higher accessory loads during the summer months are likely, which result in greater strain on the engine and increased fuel consumption throughout the day. For the non-hybrid vehicle, fuel economy dropped significantly in June and July because the vehicle spent a large amount of time out of service, during which there were large periods of idling and freeway driving. Since there were few miles driven by the vehicle during these months, the low fuel economy in these months did not have a large effect on the six-month average.

However, the overall six-month trends may obscure a more accurate understanding of how the hybrid compares against the non-hybrid. The six-month trend includes revenue service as well as out-of-service mileage such as movements to and from the depot and service yards. Further, there were periods of idling that occurred when the vehicle was out of service. Lastly, as shown in Table 3-4 vehicle mileage was split unevenly between Routes A and B, especially so for the non-hybrid. The route-specific fuel economy is analyzed further in Chapter 4.

3.4 CO_2 Analysis

Of interest is the total savings in fuel and CO_2 over the course of this test. Using the route-specific fuel economy, we calculate the savings from the hybrid, that is, the difference between the fuel that was consumed by the hybrid, and the fuel that *would have been* consumed if the hybrid were replaced by a non-hybrid. Over the six months of operation, the hybrid vehicle traveled 17,467 miles when in revenue service on Routes A and B and consumed 2,566 gallons. However, if the hybrid had been replaced by a non-hybrid it would have consumed 2,942 gallons. The difference between the two is the savings from operating the hybrid. This is shown in Table 3-7.

Table 3-7: Fuel and Carbon Dioxide Savings from the Hybrid During the 6-mo Demonstration

Parameter	Value
Distance traveled (mi)	17,467
Fuel consumed (gallons)	2,566
Fuel avoided (gallons)[a]	2,942
Total fuel saved (gallons)	375
CO_2 saved (lbs.)	7,371

[a] The amount of fuel that *would have been* used if the vehicle were a non-hybrid

In total, the hybrid saved 375 gallons of gasoline over six months of operation, corresponding to 7,371 lbs. of carbon dioxide. If this 6-month demo were extrapolated over a 7-year service life[4] of the bus,

[4] The ARBOC/Crosspoint Kinetics hybrid has been tested at the Altoona testing facility in the 7-year, 200,000 mile category. See Pennsylvania Transportation Institute Bus Testing and Research Center, "Partial STRURA Test, 7 Year 200,000 Mile Bus from ARBOC Mobility, LLC Model 2009 Gas Hybrid," September 2009, PTI-BT-R0916.

then the hybrid vehicle would save 5,255 gallons of gasoline and eliminate 51.6 tons of carbon dioxide. These GHG savings are equivalent to taking seven cars off the road or planting 875 trees.[5]

3.5 Analysis of Vehicle Speeds

Vehicle speed is a variable that affects fuel economy. Because the hybrid has the greatest benefit between 0 and 30 MPH, the best opportunity to reduce fuel consumption will be on routes with a larger percentage of time spent at those speeds. Table 3-8 and Figure 3-2 below show the distribution of time spent at different speeds, shown as a percentage of total time during the six-month demonstration.

Table 3-8: Vehicle Speed Breakdown, 6-Mo Demonstration

Speed Bin	Hybrid	Non-Hybrid
Idle	32.6%	32.7%
0-5 MPH	9.1%	8.7%
5-10 MPH	8.0%	7.7%
10-15 MPH	9.9%	9.5%
15-20 MPH	8.9%	8.5%
20-30 MPH	18.8%	18.9%
30-40 MPH	11.4%	12.5%
40+ MPH	1.4%	1.5%

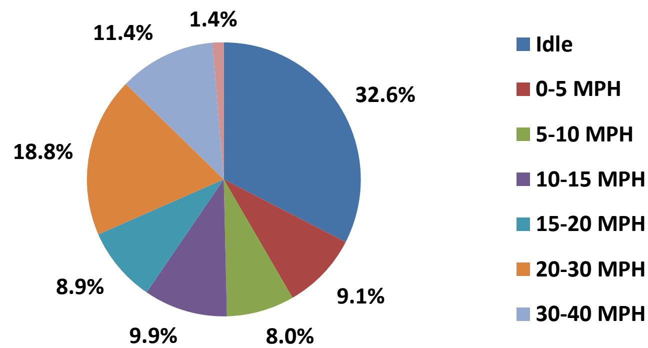

Figure 3-2: Hybrid Vehicle Speed Breakdown, 6-mo Demonstration

In both tests, the speed distribution of the hybrid vehicle closely matched that of the non-hybrid, indicating that the drivers operated both vehicles similarly. Across both vehicles 61% of driving time was spent in the 0-30 MPH range, which is the range in which the hybrid system was active. Approximately 30% of time was spent in the 0.1-15MPH range, where the hybrid deceleration and boost had the greatest impact. Figure 3-2 highlights the breakdown of this comparison for the hybrid vehicle. With less than 2% of total time spent above 40 MPH, it is clear that this vehicle rarely traveled at highway speeds.

3.6 Analysis of Idling Time

Idling was defined as any moment when the engine is on but the vehicle speed is zero, which includes en-route traffic, and fixed stops in revenue service and any out-of-service events as well. The engine data was filtered using the speed binning approach shown in Table 3-8, and highlights that both vehicles idled more than 32% of the time.

In order to better characterize the time spent idling and understand the number and length of idling events, we performed a closer analysis on a slice of vehicle data from the demonstration. We isolated engine data from one day of driving for each vehicle and route combination (hybrid and non-hybrid, Route A and Route B). Table 3-9 shows the number of idling events, the percentage of total idle time events of that duration account for, and the total amount of idling time per day.

[5] Conversions available at http://www.epa.gov/cleanenergy/energy-resources/refs.html. Accessed on September 3, 2014.

Table 3-9: Frequency and Duration of Idle Events

	Route A Hybrid		Route A Non-hybrid		Route B Hybrid		Route B Non-hybrid	
Idle Duration	Idle events	% Idle Time	Idle events	% Idle Time	Idle events	% Idle Time	Idle events	% Idle Time
1 sec	111	1%	70	1%	106	1%	77	0.5%
2 – 15 sec	295	16%	281	17%	273	11%	242	10%
15 – 30 sec	116	21%	92	18%	88	12%	98	14%
30 sec – 1 min	55	19%	64	24%	62	17%	87	24%
1 min – 5 min	27	20%	41	35%	53	37%	47	35%
> 5 min	3	24%	1	6%	6	22%	4	17%
Total operation time	12.3 hrs.		11.9 hrs.		11.8 hrs.		11.8 hrs.	
Total idle hrs.	3.5 hrs.		3.2 hrs.		4.3 hrs.		4.4 hrs.	
Total Idle %	28.5%		26.9%		36.4%		37.2%	

This table reveals several important trends on the cause of idling and provides hints on strategies to reduce the amount of idle. The hybrid idled for roughly 4 hours per day on both routes, with approximately half of the idle time lasting more than one minute and half lasting less than one minute. However, only three events each over 5 minutes long were responsible for a quarter of the daily total. These extended-idle events often occur during shift changes, when the vehicles are awaiting their new drivers or are undergoing inspections by the incoming driver. This is significant because it speaks directly to the fixed operational procedures instituted by the fleet, rather than a powertrain-related issue.

Second, while there were many events less than 15 seconds in duration, these traffic-induced stops only make up 17% of the daily idling total. A further analysis of this data on a wider data set would allow planners to distinguish between traffic stops and bus stops, optimizing fuel use while potentially reducing idle time.

Idle time was greater on Route B than on Route A (average 4.35 hours vs. 2.35 hours for the four days tested). As a general trend there are fewer shorter stops and more frequent longer stops. The first three duration bins on Route B comprise roughly 25% of the daily idling total, whereas these bins on Route A comprise 36% of the daily total.

