

## **Ultracapacitor Based “Hybrid Booster Drive®”**

Anthony J. Palumbo, Chief of Operations, Electric Vehicle Institute, Bowling Green State University, Bowling Green, OH 43403. Ph 419-372-8391 Fax 419-372-2800

Aaron Bloomfield, Data Acquisition Engineer, Electric Vehicle Institute, Bowling Green State University, Bowling Green, OH 43403. Ph 419-372-8391 Fax 419-372-2800

Jeff Major, Chief Engineer, Electric Vehicle Institute, Bowling Green State University, Bowling Green, OH 43403. Ph 419-372-8391 Fax 419-372-2800

### **Abstract**

This paper reports the design, testing and performance of the Hybrid Booster Drive® (HBD), an engine dominated, ultracapacitor assisted, parallel hybrid system. For purpose of this study and proof of concept the HBD was installed on two prototype vehicles, one a 14,900 pound GVWR delivery vehicle and the other a 20,000 pound GVWR shuttle bus. The paper includes a discussion of Hybrid Booster Drive® application recommendations, considerations and variations.

The HBD offers an efficient and economical way to integrate an ultracapacitor-based electric hybrid drive with a conventional internal combustion engine drive train. The HBD system augments traditional engine drive trains by recovering energy during braking, storing it in ultracapacitors and returning the energy to accelerate the vehicle. This system allows for the optimization of engine operation thereby reducing fuel consumption and exhaust emissions.

The potential and benefits of using ultracapacitors for energy storage in a hybrid electric vehicle has been known for many years. Ultracapacitors offer superior efficiency, longevity and are less temperature dependent as compared to batteries. This novel ultracapacitor hybrid drive system minimizes component count and energy conversion inefficiencies. The patented system consists of three hardware modules, the ultracapacitor bank, the traction drive, and the controller/inverter. Operational control software orchestrates these components.

The Hybrid Booster Drive® system is designed such that components perform throughout the useable voltage range of the ultracapacitors. As such, the HBD system does not require an electronic converter which is typically used for ultracapacitor voltage control. The absence of the electronic converter can save cost, weight and losses.

The research reported in this paper indicates that the ultracapacitor as an energy buffer in a hybrid vehicle is feasible.

### **Keywords:**

AC Motor, AC-DC, Algorithm, Braking, Bus, Communication link, Component, Control System, Controller, Data Acquisition, Demonstration, Diesel Engine, Diesel Hybrid, Double-layer Capacitors, Electric Drive, Electric Launch, Energy Consumption, Energy Density, Energy Recovery, Energy Source, Energy Storage, HEV (hybrid electric vehicle), Hybrid, Hybrid Strategy, IC Engine (ICE), Induction motor, Instrumentation, Inverter, Load Management, Low Emission Vehicle, Motor, Parallel Hybrid, Power density, W/kg, Powertrain, Propulsion System, Pseudo-capacitors, Regen, Regenerative Braking, Self-discharge, Super Capacitor, Torque Blending, Transmission, Ultra Capacitor, Vehicle Performance

## 1. Introduction

At the 1993 Sustainable Transportation Symposium held in Boston, Dr. John Miller reported the potential benefits of utilizing large electrochemical capacitors, now commonly referred to as ultracapacitors, for load leveling in electric vehicles. These benefits included high efficiency, long life, low maintenance, and temperature tolerance [1].

In 1997 the NASA Hybrid Electric Transit Bus (HETB) project demonstrated the use of ultracapacitors as an energy storage alternative to batteries. NASA awarded a grant to the Electric Vehicle Institute (EVI) at Bowling Green State University (BGSU) to design, fabricate and deliver not only the propulsion motor,



**NASA HETB**

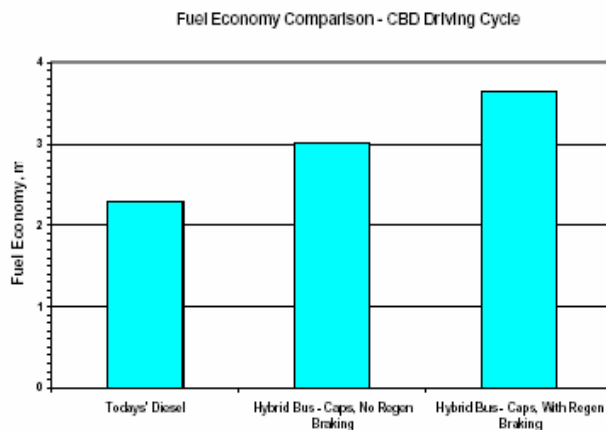


**Electric Falcon**

but also the transmission, traction controller, auxiliary motor and drive. The NASA scientists were impressed with EVI expertise with liquid cooled induction motors and high performance variable frequency inverters gained through early work on the *Electric Falcon*, a battery powered formula race car.

EVI personnel obtained valuable experience with ultracapacitors in hybrid electric drives while working on the HETB. This resulted in the development of an electric traction drive system so unique that BGSU has since been assigned a US Patent.

NASA scientists released the results of the first phase of the NASA Hybrid Electric Transit Bus (HETB) project. In the NASA report, published in January 1999, the HETB series hybrid vehicle equipped with ultracapacitors produced 56% fuel savings for the White Book central business district drive cycle over a traditional diesel-powered vehicle. The NASA report extensively documented the performance and commercial potential of an ultracapacitor-based series hybrid transit coach. It is believed to be the first heavy hybrid to use ultracapacitors [2].



that was developed from the components used during the first phase of the HETB project [3].

A Society of Automotive Engineers (SAE) paper by Palumbo and Waggoner presented the performance, major component features, and implications for an engineered hybrid drive system derived from the HETB project. The 1999 SAE paper introduced potential vehicle manufacturers and their customers to an available, cost effective hybrid drive approach

In a follow up SAE paper written in 2000, Palumbo and Waggoner outlined the requirements of cost effective ultracapacitor-based hybrid systems. The paper illustrated how both series and parallel hybrid

versions could be integrated into vehicles. The paper introduced the engine dominated, ultracapacitor assisted, parallel booster-drive, coined Hybrid Booster Drive® for short [4].

Despite eight years of ultracapacitor demonstration, promotion and performance certification by such groups as BGSU, NASA and the Transportation Research Center in Marysville Ohio, little interest was shown by existing vehicle developers and manufacturers in an ultracapacitor-based hybrid. They dismissed the ultracapacitor in favor of advanced batteries that they hoped would fulfill the need.

