Standalone Mild Hybrid System Development and

Application for Non-Hybrid Vehicles

by

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ABSTRACT

While the implementation of both mild hybrid and start-stop technology is widespread as a factory option in newer vehicles, the adaptation of hybrid technology to older or unequipped vehicles has not been fully realized. As such, a straight forward hybrid conversion system that is easily adapted to different vehicles regardless of drivetrain configuration, has been developed and applied to a test vehicle for less than $2,000. System performance was recorded both before and after hybridization using real world drive cycle tracking charts. The vehicle established a fuel economy baseline of 22.93 mpg, and achieved 26.58 mpg after the conversion. This corresponds to a 15.92% increase in fuel economy. Accounting for initial system costs and annual fuel saving, this corresponds to a 6-year payback period. Based on these results, it can be concluded that an inexpensive aftermarket hybrid system is both feasible and effective at improving fuel economy.

To my Mother and Father, whose love and support throughout my life
has made this project possible.

ACKNOWLEDGMENTS

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CHAPTER 1

INTRODUCTION

The desired fuel efficiency of personal vehicles has increased over time in conjunction with fuel costs and environmental concerns. As a result, many major auto manufacturers around the world have increasingly turned to gasoline-electric hybrid (hybrid) propulsion systems to both improve a vehicle's fuel economy, and reduce carbon-based emissions. Although alternative drive systems like battery electric, hydrogen fuel cell, and ultra-low-sulfur diesel-hybrids are viable alternatives, they suffer from limited availability in the United States and/or comparatively high cost [1].

While new and used hybrid vehicles are readily available in today's market, many are choosing to keep their cars longer; as indicated by the increasing age of vehicles on the road [2]. As an alternative to conventional hybrid systems, which are costly and complex, a standalone hybrid system was developed that is easily adaptable to different vehicles as an aftermarket accessory for $2,000 or less. This hybrid conversion consists of a DC motor coupled to the crankshaft of a test vehicle (1998 Toyota Avalon XLE) via the accessory-drive serpentine belt. A conventional electric motor controller and a 125 Ah 36 V lead acid battery bank were used.

Vehicle performance was evaluated using detailed mile per gallon (mpg) tracking charts that account for driving conditions affecting fuel consumption both before, and after the hybrid conversion takes place. A cost analysis comparing hybrid component and installation expenses to fuel savings over the expected system lifetime was also conducted.

CHAPTER 2

BACKGROUND INFORMATION

2.1 Hybrid Electric Vehicles

A hybrid vehicle is one that combines two methods of vehicle

propulsion. These two methods can consist of, but are not limited to:

gasoline/diesel-electric, gasoline/diesel-flywheel, and fuel cell-battery

orientations [1]. For the purposes of this work, a hybrid will refer specifically

to a hybrid-electric vehicle or HEV.

2.2 HEV Configurations

Hybrid electric vehicles can be configured in one of three ways: series,

parallel, and series/parallel.

2.2.1 Series Hybrid

In a series hybrid configuration, an electric motor(s) is the only power

source directly propelling the wheels. Electricity used to power the motor is

sourced from either the vehicle's battery or an internal combustion engine

(ICE) coupled to a generator. Mechanically decoupling the engine from the

electric powertrain eliminates the need for a transmission with complex

clutches, and allows the engine size to be reduced significantly [1]. This also

allows engine operation to be maximized for peak efficiency at all times by

the vehicle control unit (VCU).

Because the vehicles propulsion source is an electric motor, a battery

pack is generally the primary source of power, with the ICE acting as a range

extender to recharge the vehicle's battery. If the ICE is used as a primary

power source, the system will suffer large efficiency losses due to additional

power conversion requirements. During normal operation, the drive motor may also act as a generator, supplying regenerative power to the battery pack during deceleration. This function is called regenerative braking (regen). Figure 1 depicts a typical series hybrid configuration. In this example, an AC motor and generator were used necessitating inverters for power conversion.
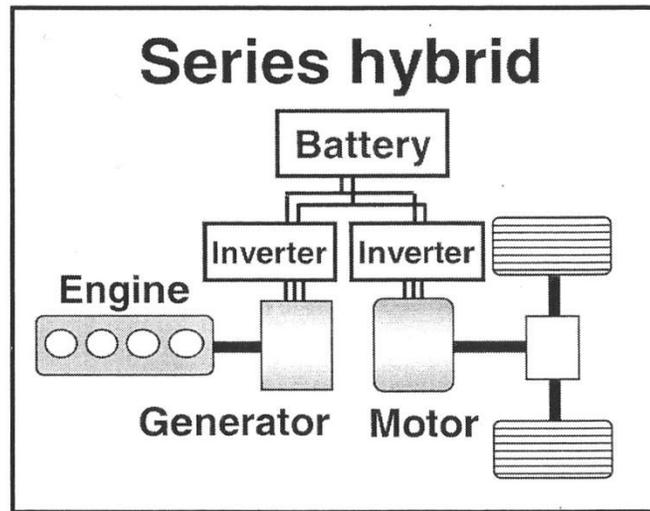
Figure 1. Typical series hybrid configuration [3].

As a plug-in hybrid (see chapter 2.3.4), the Chevrolet Volt uses a series hybrid architecture to operate as an electric vehicle for 35 miles [4]. When the Volt's battery is depleted, the ICE is used as a generator to extend the range of the vehicle.

2.2.2 Parallel Hybrid

In a parallel hybrid configuration, both the ICE and motor are used to directly propel the drive wheels. The VCU modulates the engine and motor so that the highest efficiency range of each is used according to operating conditions. Parallel hybrid systems are more complex than series systems

due to the additional challenges associated with coupling the two power sources.