Of interest is the in-motion fuel economy, that is, fuel consumption of the vehicle only when driving and factoring out fuel consumed at zero speed. We calculate in-motion fuel economy by assuming a representative idling consumption rate of 1.0 gallons per hour, and determining the amount of fuel consumed that day at idle vs. when in-motion. By dividing the daily distance traveled by the in-motion fuel consumption, the in-motion (non-idling) fuel economy is determined. Results are shown in Table 3-10.

Table 3-10: Non-Idling Fuel Economy, 6-Mo Demonstration

	Hybrid Bus	Non-Hybrid
Operation Time (hrs)	1,300	857
Idle percentage (%)	32.6%	32.7%
Time at idle (h)	424	280
Total fuel (gal)	2,853	2,217
Idle fuel[1] (gal)	424	280
In-motion fuel (gal)	2,429	1,937
Distance Traveled (mi)	18,899	12,978
Total Fuel Economy (MPG)	6.62	5.85
In-motion Fuel Economy[2] (MPG)	7.78	6.70

[1] Assumes 1.0 gal per hour at idle

[2] Calculated as total vehicle-miles divided by in-motion fuel consumed

Idling accounts for a significant portion of fuel use – 15% of fuel is consumed at idle. When idle fuel consumption is removed from the equation, the fuel economy of both buses goes up considerably – 18.9% higher for the hybrid and 14.5% higher for the non-hybrid. Also, the hybrid benefits are greater as a percentage of total fuel economy. When idling is factored out of the fuel results, the hybrid MPG is 16.1% higher than the non-idling MPG.

4. TWO-DAY TEST: FUEL ECONOMY AND EMISSIONS MEASUREMENTS

In order to validate the findings of the six-month demonstration and collect a precise measurement of fuel consumption and tailpipe emissions, Engine Fuel & Emissions Engineering (EF&EE), an expert subcontractor, performed a two-day controlled emissions test of the shuttle bus while it simulated revenue service. The instrumented vehicle did not pick up any passengers but stopped at the ten fixed stops on Routes A and B for each test run. To measure emissions EF&EE installed a portable emissions measurement system (PEMS) onboard the vehicle, which measured levels of Carbon Dioxide (CO_2), Nitrous Oxides (NOx), Carbon Monoxide (CO), Particulate Matter (PM), and Hydrocarbons (HC) in the exhaust stream. Using a carbon balance calculation, vehicle fuel economy was calculated for each test. The full emissions report from the subcontractor is provided in Appendix D.

During this controlled test, efforts were made to eliminate as many external variables as possible. We used the same driver for both test days, and used a fixed drive cycle in which the vehicle made the same stops and dwelled for the same duration for every loop around the routes. Further, we made efforts to measure fuel dispensed at the pump as precisely as possible, making sure to refill at the beginning and end of every day. This eliminates uncertainty in the manual records found during the six-month demonstration. Accessories such as HVAC were turned off for this test.

The following sections describe the test program designed for this study, the measurement equipment used during the test, and the fuel economy and emission findings.

4.1 Test Program

EF&EE instrumented one of the hybrid buses with emissions equipment, alternately engaging and disengaging the hybrid system to simulate hybrid and non-hybrid use. The bus was driven on routes A and B over the course of two days, with the testing period starting at 7am and finishing at 3pm on each day. Each route “loop” was treated as an independent test, with measurements recorded independently for all the loops. In total, twelve loops were completed, three loops for routes A and B when in hybrid mode, and three loops for each route when in non-hybrid mode. The emissions and fuel results were calculated independently for each loop, then averaged together to get the final results.

Testing on December 4th was conducted with the hybrid system enabled and on December 5th with the system disabled, except for one “makeup” test. Testing on Route A was conducted in the morning of each day, and testing on Route B in the late morning and afternoon. This was done so that traffic conditions would be as similar as possible between the hybrid-on and hybrid-off tests on the same route.

4.2 Measurement Equipment

Emission testing was performed using a PEMS system installed in the shuttle bus cabin. The system used was the Ride-Along Vehicle Emission Measurement (RAVEM™) system, with the capability to measure all the pollutants of interest for this study. The performance of this system have been validated in past studies.[6,7] The system uses constant-volume sampling (CVS) with a proportional partial-flow sampling system to achieve emission measurement capabilities similar to those of a conventional full-flow CVS laboratory in a package small enough to be mounted on a vehicle. Technical details of the RAVEM system are given in Appendix E.

Exhaust was sampled from the exhaust pipe at the rear of the bus using an isokinetic probe. The isokinetic sampling system adjusts the sample flow rate to equalize the velocity of the exhaust entering the probe with that of the exhaust surrounding the probe’s exterior. To ensure that the exhaust velocity at the probe tip reflects the average velocity in the exhaust pipe, prior experience dictates to have at least 10 diameters of straight pipe upstream of the probe tip. This required cutting the exhaust pipe upstream of a 90 degree bend at the outlet. The probe was then inserted into the end of the cut section.

The CVS dilution tunnel and the analyzers for CO_2, CO, NOx, and total HC (THC) were installed on-board the shuttle bus. The sample line from the isokinetic probe to the dilution tunnel was run through the back window of the bus. This window was propped open enough to pass the sample line, and then sealed with duct tape to prevent the entry of exhaust fumes. Electric power to operate the system was supplied by a small gasoline generator attached to the rear bumper of the vehicle.

The test vehicle carried no passengers during the emission testing, but did carry the RAVEM system and the two operators. The total mass of the RAVEM™ system, system operators, and calibration gas cylinders was approximately 1,500 lbs., equivalent to about 8 passengers.

One emission test was performed during each repetition of each driving route, and lasted the entire length of the route. During each test, NOx, THC, CO, and CO_2 emissions were recorded second-by-second in real time. At the end of each test, the NOx, CO, and CO_2 concentrations were also measured in integrated bag samples of dilute exhaust collected over the test run. Background concentrations of CO_2, CO, and NOx were determined from a separate integrated bag sample of the CVS dilution air collected over the test run. This sample was analyzed immediately after the integrated sample bag. During the second day of testing, THC concentrations were also measured in both sample bags. All emissions were measured in grams per mile, averaged over each route loop.

PM emissions during each emission test were determined from integrated samples collected on pre-weighed filters over each test run. A blank PM filter exposed to the same volume of dilution air was also collected during each test run. Any change in weight of the blank filter was subtracted from the change in weight of the sample filter in calculating the PM emissions.

Vehicle speed and position during each test run were measured by GPS, and recorded second-by-second. The exhaust temperature -- measured at the isokinetic probe – was also recorded second-by-

[6] C.S. Weaver and L.E. Petty, Reproducibility and Accuracy of On-Board Emission Measurements Using the RAVEM™ System, SAE Paper No. 2004-01-0965, March, 2004.
[7] Weaver, C.S. and M.V. Balam-Almanza, "Development of the RAVEM™ Ride-Along Vehicle Emission Measurement System for Gaseous and Particulate Emissions." SAE Paper No. 2001- 01-3644

second. The ambient temperature, humidity, and barometric pressure at the start of each test were also recorded automatically by the system.

The PM filter changes, gas analyzer calibration, and reading of gas sample bags at the end of each test were carried out after the end of each route, with the test vehicle parked at the transit center.

The values for the mass of fuel consumed during each test were calculated by summing the carbon content of the CO_2, CO, and THC emissions; then dividing by the estimated fuel carbon content of 82.9% by weight. This carbon content was calculated assuming 10% ethanol by volume in the CaRFG3 fuel blend.