## **2. Hybrid Booster Drive**

The Hybrid Booster Drive® (HBD) is a parallel electric hybrid configuration. The HBD is employed to supplement conventional engine power on vehicles that are used for missions requiring numerous starts and stops. The major objective is to recover as much of the kinetic energy of the vehicle as possible during stopping, store it on board while the vehicle is stopped and then to use that stored energy to help accelerate the vehicle. Vehicle acceleration is accomplished with a combination of power from the conventional engine and an electric dynamo. This can add to the available energy to accelerate the vehicle. The engine and electric drive is controlled in such a manner that engine fuel consumption is minimized and emissions are reduced.

To keep costs and complexity as low as possible, the kinetic energy is converted to electric energy by the same dynamo during the deceleration event. The electric energy is stored onboard the vehicle using ultracapacitors. The HBD supplements the conventional propulsion system by the addition of three basic hardware components which are orchestrated by proprietary operating system software. These three components are the ultracapacitor bank, the traction motor, and the traction controller.

## **3. Hybrid Diesel Project**

### **3.1 Initial Design and Feasibility Study**

In 2001, the BGSU EVI team used the experience gained from the *Electric Falcon* and two NASA projects to generate a practical design of the Hybrid Booster Drive® concept that was presented in the Palumbo Waggoner paper [4]. A key approach to the BGSU design was to capitalize on past involvements with NASA. The ultracapacitor energy storage that was successful on the Hybrid Electric Transit Bus was incorporated along with the motor and mechanical drive developed for the NASA Dynamic Load Simulator project. An early requirement of the project dictated that as many components as possible were to be commercial off-the-shelf. This was done to keep the development costs down, insure system durability, stimulate the industrial economy, and to help insure that the system could be introduced into production with minimum expenditure and without government subsidy.

The target application was medium size delivery trucks and shuttle buses in the 14,000 to 20,000 pound GVWR range with missions requiring frequent stops. EVI completed a feasibility study to show the economic potential of the Hybrid Booster Drive® in order to help justify funding for a proof of concept project. A comparison of a simulated vehicle with and without the HBD was made [5].

In 2002 the Electric Vehicle Institute received a sizeable Federal grant to develop the Diesel Hybrid Vehicle Propulsion System. It then became possible to prototype and demonstrate the HBD system.

### **3.2 Project Objectives**

The objectives of the Hybrid Diesel Project were to:

1. Develop an electric hybrid system to supplement the existing diesel drive train on delivery vans and shuttle buses to reduce fuel consumption and emissions.

2. Develop the system such that the fuel savings would justify the HBD cost.
3. Utilize as many components as possible that were commercially available.
4. Maintain the payload capacity of the vehicle as much as possible.
5. Make the system relatively easy for a vehicle manufacturer to install.
6. Make the system transparent to the operator.
7. Allow the vehicle to complete its mission using the conventional drive train in the case of hybrid system failure.
8. Reduce engine, driveline and brake maintenance on the hybrid vehicle.

### 3.3 Project Method

To accomplish the objectives of the project the researchers intended to follow this plan:

1. Review HBD system design.
2. Select components based on vehicle and mission parameters.
3. Model components and run simulations.
4. Procure an appropriate chassis.
5. Install system components.
6. Instrument the chassis.
7. Conduct initial performance tests on the chassis to determine suitability of the components and configuration.
8. Develop HBD operating system on the chassis.
9. Evaluate competing vendors' components on the chassis.
10. Use the chassis installation for design review.
11. Take the best of what was learned on the chassis and outfit a suitable delivery truck.
12. Install the latest operating system.
13. Instrument and verify the delivery truck performance.
14. Use the HBD converted delivery truck for demonstration to manufacturers and operators.
15. Continue development of hardware and software on the chassis.
16. Equip a mid-size bus with HBD system and instrument for demonstration.
17. Submit vehicles for verification tests.
18. Publish results.

At the onset of the project, a setback in logistics delayed the delivery of the development chassis several months. This caused the researchers to modify the work plan to utilize an available delivery van for the proof of concept testing rather than the chassis.

## 4. Prototype Delivery Van



**Workhorse Test Van**

A 14,900 pound GVWR step van was selected as the first prototype and provided the development platform. The van was equipped with a 170 peak hp Cummins engine coupled to an Allison series 1000 automatic transmission. Although this model van is available with larger engine options, it was theorized that the smaller engine with hybrid boost would perform equally well with approximately 200 lbs of engine weight savings.

The HBD system installed in the step van operates at 300 volts DC, nominal. The onboard electrical energy storage is sized to approximately 0.6 megajoules. As three different brands of ultracapacitors were to be evaluated in the vehicle, the 300 volt

system and energy requirement of the step van provided an economical means to evaluate several brands of ultracapacitors.

The power and control electronics were mounted on the interior wall of the cargo compartment. Two types of ultracapacitors were installed in the cargo compartment as well. This allowed the project technicians to have ready access to the system for inspection and adjustment.

Ballast was added in the cargo bay to bring the GVW up to rating.

## **4.1 PTO Drive Configuration**

Following the Palumbo Waggoner paper [4], development began by equipping the van with a small electric motor and Power-Take-Off (PTO) mechanical interface. This places the parallel mechanical connection into the driveline behind the engine torque converter, ahead of the transmission gearing. This option appeared to be the easiest and quickest way to get the van operational. It also was thought that the transmission gearing would provide the necessary torque multiplication to allow the small motor to achieve the desired result.

### **4.1.1 PTO Drive Specification**

Several EP design iterations were installed on the PTO drive and tested. The last version consisted of an air cooled NEMA 215 frame motor driving through a 1.2 to one, step-up PTO ratio. This version yielded EP power of about 55 kW peak and provided nearly maximum allowable torque input to the transmission through the PTO gear.

The NEMA 215 frame motor was non-ventilated and thermally limited to about one hour of run time; however it did provide adequate power. It allowed sufficient run time to demonstrate that a parallel hybrid system using ultracapacitors has the capability to improve fuel economy. It provided an invaluable platform on which the critical control algorithms were further developed. This 215 frame motor is near the size limit that can be accommodated within the frame rails of the chassis without interfering with the drive shaft. The need for improved cooling is clearly evident.