4.3 Fuel Economy Results

Driving data from each test is summarized Table 4-1. This table shows the distance travelled during each test run, as measured by the EF&EE GPS device, as well as the total time required and the amount of time spent with the vehicle stopped (GPS speed of zero). Stopped time was mostly spent at traffic lights, as the driver was instructed to stop only momentarily at the scheduled bus stops.

Table 4-1 Summary of Driving Data for Emission Tests

Vehicle	Route	Test Num	Dist (mi)	Time (min)	Idle Time (min)	Avg. Speed (MPH)
Hybrid	Route A	1	15.7	50.6	6.3	21.3
Hybrid	Route A	2	15.8	51.7	7.1	21.2
Hybrid	Route A	3	15.7	50.1	4.2	20.5
Hybrid	Route B	1	11.4	53.4	10.7	16.1
Hybrid	Route B	2	11.5	48.6	8.3	17.1
Hybrid	Route B	3	11.5	55.3	15.4	17.3
Non-hybrid	Route A	1	15.7	55.9	7.8	19.6
Non-hybrid	Route A	2	15.8	54.6	10.1	21.2
Non-hybrid	Route A	3	15.8	52.3	6.9	20.8
Non-hybrid	Route B	1	11.5	47.8	10.0	18.3
Non-hybrid	Route B	2	11.5	49.5	10.1	17.5
Non-hybrid	Route B	3	11.5	51.5	8.9	16.2

Table 4-1 also shows the average driving speed of the vehicle which is calculated by dividing the distance travelled by the total time minus the time spent stopped. Aside from the test runs shown above, two tests were aborted, and data from another was lost, underscoring some of the difficulties in conducting on-road tests. However these losses were insignificant and make-up tests were successfully completed to overcome any loss in overall data. One final test, gaseous (but not PM) emission measurements were taken for the purpose of calculating fuel consumption for each test. As a double check, total fuel use was also measured at the end of each day. Table 4-2 below lists the individual fuel consumption for each emissions test, calculated in this manner.

Table 4-2: Summary of Fuel Economy Data for Emissions Tests

Vehicle	Route	Test Num	Fuel (Gal)	Fuel Economy (MPG)
Hybrid	Route A	1	1.8	8.93
Hybrid	Route A	2	1.9	8.45
Hybrid	Route A	3	--	--
Hybrid	Route B	1	1.4	7.97
Hybrid	Route B	2	1.6	7.13
Hybrid	Route B	3	1.7	6.82
Non-hybrid	Route A	1	2.3	6.94
Non-hybrid	Route A	2	2.1	7.45
Non-hybrid	Route A	3	2.4	6.66
Non-hybrid	Route B	1	1.9	6.17
Non-hybrid	Route B	2	1.8	6.29
Non-hybrid	Route B	3	1.9	6.05

The twelve test runs shown above sum to 20.7 gallons of fuel consumed. In total 32.5 gallons of fuel were consumed over the two-day testing period, which includes the three runs that were discarded and travel distance at the beginning and end of each test day. Fuel economy was calculated by dividing the RAVEM™ mileage values from Table 4-1 by the fuel consumed during each test.

4.3.1 Route-Specific Fuel Economy

Summarizing the fuel economy findings from Table 4-2 by vehicle and route, we notice major improvements in fuel economy; these are shown below in Table 4-3.

Table 4-3: Fuel Economy Results for Each Route

	Route A	Route B	Combined
Hybrid Fuel Economy (MPG)	8.69	7.31	7.86
Non-Hybrid Fuel Economy (MPG)	7.02	6.17	6.59
% Improvement	23.8%	18.5%	19.2%

When both routes are averaged together, the hybrid bus achieved a fuel economy of 7.86 MPG, while the non-hybrid bus achieved a fuel economy of 6.59 MPG – an improvement of 19.2%. The benefits were seen on both routes, with a greater fuel economy boost on Route A, 23.8%, compared to Route B, 18.5%.

The greatest fuel economy was achieved on Route A, where the hybrid system operated at 8.69 MPG. Total MPG was less on Route B, where the hybrid system operated at 7.31 MPG (15.9% difference between routes). In the non-hybrid, the difference between Route A and Route B was smaller, just 12.1% between the routes. This implies that the hybrid system is more effective on Route A, where the higher average speed might allow the engine to operate more efficiently.

The fact that the hybrid provides greater benefit on Route A than Route B is consistent with the benefits of the hybrid system, in which the hybrid contributes more power to the vehicle when there are more stops and starts. This provides more opportunity for the hybrid system to capture energy through regenerative braking and return that energy to the wheels through acceleration boost. This reinforces the need for transit agencies to be strategic in deploying HEBs in their fleet, and when selecting the optimal routes for HEB operation.

4.3.2 Drivecycle, Speed and Idling Analysis

Comparing the fuel economy results from the demonstration period (Table 3-6) against those shown above in Table 4-3 we see that fuel economy was higher across the board in the two-day test than in the six-month demonstration. This differential can be partially explained by the more controlled environment in which the two-day test was performed, with no A/C load and nearly half the amount of idling as over the demonstration. The performance of the hybrid in the two-day test closely mirrored the results from the first month of testing, in which driver training was freshest and the weather was cooler (less demand for A/C). These results indicate that higher MPGs and hybrid benefits are achievable in Tracy if the vehicles are driven with a focus on efficiency. The distinction in routes was also investigated using data collected from the CALSTART data loggers during test runs on each route. Figure 4-1 and Figure 4-2 show these drive-cycles on Route A and Route B.

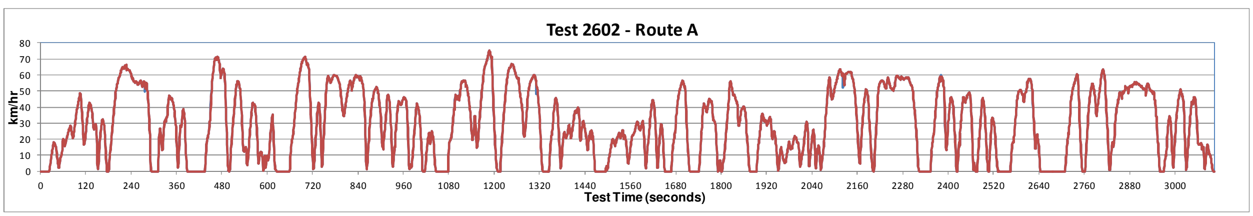

Figure 4-1: Drive-Cycle Plot for Test on Route A

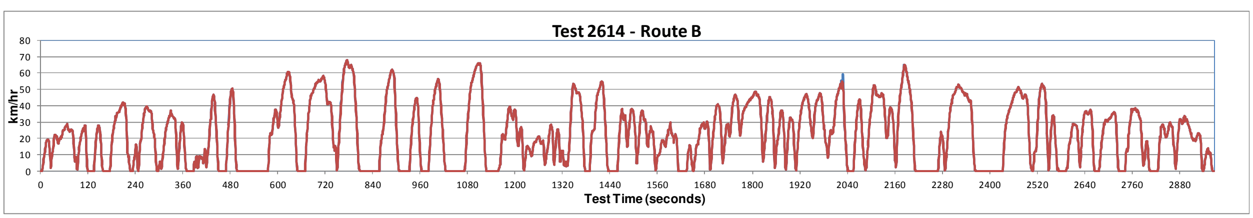

Figure 4-2: Drive-Cycle Plot for Test on Route B

Route A contains more segments of sustained high speed than Route B. There appear to be more peaks and drops in Figure 4-1 than Figure 4-2, indicating more stop-and-go driving while the average peak height on Route B is lower than Route A which is in-line with lower average driving speed reported in Section 3.2.