### **4.1.2 PTO Drive Findings**

During this study it was found that:

1. This combination yielded a modest increase in fuel economy.
2. The torque input limitation on the PTO is insufficient for adequate regenerative braking (REGEN) and for low speed acceleration.
3. Although the transmission gearing would help on acceleration, the transmission's programmed down shift during deceleration was not aggressive enough to help the EP bring the vehicle to a stop in the required time. This required using the service brakes and corresponded to a significant loss in energy available to be recovered.
4. Forcing the transmission into a low gear earlier during deceleration proved that the EP could stop the vehicle but durability and drivability would be sacrificed.
5. In deceleration events much of the available energy is absorbed in the engine and torque converter. The addition of an overrunning clutch between the engine and transmission to decouple the engine during REGEN is therefore desirable. For this project, however, it was determined that this option would be time and cost prohibitive as it required the development of special components.
6. The EP mechanical drive needs to be sized for desired braking power rather than acceleration power.

Based on the findings above, it is prudent to shelve the PTO EP configuration for HBD applications of this size. It may be considered for series hybrids or HBD drives for lighter vehicles.

## 5. Prototype Shuttle Bus



**Goshen Coach Demonstration Vehicle**

A 20,000 pound GVWR shuttle bus was selected for the second prototype vehicle. The bus was equipped with a 210 peak hp Cummins 6 cylinder engine coupled to an Allison series 2000 automatic transmission. This was the smallest engine available on the standard chassis. Unfortunately, the 200 lbs of weight savings would not be realized on this application, since the 4 cylinder engine was unavailable.

The HBD system designed for the shuttle bus operates at 600 volts DC, nominal. The energy storage is approximately 1.2 megajoules. Although the bus is only about 40% heavier than the step van, the 100% additional energy and power resulting from the higher

voltage system allows latitude in testing and development.

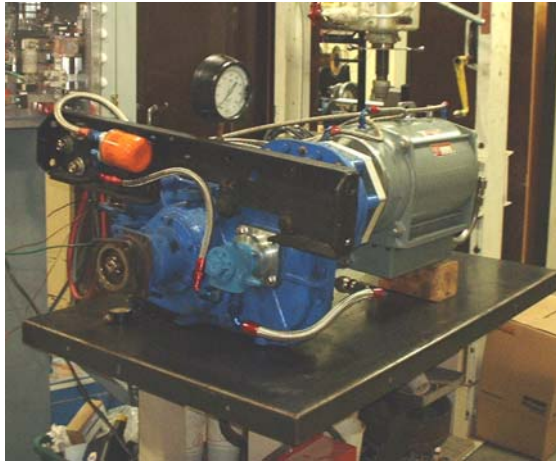
The HBD components would be installed on the chassis of the shuttle bus in order to give an OEM appearance. Lessons learned from the step van guided the configuration and component selection. A gear-driven transfer case couples a NEMA 215 frame liquid cooled motor to the driveshaft midway between the transmission and rear differential. Ultimately, this bus can provide potential manufacturers and users an example of a well executed HBD installation. As configured, it can be used for “ride and drive” demonstrations and actual shuttle service where passenger safety, reliability and comfort are paramount.

All of the HBD components are mounted under the floor to minimize intrusion into the passenger compartment of the bus. This was done to maintain maximum interior flexibility for the coach manufacturer. Weatherized cabinets for the electronics and ultracapacitors were designed and fabricated. The cabinets are vented from the passenger compartment to insure reasonable weather tightness and tempered air for cooling the electronic components. The mounting points and location of all HBD components were done in concert with the coach manufacturer to ensure minimum intrusion and maintain conformity with existing assembly processes.

### 5.1 Split Shaft Drive Configuration

The researchers selected the “split shaft” method of coupling the EP to the standard driveline for the larger chassis based on alternates suggested in the Palumbo Waggoner paper [4]. “Split shaft” is the common term used by commercial vehicle builders to describe a device that is installed into the drive shaft between the transmission and the rear differential housing. This configuration provides the means to derive or deliver torque to the drive shaft. Traditionally, split shafts are used to direct engine power from the driveline to optional loads such as water pumps or air compressors in commercial truck applications. In the HBD application, the attachment would be made to the electric motor via an appropriate gear reducer. The split shaft approach overcomes limitations associated with the transmission PTO method but cannot take advantage of gearing in the transmission. The PTO method keeps the motor speed proportional to engine speed, whereas the split shaft method has the motor speed proportional to vehicle speed. A number of advantages are realized with the split shaft configuration in the areas of gear ratio selection, smoothness of EP operation and the ability to decouple the engine during braking events.

### 5.1.1 Split Shaft Drive Specification



**Split Shaft motor and gear box**

Several configurations of the split shaft were considered. An early option considered using a direct coupled motor. The low speed and high torque requirement would have required a special motor be built. The excessive motor weight and long lead time dictated that this approach be abandoned for this segment of the project. It was soon realized that a smaller motor operating at a greater speed through a gear reducer was a more favorable approach.

The configuration as tested on the prototype shuttle bus applies a liquid cooled motor that was developed for the NASA Dynamic Load Simulator project. This power dense NEMA 215 frame motor can develop the power required when operated at increased speed. A close-coupled gear box developed for the same NASA project provides the gearing to operate the motor at the

appropriate speed. The motor and gear box assembly is tied to the vehicle driveline via a commercially available transfer case between the transmission and rear differential.

## 6. Ultracapacitor Bank Comparison

The following chart shows a comparison of the energy storage systems that were evaluated on the 14,900 pound GVWR step van. The system operated between 200 and 400 volts, DC. Each bank of ultracapacitors was packaged and secured in the cargo compartment of the van.

Brand	Tavrima	ESMA	Maxwell
Model	PSCAP90/200	EC104	BCAP0010
# of cells	N/A	270 cells	160 cells
# of modules	10 modules	9 modules	N/A
Energy (available)	650 kJ	612 kJ	975 kJ
Weight (cells)	N/A	202 lbs	185 lbs
Weight (modules)	814 lbs	351 lbs	N/A
Volume (cells)	N/A	1.65 cu ft	3.06 cu ft
Volume (modules)	13 cu ft	4.68 cu ft	N/A
# of cell connections	N/A	270	160
# of module connections	10	9	N/A
Balance resistors	10	none	160
Self discharge	yes	no	yes

They were terminated with quick connectors which facilitated easy connection to the hybrid drive. The ultracapacitor comparison does not include packaging requirements which can add significant weight and installed cost. The ESMA ultracapacitor is asymmetric generation III type which has a natural state of high potential and requires no external voltage balancing means. It will also remain at charged state for very long periods, thereby not requiring external initial charging. The Tavrma required only ten resistors for balancing. The Maxwell product requires a voltage balance circuit on each cell, 160 in this case. Both the Tavrma and Maxwell products need a means to charge them initially, because each will discharge over the course of a day or two if left idle. This was accomplished on the van using a small DC /DC converter which was connected to the 12 volt system.