The vehicle speed distribution in the test (Table 4-4, Figure 4-3) is similar to that seen in the demonstration period, with the exception of time spent idling.

Table 4-4: Vehicle Speed Breakdown, 2-Day Emissions Test

Speed Bin	Hybrid	Non-Hybrid
Idle	16.4%	17.0%
0-5 MPH	9.7%	9.9%
5-10 MPH	10.4%	9.8%
10-15 MPH	13.6%	13.4%
15-20 MPH	11.4%	11.2%
20-30 MPH	22.6%	22.5%
30-40 MPH	13.1%	13.9%
40+ MPH	2.8%	2.5%

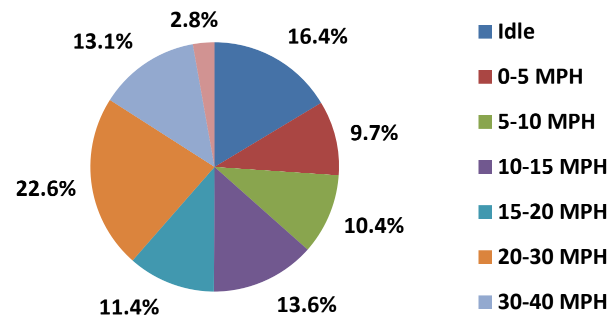

Figure 4-3: The Hybrid Speed Breakdown During the 2-day Emissions Test

Vehicles in this test spent 16.4% of time idling, while the vehicles in the demonstration period idled for roughly 32% of engine-on time, approximately double. This may be due to shorter dwell times at bus stops (the bus was in simulated revenue service, but not actually taking passengers) as well as less long-duration idling at the depot and between shifts.

4.3.3 Route-Specific CO_2 Analysis

Improved fuel economy means a decrease in CO_2 generated. Gasoline produces 19.7 lbs. of CO_2 for every gallon that is consumed,[8] so reductions in fuel use can be directly translated to reductions in CO_2 emissions. A conversion of the fuel economy findings shows that the hybrid bus produces 2.87 lbs. of CO_2 per vehicle-mile (averaged between Route A and Route B); while the non-hybrid bus produces 3.29 lbs. of CO_2 per vehicle-mile (see Table 4-5). Accordingly, the hybrid reduces CO_2 emissions by 12.9% compared to the non-hybrid.

Table 4-5: CO_2 Emissions by Route (lb./mi)

	Route A	Route B	Average
Hybrid	2.68	3.09	2.87
Non-Hybrid	3.09	3.52	3.29
% Improvement	-13.5%	-12.1%	-12.9%

4.4 Emission Results

The emission measurements from the RAVEM™ system across all test runs were categorized by vehicle type and route in Table 4-6 below.

[8] U.S. Energy Information Administration, "Independent Statistics and Analysis" available at http://www.eia.gov/tools/faqs/faq.cfm?id=307&t=11. Accessed on September 3, 2014.

Table 4-6: Emission Measurements[a] by Vehicle and Route (g/mi)

	Route A		Route B		Combined	
Bus	NOx	CO	NOx	CO	NOx	CO
Hybrid	0.29	2.09	0.24	2.25	0.27	2.17
Non-hybrid	0.35	1.93	0.27	0.97	0.31	1.45
% change	*-18%*	*+8%*	*-12%*	*+133%*	*-15%*	*+50%*

[a] PM and HC found to be below detectable limits.

Averaged over both routes, NOx emissions on the hybrid bus were 15% lower than the non-hybrid, but CO emissions were 50% greater. When comparing routes, the variation between routes was small for NOx, but great for CO. As shown above, measured NOx on the hybrid vehicle were 12% and 18% lower than the non-hybrid on Routes A and B, respectively, but CO emissions increased substantially: 8% on Route A and 133% on Route B.

Hydrocarbon (HC) emissions were too low to measure accurately, given the variability in ambient background THC concentrations. Similarly, measured PM emissions on Route A were below detection limits when the hybrid system was off, and slightly above the detection limit with it on. Particulate Matter (PM) emissions on Route B were below the detection limit in both conditions. More testing would be needed to determine whether the apparently higher PM emissions with in Route A with the hybrid on are due to a real effect or a statistical fluke. Both HC and PM are reported as "below detectable limits."

The increased CO numbers led to investigations of the second-by-second THC emissions to determine whether the two were occurring at the same time. Figure 4-4 and Figure 4-5 show these two data sets.

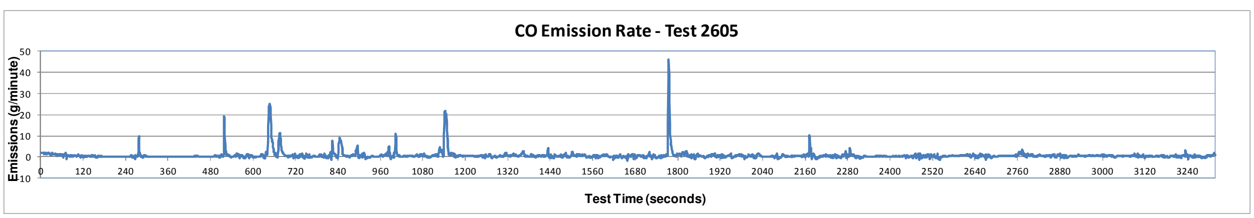

Figure 4-4: CO Emission Rate for One Hybrid Test Run

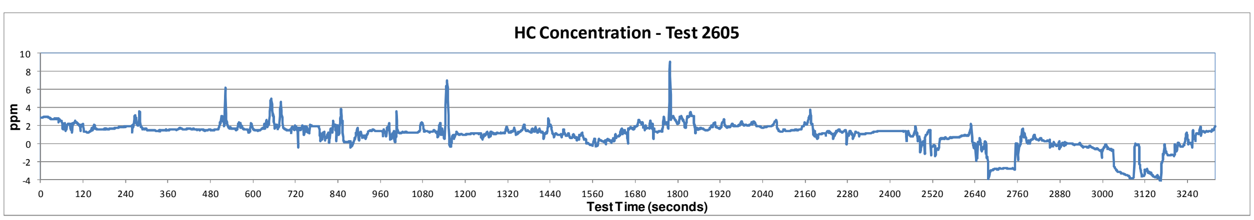

Figure 4-5: THC Concentration for One Hybrid Test Run

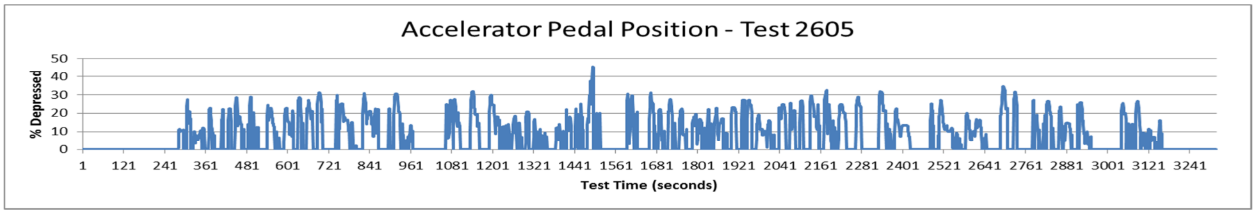

Figure 4-6: Acceleration Pedal Position for One Hybrid Test Run

The second-by-second data in Figure 4-4 and Figure 4-5 show that THC emissions were also concentrated in a small number of spikes, which were simultaneous with the spikes in CO. These are likely due to mixture enrichment for increased power during acceleration.

It was expected that the hybrid drive system would reduce CO emissions, since, if operated correctly, the hybrid boost takes load off of the engine. However, a 50% average increase in CO demanded further investigation.

We correlated the emissions data with the accelerator pedal position from the OBD loggers used in the demonstration. In most cases analyzed, the CO peak in the emissions data roughly correlated to a rapid acceleration event. In Figure 4-6 we see a major depression of the accelerator pedal—corresponding to a spike in the graph—slightly before one of the major CO and THC peaks. The delay in emissions spike from this acceleration event could be measurement error either from the data collection equipment or emissions measurement system. We believe this abrupt increase in engine throttle position caused a temporary shortage of combustion air and the resulting CO peak. In some cases, rapid acceleration may be required for safe driving. In other cases, training the driver to moderate their accelerations will reduce the frequency of the CO peak events and the generation of CO.

However, even with this analysis, the CO results benefit from further scrutiny. For three of the four testing scenarios – hybrid on Route A, hybrid on Route B, and non-hybrid on Route A – there was a relatively narrow band in CO emissions, between 1.93 and 2.25 g/mi, as shown in Table 4-6. However, for the fourth scenario – non-hybrid on Route B, CO emissions were measured at 0.97 g/mi. A visual analysis of the CO emissions profiles like the one in Figure 4-4 suggests that CO emissions were close in magnitude across all runs. This inconsistency suggests additional comparison and emission testing is necessary to validate the summary results.

5. MAINTENANCE AND RELIABILITY FINDINGS

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. Since data were collected over the course of six months, the findings are more representative of the ongoing costs that a transit agency might expect than would be the case with a short term analysis or parts study. 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.

5.1 Methodology

The hybrid and non-hybrid shuttle buses were serviced by MV Transportation in Stockton, CA, the service and maintenance partner for this study. MV performed periodic maintenance (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. MV 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 non-hybrid 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/5000 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 Sacramento 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.

Lastly, we coordinated with MV and Crosspoint Kinetics to collect information on hybrid issues that arose during the test and details on an upgrade and warranty extension that occurred during the demonstration period.

5.2 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 are displayed below in Table 5-1.

Table 5-1: Monthly Demonstration Period Maintenance Summary Combined for Both Vehicles

Month	Distance (mi)	Parts Cost	Labor Time (hrs)	Labor Cost	Total Cost	Cost/ Mile
May	6,899	$1,137.86	43	$1,334.76	$2,472.62	$0.36
Jun	4,586	$60.24	18	$563.30	$623.54	$0.14
Jul	5,667	$36.63	10	$311.00	$347.63	$0.06
Aug	8,420	$226.93	16	$603.67	$830.60	$0.10
Sep	8,236	$1,866.70	18	$550.53	$2,417.23	$0.29
Oct	8,459	$19.97	4	$118.99	$138.96	$0.02
Total	**42,267**	**$3,348.33**	**109**	**$3,482.25**	**$6,830.58**	**$0.16**

Over the six-month demonstration there was $6,831 in maintenance costs combined for both vehicles, split evenly between parts and labor. Normalized with VMT, the vehicles cost $0.16 per mile for service and maintenance. The total service costs over the life of the demonstration were primarily driven by a small number of expensive service events to brakes, tires, and the starter system (alternator, batteries, and starter). As a result, the month-by-month costs varied greatly, from a low of $139 in October to $2,473 in May.

The most expensive month for the project came towards the beginning of the demonstration period, which is in line with feedback from MV Transportation technicians who had to troubleshoot a handful of issues in May. Additionally, it should be noted that the high parts cost in September was due to tire replacements on both buses and a starter system replacement on the non-hybrid bus.

The high costs in the month of May and September are explained by a small number of service events on major vehicle systems. In May, the hybrid vehicle received an alternator ($948 parts and labor), brake ($242 parts and labor) and tire ($240 parts and labor). In September, the hybrid vehicle received a second tire change ($580 parts and labor), and the non-hybrid bus received a new starter, batteries and regulator ($1,017 parts and labor) as well as new brakes ($142 parts and labor) and tires ($280 parts and labor). Otherwise, the PM and miscellaneous maintenance costs in these months were in line with the other months of the test.

5.3 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:

- Periodic 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

After categorizing each service event, the total parts and labor cost for each category were summed for both buses; the results are in Table 5-2 below.

Table 5-2: Breakdown of Vehicle System Maintenance Cost per Mile

Vehicle System	Total Cost	Cost/Mile	Percent
Propulsion Systems[1]	$1,997.26	$0.05	29%
Tires	$1,131.49	$0.03	17%
Periodic Maintenance[2]	$1,163.24	$0.03	17%
Cab, Body & Accessories	$1,036.36	$0.02	15%
Brakes[3]	$657.71	$0.02	10%
HVAC	$416.03	$0.01	6%
Frame, Steering and Suspension	$358.23	$0.01	5%
Lights	$46.95	$0.00	1%
Air systems	$0.62	$0.00	0%
Axles/Wheels	$22.68	$0.00	0%
Total	**$6,830.58**	**$0.16**	**100%**

[1] Repairs for exhaust, fuel, engine, electric motors, traction batteries, and propulsion control, non-lighting electrical, air intake, cooling, transmission, and hydraulics.

[2] Labor only for inspections during preventive maintenance.

[3] Excludes regenerative braking for the hybrids, which is included in propulsion-related systems.

Service problems were spread over several categories. Two of the four most expensive categories were brakes and tires – components that require regular replacement. Two other categories, propulsion systems and accessory systems, were expensive due to parts failures that required replacement. Ongoing preventative maintenance was a last expensive item; each maintenance service was inexpensive, but the regular maintenance schedule caused the category to be expensive over time.

The Periodic Maintenance inspection costs reported in the service logs are somewhat higher than the true PM costs due to mechanics' practice of using a PM as a catch-all for any minor issues that are reported on the vehicle. As a result, some of the labor hours reported as periodic maintenance are actually spent servicing a parts failure in another vehicle system. Due to data limitations, the PM costs cannot be broken out to allocate repair costs to different categories, but the bias in the results is noted here.

Not relayed in Table 5-2 are the issues that did not incur service costs but caused inconveniences or affected availability. For example, the HVAC system on the non-hybrid bus, which frustrated mechanics throughout the ownership of the vehicle. The cost per mile associated with the HVAC system is very low because few parts were purchased for it; instead drivers continually noted the bus in need of repairs which tied up resources at the maintenance facility.

5.4 Unplanned Hybrid System Service Issues

There were two unforeseen hybrid-system incidents during the demonstration period that required specific assistance from Crosspoint Kinetics staff, either by phone or on-site. On May 23rd an audio alarm on the hybrid bus would not turn off, confusing drivers who believed the hybrid system was malfunctioning. Upon further inspection, a poor connection inside the alarm electrical harness was discovered.

In June, the non-hybrid bus was being driven to a dealer for an air-ride suspension issue when a defective bearing-and-cup assembly in the hybrid motor failed while on the freeway (the non-hybrid bus was equipped with a hybrid boost system that was disengaged for the purpose of this test). A staff member from the manufacturer met the bus at the dealership and installed a new motor on the vehicle, completing all repairs in approximately four days. While the cost of the repair was covered under warranty, the vehicle remained at the dealership for two weeks after these repairs waiting for personnel and parts to address the initial air-ride issue, drastically diminishing the non-hybrid bus' availability in June and July.

These issues highlight a challenge with the hybrid system. Both issues required assistance from the dealership technicians or Crosspoint Kinetics staff, and could not be serviced directly by City of Tracy technicians. While the two service issues related to the hybrid system were not expensive because they were covered under warranty, these issues caused the buses to go out of service for longer than would have been needed if the vehicles were serviced on-site.

This points to an opportunity to improve vehicle availability and ease of maintenance by providing training and tools to transit agency technicians so they can maintain the technology on-site.