The Tavrma product was available only in modules. Maxwell was available only as individual cells. The ESMA product was supplied in 30-cell modules which included cooling fans. It was possible however to use the ESMA cells and provide cooling to the entire lot.



Tavrma



Maxwell



ESMA

The difference in available energy between the brands is due to the available standard cells from those companies which could be configured to produce the appropriate system voltage in the van application.

Tests were conducted on each of the ultracapacitor banks. The van was driven over the same test course which closely simulated the Central Business District (CBD) cycle called out in the White Book baseline for transit vehicles. The onboard data acquisition system recorded pertinent parameters such as vehicle speed, ultracapacitor voltage, current and temperature among others. No problems were experienced with any of the ultracapacitors and minimal performance differences were noticed. The Tavrma and ESMA products were operated at temperatures below freezing with no noticeable degradation in performance. Maxwell's product was not available until summer.

## 7. Electronic Hybrid Control Development

The effectiveness of the Hybrid Booster Drive® relies on its ability to provide power assist during vehicle acceleration and power absorption during deceleration. In crude fashion, this could be accomplished by two switched electric circuits, one for motoring current and the other for generating current. It is conceivable that the motor activating switch could be coupled directly to the vehicle accelerator pedal while the generator activating switch coupled to the brake pedal. While this technically may accomplish the essence of the hybrid drive system, by no means would this be ideal. Problems with abrupt power transitions, high electric current surges, and mismatched contribution of engine and electric drive with driver demand can certainly be imagined. For optimal boost effectiveness and minimal change in operator feel, the hybrid drive must be apportioned at opportune times during drive cycles, while blending

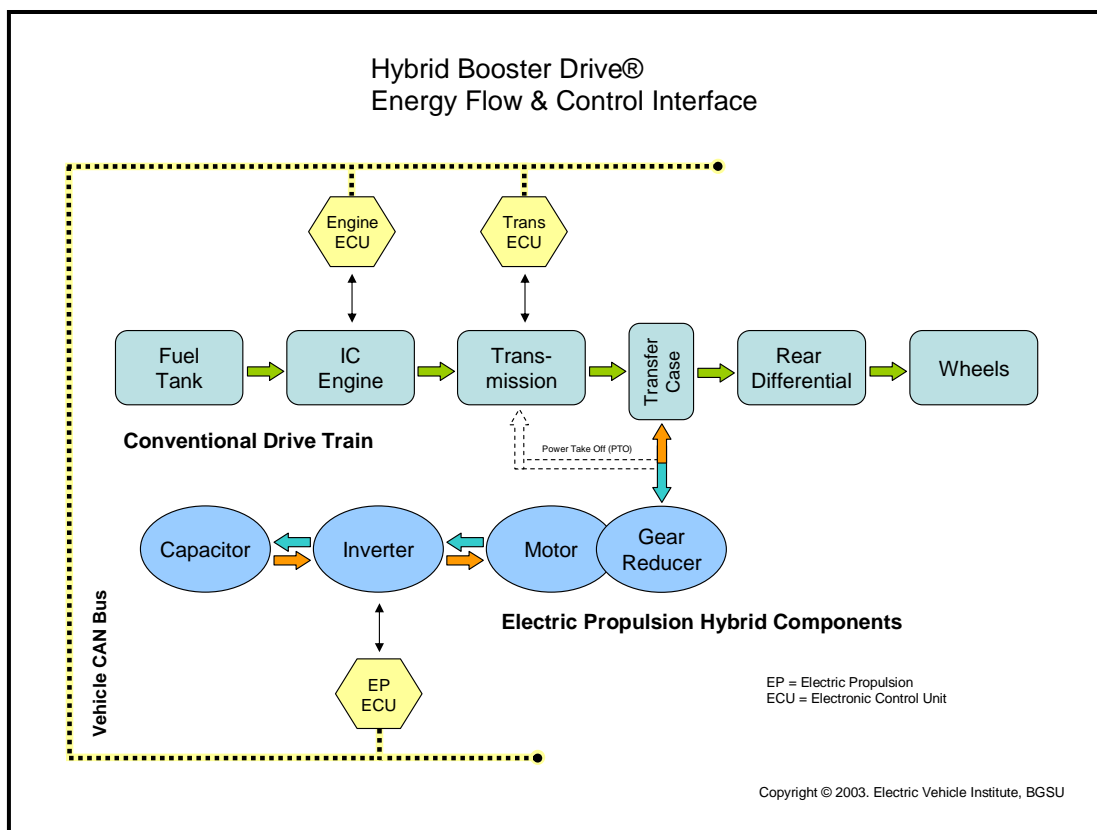
engine torque and motor torque for smooth transitions. For this reason among others, an electronic programmable controller is embedded in the Hybrid Booster Drive® controller.

Since the conception of the HBD system, the main objectives of the control system have been:

1. The seamless operation of the hybrid electric drive with the existing vehicle systems.
2. A drive-by-wire strategy with a single control connection to the vehicle data network.
3. To realize enhanced fuel economy and lower emissions with little or no change in operator feel.

A noteworthy feature of the HBD system controller is the single network connection to the vehicle data bus for operation. This feature alone saves installation costs by minimizing the need for a special wiring harness and connectors. As a node on the network, the hybrid controller transmits and receives data and control messages freely from the engine and transmission electronic control units. Both test vehicles use a data bus/control network based on the CAN 2.0 B specification operating at a bus speed of 250K bits per second. The protocol for message transmission follows the SAE J1939 standard [6].

Below is a block diagram illustrating the control interface of the HBD.