5.5 Vehicle Uptime

Both vehicles experienced maintenance issues that limited their availability to the fleet during the demonstration period. Vehicle uptime is defined as the percentage of days that a vehicle was available for service, whether it was used or not. The City of Tracy used these buses as much as possible; if they were available for service Monday thru Saturday, they were used. Uptime was calculated for each vehicle by dividing the number of days spent in revenue service each month by the total number of possible service days in that month. Table 5-3 and Figure 5-1 below show the vehicle uptime by vehicle and by month.

Table 5-3: Vehicle Uptime by Month

Month	Hybrid	Non-Hybrid
May	81%	74%
Jun	100%	16%
Jul	93%	26%
Aug	96%	70%
Sep	96%	80%
Oct	93%	93%
Average	**93%**	**60%**

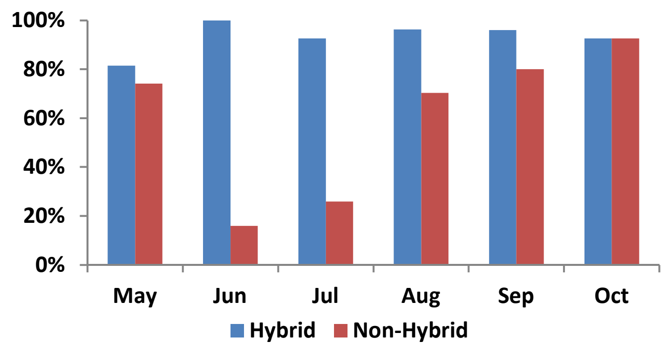

Figure 5-1: Vehicle uptime chart by month

The hybrid bus remained available to the fleet for service an average of 93% of the time, whereas the non-hybrid maintained an average of 60%. The much lower non-hybrid availability is due mainly due to an extended period of time during the demonstration period when the bus remained at a dealership awaiting parts and labor for warranty-specific issues that could not be completed by MV.

Apparent in Figure 5-1 are the distinctly lower uptime values for the hybrid in June and July. This is due mainly to a non-hybrid air-ride system issue that kept it at a dealership for multiple weeks waiting for parts and personnel. This issue is emblematic of the MV experience as explained by technicians and managers, wherein poor design and complications with specific systems took the vehicles out of service for longer periods of time than their counterparts.

Throughout the test, the hybrid bus remained available over 80% of the time. It was only in October, after significant upgrades to the hybrid system were made in September, that both vehicles approached an acceptable threshold of availability to the fleet. This highlights the need to adequately maintain all hardware and software components of the hybrid system, as they are more than partially responsible for full functionality.

5.6 Hybrid System Upgrades and Warranty Extension

One major aspect of hybrid functionality is completing upgrades and ensuring parts serviceability remains under warranty. Towards the end of the testing period, Tracy purchased an extended warranty and upgrade to the hybrid system from Crosspoint Kinetics. While the cost of this upgrade was not included in the maintenance analysis (it was unrelated to any service issues that arose), information about this upgrade is included here as it may be of interest to other transit agencies running shuttle buses with the Crosspoint Kinetics system.

Tracy purchased these vehicles in 2012. Since that time, the manufacturer had designed a new-generation hybrid system, and the warranty on the buses had expired. Tracy purchased a system upgrade and warranty extension package in which the manufacturer upgraded the hybrid system with the newest technology and extended the warranties an additional 18 months.

The manufacturer developed the "Turbo Boost Upgrade" to provide new hardware and software to previous hybrid customers. Several improvements were made to increase durability, raise hybrid torque through software enhancements and provide a more reliable system. These improvements were validated for performance and life on a Cummins Engine Corp. dynamometer test setup.

This upgrade included several hybrid software changes that increase boost and regeneration torque an average of 25% over the original hybrid system. The package included:

- Replacement of the hybrid motor and controller with reconditioned units containing the new hybrid technology.
- All labor to complete the upgrade.
- An 18 month extended service contract on the upgraded hybrid system.

The total upgrade, installation and service contract cost was $11,695 per vehicle. This work was completed in December 2013.

6. DRIVER AND MANAGER FEEDBACK

The purpose of evaluating driver and manager feedback is to assess impressions of the vehicle from the driver, maintenance and fleet managers’ points of view. Comparisons were made between the hybrid and a non-hybrid vehicle to determine the advantages or disadvantages during normal everyday use.

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, middle and upon completion of the demonstration period. This survey 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 from MV Transportation was interviewed by phone 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. These interviews were conducted at the middle and end of the demonstration period to look for any improvement or decay of bus components.

The Fleet Manager from the City of Tracy 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 hybrid systems were made functional by Crosspoint Kinetics 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 Driver survey is shown in Appendix F. The Maintenance Manager questionnaire is shown in Appendix G. The Fleet Manager questionnaire is shown in Appendix F.

6.1 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. The City of Tracy was responsible for distributing, coordinating, and collecting completed driver forms. Surveys were distributed via the Fleet Manager at the beginning, middle and end of the demonstration period to as many drivers as possible.

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: Both vehicles had a low-floor chassis with a flip-down wheelchair ramp that was much quicker than the standard lift. This metric queries whether this and other hybrid advancements affected drivers' ability to cover their routes any quicker with the hybrid.

The following results (Figure 6-1) from the final round of surveys display the combined ratings of all five drivers surveyed and indicate their thorough perceptions after significant experience with the vehicle.

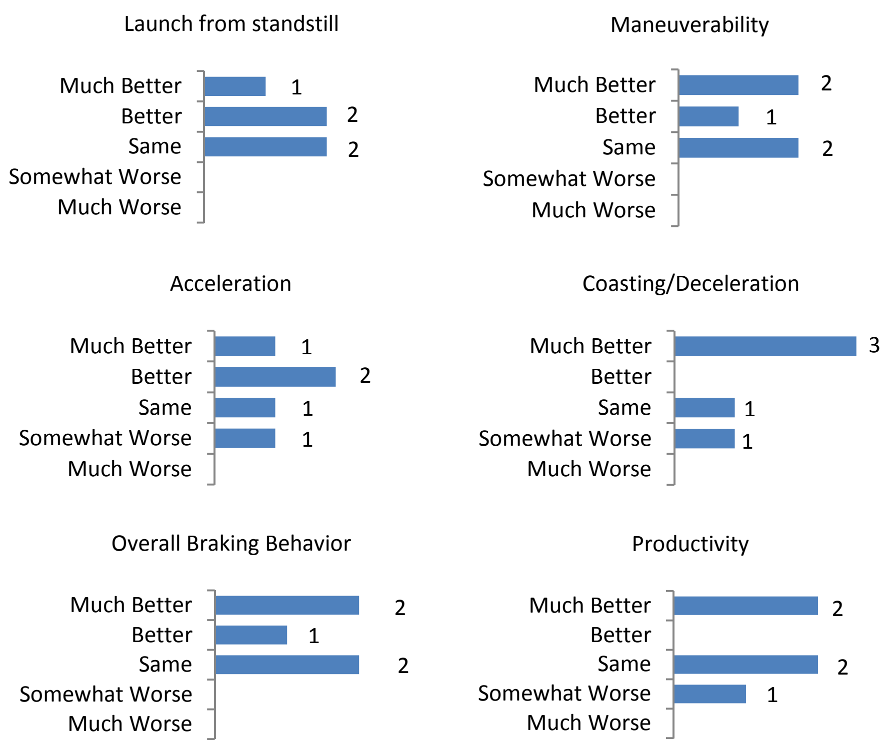

Figure 6-1: Final Driver Survey Performance Ratings

Across all responses, drivers indicated that the hybrid vehicle outperformed a comparable conventional shuttle bus. Perhaps most noticeable from all six of these charts is that only one driver included any negative ratings, in Acceleration, Coasting/Deceleration and Productivity. The driver in question had significant experience with the vehicle and his responses highlight areas for improvement. Drivers came to accept many of the performance traits of the vehicle, noting that some areas were actually improvements over the conventional vehicles they were accustomed to driving.