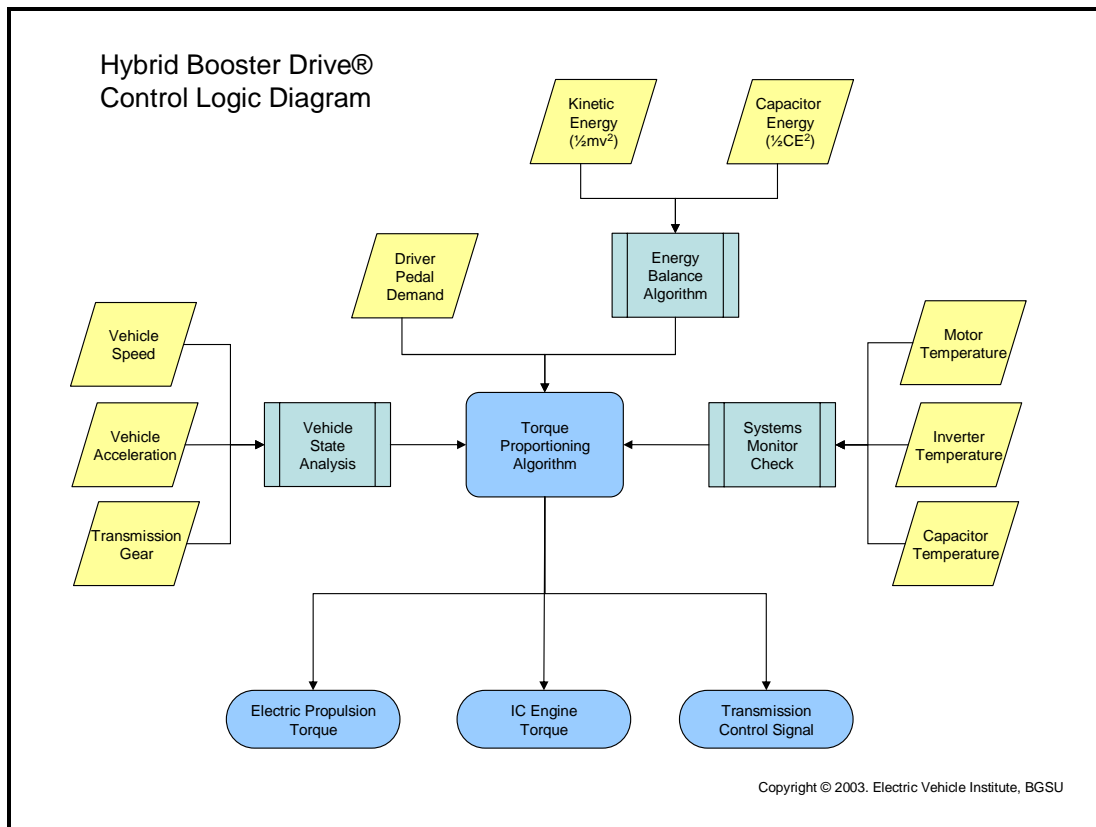


The physical connection to the network on the vehicles is made as a parallel tap from the CAN J1939 diagnostic port (9-Pin Datalink Interface Connector, Deutsch HD10-9-1939P) mounted under the dashboard. This left the port available for technicians wishing to connect diagnostic tools to the vehicle while the hybrid drive system was operational.

Appropriate control messages are sent to the engine electronic control unit and hybrid motor controller to proportion the amount of torque produced by each during acceleration and deceleration events using a proprietary hybrid control algorithm. To maximize hybrid drive performance the control messages are

also sent to the transmission to optimize the drive train configuration by altering shift points, disabling torque converter lockup, and disengaging the driveline.

Below is a block diagram illustrating the HBD control logic as tested on the prototype vehicles.



## 8. Instrumentation and Data Acquisition

A high speed instrumentation and data acquisition package was installed to facilitate systematic testing throughout each development phase of the Hybrid Booster Drive®. Functioning as a real-time monitor and data recorder, this acquisition system enabled objective evaluation of the hybrid drive systems during and after test sessions.

The data acquisition system used on the HBD project consisted of a high-speed programmable processor unit and data logger, remote sensing and signal conditioning modules, a vehicle network interface, and software for analysis and real-time monitoring. This system enabled logging of key operating parameters at sufficiently high sample rates to render test events in pseudo-real time.

This system allows programming changes to the control algorithm and evaluates the effectiveness at the conclusion of a run. Performance calculations and evaluations of the mechanical, electrical, and electronic control systems can be made almost immediately. The data acquisition system makes efficient use of testing opportunities and promotes a shortened development timeline. The availability of the test data in the field allows control algorithm changes during test and tune sessions.

## 9. Vehicle Testing

The prototype vehicles were operated following a Modified Central Business District test cycle (MCBD).

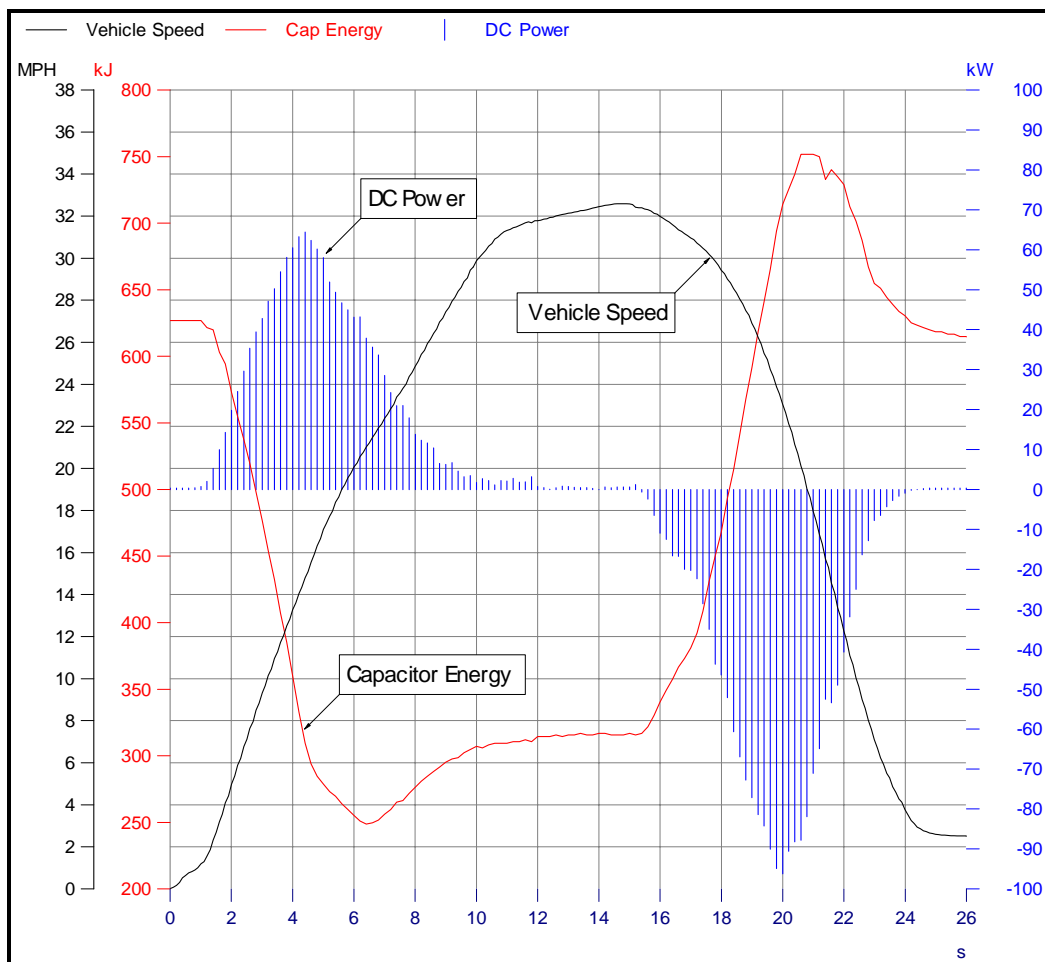
The cycle was modified from the standard CBD cycle in order to more realistically represent the start/stop events of pick-up and delivery vehicles.