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 (Figure 6-2), where the averaged response to each question is shown for the initial, mid-test, and final survey.

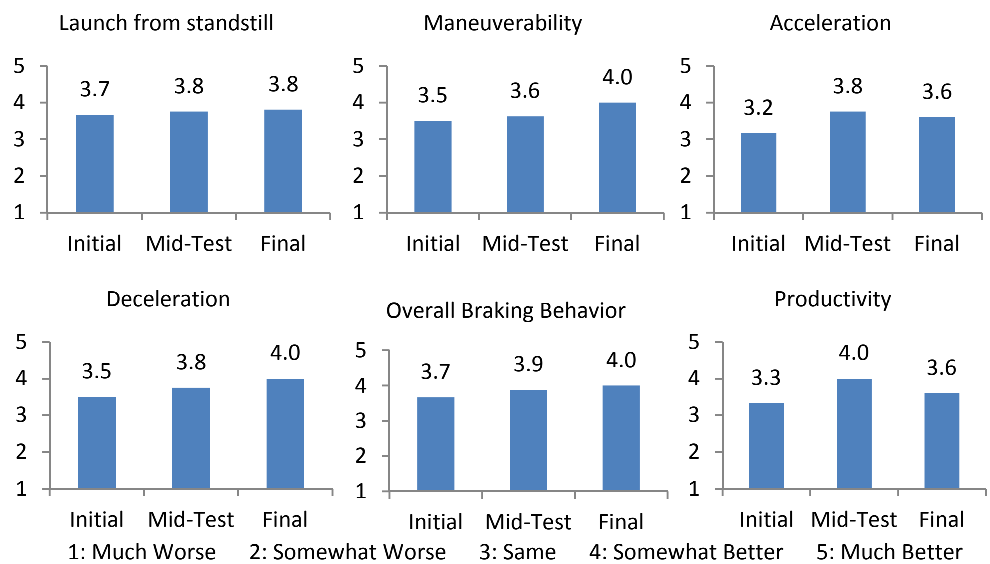

Figure 6-2: Driver Survey Performance Historical Trends

For most metrics, drivers grew to like the hybrid more as they gained experience with it, and overall scores continued to increase from the beginning to the end of the test. On all surveys, every question scored an average of 3 or greater, corresponding to rating the metric as "same", "somewhat better", or "much better". In Figure 6-2 above, the Productivity chart shows the exaggerated effect of the wheelchair ramp (in place of a lift) on drivers' perceptions of the test vehicles in the mid-test survey. They were quick to recognize the increased speed with which they could load wheelchairs on their vehicles, but by the end of the test this productivity rating equilibrated at a level slightly above the conventional vehicle. The deceleration and braking of the vehicle steadily increased throughout the test as drivers gained experience and feel for the Crosspoint Kinetics regenerative braking scheme.

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.
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 non-hybrid 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. However some may have responded regarding with the ergonomics of the interior body space in mind as well.

The results from the final surveys are displayed below (Figure 6-3) and indicate drivers' thorough perceptions after significant experience with the vehicle.

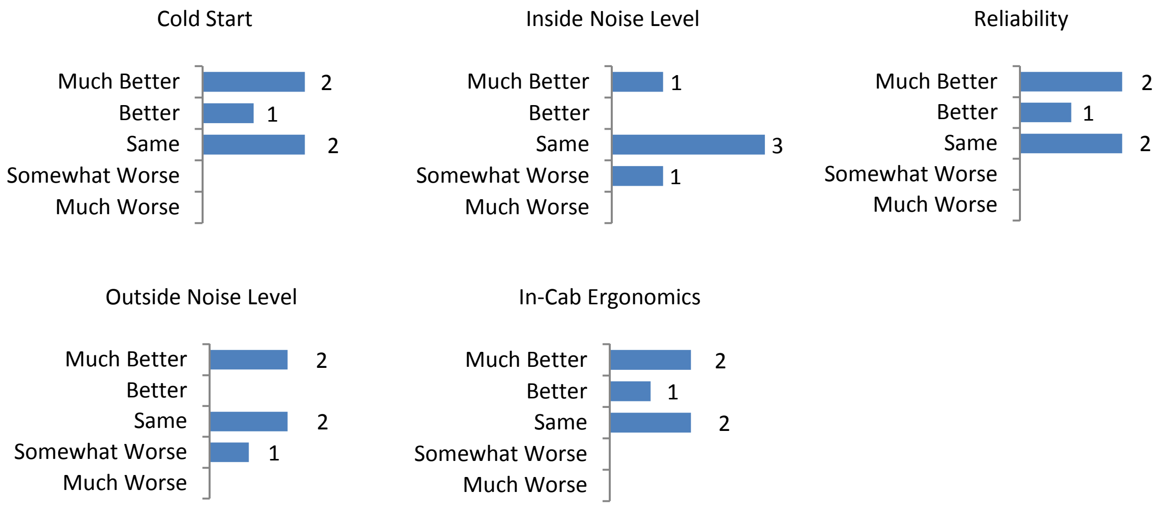

Figure 6-3: Final Driver Survey Operational Metric Ratings

Drivers had the strongest opinions about the Inside and Outside Noise Levels on the hybrid vehicle. This is almost certainly due to the addition of the Crosspoint Kinetics hybrid system and its location directly below passengers' feet. The improvements in the Ergonomics scores are most likely related to reduced noise in the driver area.

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 for the initial, mid-test, and final survey (shown in Figure 6-4).

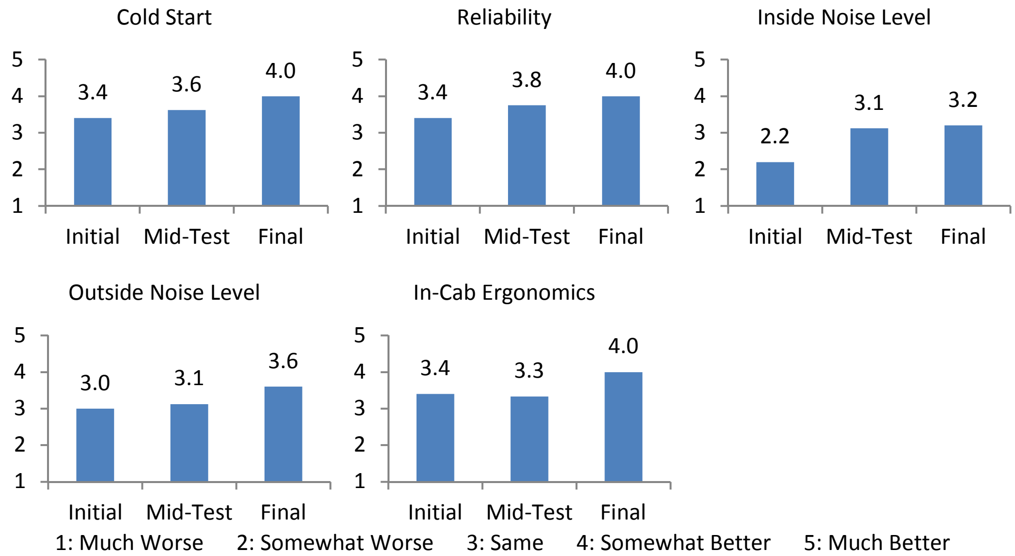

Figure 6-4: Driver Survey Operational Metric Historical Trends

Every single operational metric rating improved from the beginning to the end of the demonstration. The improvement in the Inside Noise Level rating demonstrates drivers getting used to the new sound of the hybrid system and perhaps receiving fewer passenger complaints over time. As the manufacturer upgraded the system during the demonstration period it is also possible that a better calibrated hybrid system was responsible for noise reduction. The In-Cab Ergonomics and Reliability ratings also improved as compatibility with the interface and service issues were resolved, respectively.

These surveys tell us that at this point the drivers accept the hybrid vehicles to the point where they are close to being interchangeable with the conventional buses from a performance standpoint. This integration did not happen overnight, but drivers show an openness and capability to get used to basic performance differences. The vastly improved rating of Interior Noise Level could be due to a few different factors, but the consequences are all the same: over time, end users can equilibrate the level of sound to that of a conventional vehicle.

6.2 Maintenance Manager Interviews

Interviews were conducted by phone and in person at the middle and end of the demonstration period and were based off of a maintenance manager evaluation questionnaire. In order to evaluate the serviceability and maintainability of the hybrid vehicle, the maintenance manager was asked to provide feedback on various service and maintenance aspects of the hybrid bus compared to the non-hybrid 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 shuttle bus experienced numerous problems throughout the duration of the demonstration period, most of which were related to bus components rather than the hybrid system. However, the maintenance manager noted that the hybrid system does add a level of complexity to the vehicle, which is partially responsible for the "high percentage of failures on all 7 vehicles [including 3 from a separate fleet], a number [he] would expect from a fleet of 100 vehicles." While it is difficult to compare the test vehicles with a fully conventional fleet, the nagging issues that spanned the entirety of the demonstration period, such as the HVAC problems noted in Section 5.3, reinforce the maintenance manager's opinions of added complexity and poor build quality. Additionally, with these brand new vehicles and system componentry, one would expect significant formal training for all personnel types, but in fact the opposite was true; staff were trained ad-hoc with little to no instruction on software for the air lift, HVAC or hybrid systems. When hybrid maintenance or upgrades were performed Crosspoint Kinetics staff did provide instructions or demonstrate techniques for MV Transportation technicians, but these events were rare, resulting in limited knowledge transfer.

As new maintenance issues occurred, MV Transportation discovered problems with vehicle design resulting in serviceability issues. For example, the rear suspension hinders brake pad replacement in unforeseen ways, the brake hoses initially interfered with front cross-members before adjustments were made, and one of the air-ride suspension bags rubbed on a brake component so much it eventually began to tear. These and other shuttle bus problems were shared and discussed with other MV-serviced fleets across the country in an attempt to lessen the impact on fleet operations.

The collective group knowledge of the hybrid system increased steadily for the MV Transportation maintenance team in Stockton as they became more accustomed to system intricacies and worked with the manufacturer when repairing and upgrading the hybrid system. The manager suggested a better indicator module (signal light or other) of hybrid functionality to inform drivers of its behavior. This suggestion was made independently of either the fleet manager or drivers themselves, but was echoed by both of these groups.

6.3 Fleet Manager Interviews

The fleet manager has a unique position and perspective on the hybrid vehicle and therefore was interviewed along with the maintenance manager. In the same vein as the maintenance manager interview, this discussion 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 he receives from drivers, mechanics, and Tracy personnel, respectively. Adding safety and reliability to the list speaks to the manager's capability of comparing the hybrid vehicle to the rest of his fleet.

The fleet manager for the City of Tracy explained that the two shuttle buses in this test were run every day that they were available, Monday thru Saturday. This underscores the importance of keeping the vehicles roadworthy, which heavily influenced the perception of their reliability. While the reliability of a one year-old hybrid is better than a five year-old conventional vehicle, "the hybrids generally have a worse maintenance record because of the additional piece we're trying to work out." This echoes both the nagging issues seen in the maintenance records and the added level of complexity mentioned by the maintenance manager.

With regards to vehicle performance and fuel consumption, the fleet manager recognized that in a small fleet (only 15 vehicles) one particularly efficient bus could account for noticeable change, yet it was somewhat premature to determine the impact of these vehicles on the fleet thus far. To increase fuel savings via driver performance, he suggested a three step approach that incorporates a hybrid-driving training component, an improved charge indicator module in the cab, and continual reporting of the Average Fuel Economy statistic (AFE) on the driver shift logs. The AFE is self-reported by drivers after their shift directly from the in-cab gauge readout. With this three-pronged approach, drivers will initially be exposed to proper practices, then able to "see how they're doing so they can make adjustments on the fly" while en-route, then immediately see the impact of their efforts at the end of each shift. In this way, the fleet would get the best fuel economy out of the hybrid vehicles and engender a culture of fuel-efficient driving habits.

6.4 Lessons Learned

The historical trend in driver surveys indicated that drivers and passengers can get used to the noise emanating from the hybrid system under the floor. This is important because it suggests that the noise from the system is not objectively that much louder than the conventional vehicle, rather it is just a different sound generated somewhat closer to the passengers' feet. The fleet could install an explanatory placard indicating full functionality of the bus despite the noise from the hybrid system located under the low-floor chassis; this would provide users with an added sense of security upon entering the vehicle.

To ease the hybrid-related repairs, mechanics and managers need better component training, including all requisite software. An increasingly available parts supply and support network for both the shuttle bus and the hybrid system will decrease the lead time on repairs, getting vehicles back on the road sooner. Addressing the handful of shuttle bus design issues identified by MV that required internal re-work could have great impact on the overall serviceability of the vehicles.

As the hybrid system itself is continually optimized, so too can individual driver performance be improved. A more intuitive charge indicator module in the vehicle cab would inform drivers on the proper operation of the hybrid system and how to achieve optimum fuel economy. A module of this type is currently being developed by the manufacturer and could conceivably be beta-tested on the City of Tracy fleet.

Roughly two-thirds of the way through the demonstration period, the pool of drivers operating the hybrid vehicle expanded to include drivers who had not received training on optimal operation. This resulted in a noticeable drop-off in MPG measurements. Whenever new drivers begin working with the hybrids, this decrease in fuel efficiency could be greatly reduced with a more effective in-cab training module.

7. SUMMARY AND CONCLUSION

This project quantified the benefits of an ultracapacitor hybrid system on a municipal shuttle bus. The hybrid and non-hybrid baseline vehicle were instrumented and tested in real-world service for the City of Tracy. In addition, a Portable Emissions Measurement System (PEMS) test was conducted at the conclusion of a six-month demonstration period, capturing emissions data from the hybrid vehicle with the ultracapacitor system engaged and disengaged. 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:

1. The combined fuel and CO2 savings for the hybrid over the course of the six-month demonstration period were 375 gallons and 7,371 lbs., respectively.
2. All fuel economy results were higher for the two-day test than the six-month demonstration, likely due to the increased test control, reduced idling, and lack of air conditioning load in the two-day test.
3. Emissions data demonstrated a reduction in NOx with the hybrid, but an increase in CO, likely due to fuel enrichment during rapid acceleration events.
4. Occasional maintenance issues affected the hybrid vehicle, whereas major repairs were performed on the conventional baseline vehicle at two separate times during the demonstration period.
5. Vehicle availability of the non-hybrid baseline varied throughout the test due to these extended service issues; meanwhile the hybrid vehicle retained 93% availability.

APPENDICES

Appendix A: Fuel Calculation Methodology

Appendix B: Fuel Log

Appendix C: Driver Shift Log

Appendix D: PEMS Report

Appendix E: RAVEM System Detail

Appendix F: Driver Survey

Appendix G: Maintenance Manager Questionnaire

Appendix H: Fleet Manager Questionnaire