A course was marked out and the vehicles were operated each time using the MCB cycle for comparisons of vehicle performance with and without the hybrid system active.

## 10. Vehicle Test Results

Examples of test results for the 14,850 pound GVW delivery van equipped with the Split Shaft HBD drive, and using the Tavrira ultracapacitors, are shown in the following figures.

The chart below shows van speed, capacitor energy, and the power delivered and reclaimed by the capacitor during an acceleration deceleration cycle. The van accelerates from a stop to 32 mph in about

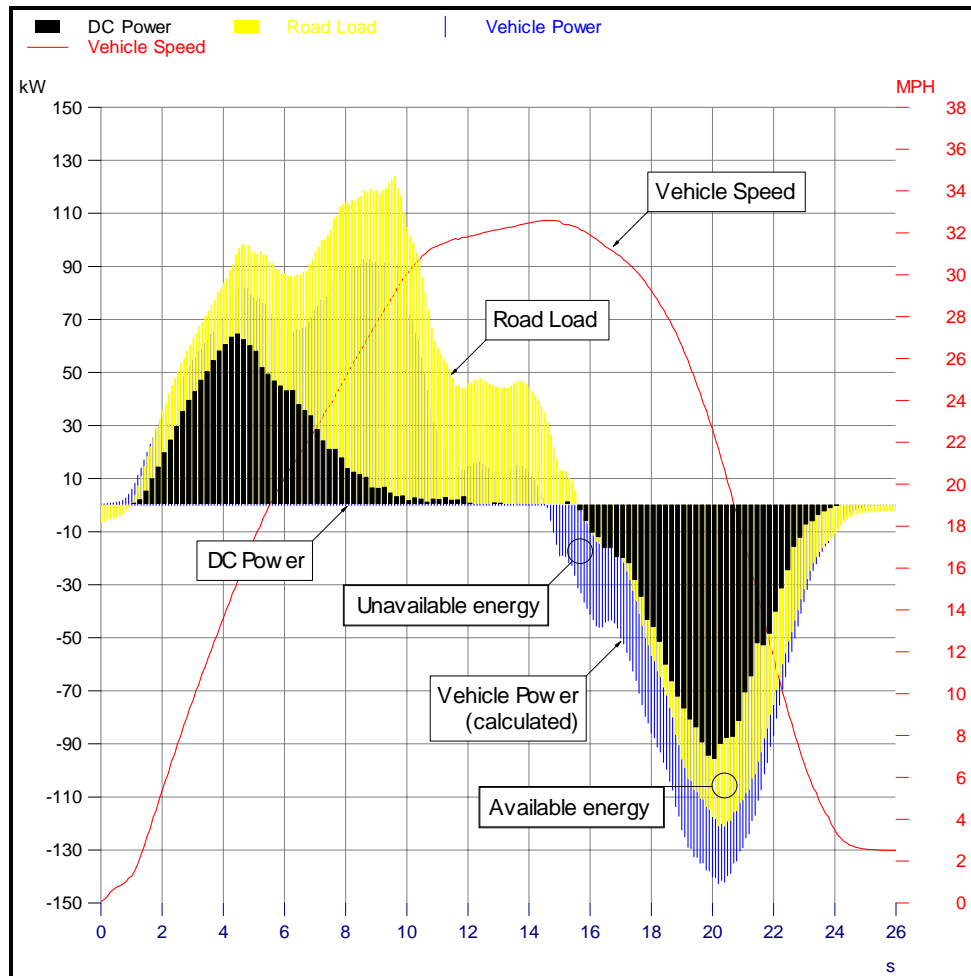


14 seconds and then decelerates to 4 mph in the subsequent 10 seconds. During acceleration, the power delivered by the capacitor during acceleration peaks at almost 65 kW between 4 and 5 seconds into the acceleration and then declines so the capacitor is delivering very little power by ~10 seconds. Capacitor energy decreases nearly linearly for the first 5 – 6 seconds of the acceleration and then remains nearly constant as the capacitor is largely depleted after 6 seconds.

During braking, the capacitor energy increases again as power is delivered to the capacitor especially during the first 4 – 6 seconds of deceleration. The DC power delivered to the capacitor peaks at about

100 kW during braking. The capacitor energy curve shows that the energy recovered during braking is only 25 KJ lower than was used during acceleration. This shows a near even input output relationship.

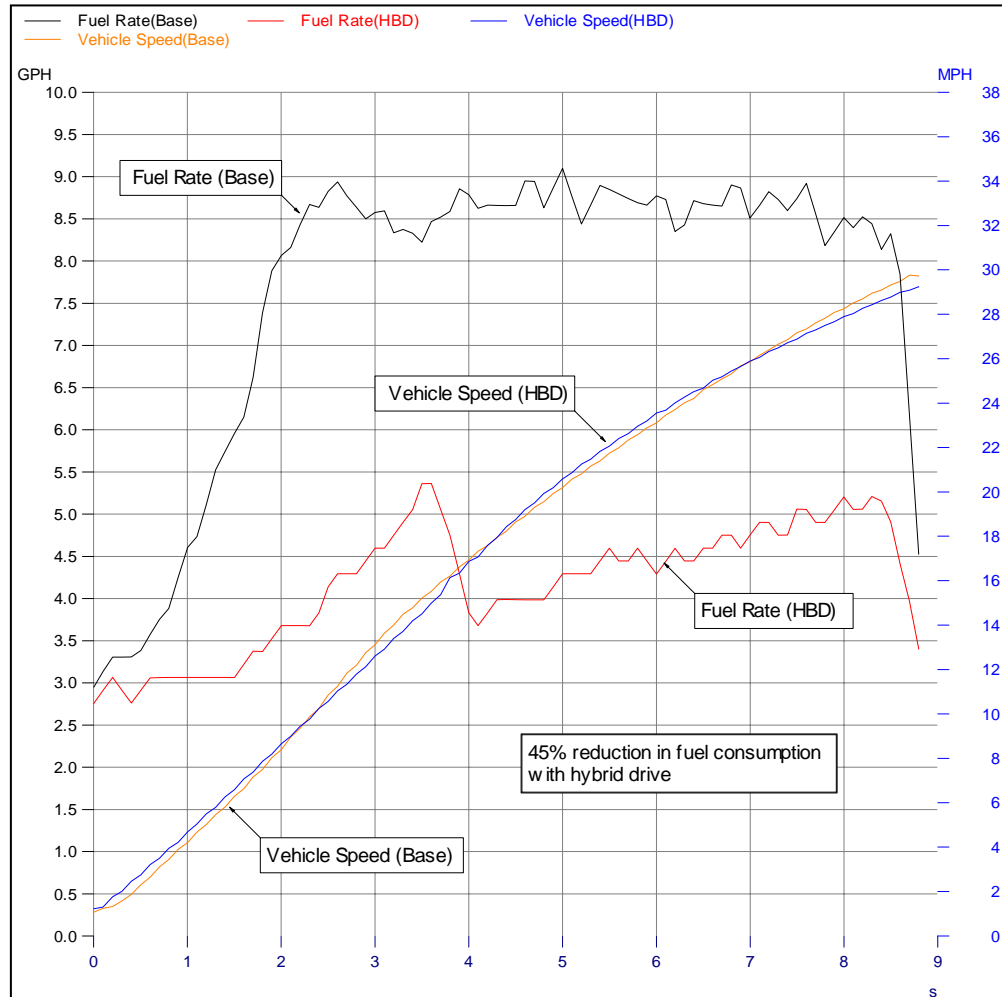
The chart below shows the vehicle power requirements and the performance of the HBD for the same acceleration deceleration cycle as shown in the previous figure.



For the acceleration part of the cycle, the area between the DC power curve and the base line is the energy contributed by the HBD. The area above the line is the energy contributed by the engine. An analysis of this data shows that the HBD Split Shaft Drive contributed ~34% of the energy necessary to accelerate the vehicle.

Of particular interest is the braking part of the cycle. The area between the calculated vehicle power curve and the zero base line represents the total energy of the vehicle. The area between the road load curve and the zero base line is the energy required to decelerate the vehicle in the required time. Without the HBD all of this energy would be absorbed by the vehicle service brakes. The area between the road load curve and the total energy curve is lost to rolling friction, engine pumping loss and aerodynamic drag. This energy is not absorbed by the service brakes and is unavailable to be recovered by a hybrid drive. The area between the DC power curve and the zero base line is the energy that was recovered by the HBD drive. The area between the DC power curve and the road load curve is energy that is absorbed by the service brakes or could be captured by an improved hybrid configuration. The chart indicates that the HBD has captured 71% of the recoverable energy in the braking event.

The chart below is a composite of two acceleration runs of the van, one using and one not using the HBD. In the run using the HBD, only the amount of braking energy recovered during the previous stop was used



to provide electric assist to accelerate the vehicle. In both cases the vehicle accelerates to 30 mph in about 9 seconds. The comparison of the fuel rate curves shows the effect that the HBD has on fuel economy during acceleration. The area between the two fuel rate curves represents a 45% reduction in fuel consumption when the HBD is active.

## 11. Conclusions

The following conclusions can be drawn from observations and testing completed to date:

1. Initial testing of the HBD system confirms that a parallel hybrid system utilizing electrochemical capacitors (ultracapacitors) will work without a voltage regulator between the capacitors and motor controller.
2. Hybrid system control can be integrated into vehicle data network for optimum effectiveness.
3. Significant fuel savings have been achieved during acceleration with the HBD.
4. Additional fuel savings can be expected with refinement of control algorithms.
5. Additional fuel savings can be expected with improvement of the electric propulsion system.

6. The ultracapacitor sets evaluated to date are adequate in size and have performed equally well.
7. Operation of the hybrid drive can be transparent to the operator.
8. The PTO drive configuration as tested does not utilize the full potential of the parallel hybrid.
9. Off-the-shelf components can produce a working hybrid drive train.
10. The HBD augments the vehicle drive train with one mechanical and one control interface, leaving the conventional drive intact. The vehicle can operate with or without the hybrid system active.

## 12. Recommendations

It is recommended that research continue in order to fully develop and evaluate HBD system performance. This research should aim to:

1. Improve the HBD system to recover more energy from braking.
2. Place an HBD-equipped prototype into service to test component longevity and quantify vehicle overall fuel mileage improvement.
3. Determine the effectiveness and means of providing engine-off operation.
4. Conduct a cost benefit analysis and manufacturability study of the HBD.
5. Conduct life cycle tests on HBD components including ultracapacitors.
6. Test vehicle emissions to determine effectiveness of hybrid drive.
7. Quantify increased life of service brakes.
8. Reduce weight of HBD system components to regain more payload capacity.
9. Determine gross cost of installation, weight and volume of the three ultracapacitor modules.

## 13. Summary

This project has yielded two functioning vehicles, each of which features the Hybrid Booster Drive® system. One vehicle is a delivery truck, or step van, commonly used by parcel delivery services. The second is a medium size bus commonly used in shuttle service. These two vehicles will provide manufacturers and operators with an opportunity to examine first hand the HBD system.

Although the medium duty truck and bus applications were the focus of this project, the HBD system is scalable to larger and smaller vehicles.

The HBD offers the vehicle designer a straightforward, cost justifiable approach to achieving increased fuel mileage and reduced emissions. It can be expected that the HBD can be implemented in current diesel chassis using existing production processes. HBD technology is a sensible approach which enables vehicle manufacturers to include a hybrid option to their line in the near term. Other hybrid approaches are typically more complex and often more expensive and less likely to spur investment without financial subsidy.

As a result of the research reported in this paper, there should be little doubt as to whether the ultracapacitor as an energy storage buffer is feasible in hybrid vehicles of the type presented. Vehicle manufacturers are encouraged to consider ultracapacitors as an alternative to batteries in hybrid applications with missions requiring numerous starts and stops.

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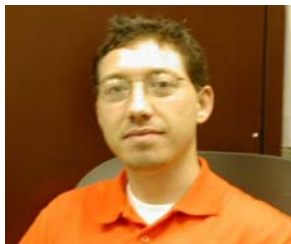
## 15. Authors



**Anthony J. Palumbo**, Chief of Operations, Electric Vehicle Institute, Bowling Green State University, Bowling Green, OH 43403. Tony holds title of Associate Professor Emeritus of energy, power, instrumentation and control in the Department of Technology Systems after retiring from teaching after 30 plus years. During his years of service at BGSU, he has been involved with many successful practical research projects. Since retiring from his teaching role he has been retained to serve as the Chief of Operations for the EVI. Tony holds three US patents. He has expertise in energy and power systems including electric motor and controllers, manufacturing engineering, product design and development and systems integration. He has led the technical group in the Institute from its beginning in 1994.



**Jeff Major**, Chief Engineer, Electric Vehicle Institute, Bowling Green State University, Bowling Green, OH 43403. Jeff has been with the Electric Vehicle Institute for the past nine years and has been a significant contributor in motor and controller development. Jeff holds a BSEE from the University of Toledo. He has served as a part time instructor at the University of Toledo, College of Engineering in energy conversion and at Bowling Green State University, College of Technology in electronics. Jeff completed eleven years experience in industry with the Prestolite Company, Toledo, OH. He held positions of Product Engineer and Manager of Engineering for the motor group with responsibilities for product engineering and R&D. He has seven US patents issued for motors and related apparatus. Jeff has extensive experience and expertise in electric vehicles, electromechanical energy conversion and power electronics.



**Aaron Bloomfield**, Data Acquisition Engineer, Electric Vehicle Institute, Bowling Green State University, Bowling Green, OH 43403. Aaron has recently joined the Institute to provide full time expertise in data acquisition and computer programming. He has a BS in Computer Science from BGSU. Aaron participated as the DAQ specialist in several other projects working as a consultant for EVI. He has expertise in computer applications, capturing real time test data and implementation of controls in the automotive environment. Prior to joining EVI, Aaron spent 5 years at Libbey Inc as an Applications Support Specialist.

### Appendix 1

BASE VEHICLE		75	m/day	350	stops at		0.5	min ea	8	hr day	260	days/yr	\$2.00		per gal fuel
		\$0												estimated added cost of vehicle	
activity	event mi.	miles/day	mi/hr	% time	event(sec)	time(hrs)	Hp acc	Hp road	drive eff	Hp req	act. fuel	sp fuel cons	gal	mi/ gal	\$ fuel cost
inter city travel		10.00	55.00	2.3%		0.18	9.50	90.00		99.50		0.0530	0.96	10.43	\$1.92
				0.0%											
lunch		0.00	0.00	6.3%		0.50	0.00	0.00	1.00	0.00		0.0000	0.00	0.00	\$0.00
sub total intercity		10.00		8.5%		0.68							0.96	10.43	\$1.92
In town		65.00		91.5%		7.32									
stops		0.00	0.00	36.5%		2.92	0.00	0.00	1.00	0.00		0.0000	0.00	0.00	\$0.00
accel to 30	0.04	13.685	16.76	10.2%	8.400	0.81667					0.019		6.5345	2.09	\$13.07
decel from 30	0.06	21.07	15.51	17.0%	13.970	1.35819					0.00073		0.2555	82.47	\$0.51
steady at 30mph		30.25	30.00	12.6%		1.01	9.50	39.00		48.50		0.0530	2.59	11.67	\$5.18
stopped in traffic		0.00		15.2%		1.22	9.50	0.00	1.00	9.50		0.0530	0.61	0.00	\$1.23
total in town		65.00		91.5%		7.32							10.00	6.50	\$19.99
daily totals		75.00		100.0%		8.00							10.95	6.85	\$21.91
yearly totals		19500.00				2080.00							2847.99	6.85	\$5,695.99
fuel economy vs base vehicle				base vehicle mpg			this vehicle mpg		mpg improvement		\$savings/year		simple ROI		
				6.85			6.85		0%		\$0.00		0.00	years	
BASE VEHICLE		\$7,500												estimated added cost of vehicle	
		with Hybrid Booster Drive													
activity	event mi.	miles/day	mi/hr	% time	event(sec)	time(hrs)	Hp acc	Hp road	drive eff	Hp req	act. fuel	sp fuel cons	gal	mi/ gal	\$ fuel cost
inter city travel		10.00	55.00	2.3%		0.18	9.50	90.00		99.50		0.0530	0.96	10.43	\$1.92
				0.0%											\$0.00
lunch		0.00	0.00	6.3%		0.50	0.00	0.00	1.00	0.00		0.0000	0.00	0.00	\$0.00
sub total intercity		10.00		8.5%		0.68							0.96	10.43	\$1.92
In town data		65.00		91.5%		7.32									
stops		0.00	0.00	36.5%		2.92	0.00	0.00	1.00	0.00		0.0000	0.00	0.00	\$0.00
accel to 30	0.04	13.685	16.76	10.2%	8.400	0.81667					0.010		3.5	3.91	\$7.00
decel from 30	0.06	21.07	15.51	17.0%	13.970	1.35819					0.00073		0.2555	82.47	\$0.51
steady at 30mph		30.25	30.00	12.6%		1.01	9.50	39.00		48.50		0.0530	2.59	11.67	\$5.18
stopped in traffic		0.00		15.2%		1.22	9.50	0.00	1.00	9.50		0.0530	0.61	0.00	\$1.23
total in town		65.00		91.5%		7.32							6.96	9.34	\$13.92
daily totals		75.00		100.0%		8.00							7.92	9.47	\$15.84
yearly totals		19500.00				2080.00							2059.02	9.47	\$4,118.05
fuel economy vs base vehicle				base vehicle mpg			this vehicle mpg		mpg improvement		\$savings/year		simple ROI		
				6.85			9.47		28%		\$1,577.94		4.75	years	