The main benefit of parallel hybrid systems is that substantial efficiency gains can be realized without the use of a large (and expensive) battery pack. This reduces vehicle weight and system cost. While many options exist, a typical parallel hybrid configuration is depicted below in Figure 2. As an alternative to this traditional architecture, in a *through-the-road* parallel hybrid, two wheels are powered by the ICE (front or rear), and the remaining two wheels are powered by an electric motor(s). The separate ICE and electric powertrains are operated independently or simultaneously depending on driving conditions, with the driving surface (roadway) acting as a substitute for a mechanical connection.
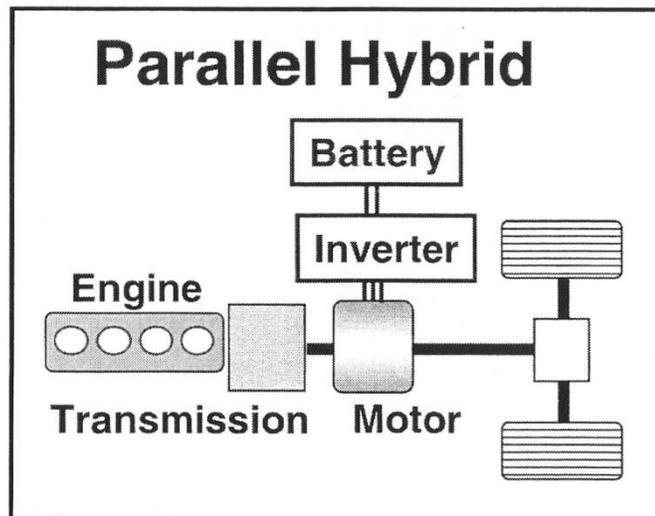
Figure 2. Typical parallel hybrid configuration [3].

As the second largest manufacturer of hybrid vehicles in the United States, Honda uses parallel hybrid architecture extensively in the Insight, Civic Hybrid, and Accord Hybrid [5].

2.2.3 Series/Parallel Hybrid

A series/parallel hybrid combines both series and parallel configurations. This can also be referred to as a power-split or two-mode hybrid, which references the drivetrain's ability to operate in all-engine and all-electric modes. A power-split device (typically a clutch controlled or planetary gearbox) is capable of decoupling the ICE from a parallel operating mode to a series operating mode [6]. While the separate benefits of each system may be achieved, power control becomes extremely complex due to the increase in drive configurations and continual modulation based on driving conditions.

As the largest hybrid manufacturer of hybrid vehicles in the US, the Toyota Corporation is responsible for 73% of hybrid vehicles on the road [5]. Toyota uses series/parallel hybrid technology (Hybrid Synergy Drive) extensively in all of its hybrid vehicles, including the Prius—the most popular hybrid in the United States [5].

2.3 Degree of Hybridization

It is useful to quantify the extent of electric power potential in a hybrid vehicle separate of its series, parallel, or series/parallel configuration. To do this, a variable called degree of hybridization (DOH) has been developed as stated in Figure 3.

$$DOH = \frac{P_{em}}{P_{em} + P_{ice}}$$

Figure 3. Degree of hybridization [7].

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In this equation P_{em} refers to the power of the electric motor and P_{ice} refers to the power of the internal combustion engine. The degree of hybridization can vary from zero to one, but can also be reported as a percentage. A DOH of zero corresponds to a conventional non-hybrid ICE vehicle, while a DOH of one corresponds to a 100% electric vehicle (EV). As DOH increases, so does the likelihood of increased efficiency. Larger electric motors increase a vehicle's electric operating capacity, and enable the use of smaller ICEs which can accordingly be run closer to optimal efficiency. Since DOH is independent of battery capacity, it is assumed that the electric motor is not underpowered. While DOH is a useful classification tool on its own, it is not a direct indication of a vehicle's hybrid architecture or capabilities. As such, HEVs can also be categorized as micro, mild, full, and plug-in hybrids with their DOH percentage increasing respectively (Figure 4).
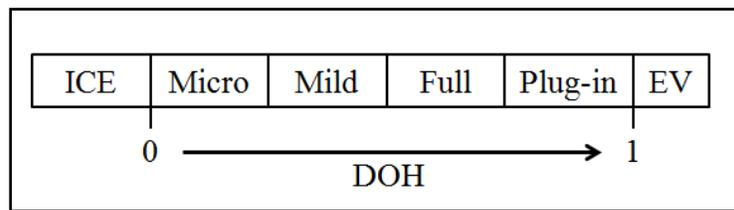
Figure 4. DOH variation by hybrid categorization.

2.3.1 Micro Hybrid

Micro hybrids typically utilize an integrated starter generator (ISG) and have the lowest degree of hybridization. They are still fully reliant on the ICE for propulsion. An ISG acts in place of an engine's traditional alternator and starter by combining the two functions into one electronically controlled unit. It is connected to the vehicle's crankshaft allowing the VCU to disable the engine during idle while stopped (start-stop or idle-off). This is possible

because the ISG is capable of quickly spooling the parent ICE to normal idle rpm with the fuel injection cut, eliminating unburned fuel and associated hydrocarbon emissions [3]. The ISG is also capable of providing minimal power assistance to the ICE during initial acceleration, and is used to recharge the battery during deceleration. A fully integrated micro hybrid can see fuel economy gains up to 10% when compared to non-hybrids [8]. A simple idle-off configuration can result in a 5-8% reduction in fuel consumption [3].

2.3.2 Mild Hybrid

A mild hybrid operates much in the same way as a micro hybrid, with the main difference being a separated electric motor and alternator (no ISG). Added benefits can include deceleration fuel cutoff, idle-stop, torque converter lockup, as well as low speed engine and launch assist [1]. Mild hybrids are also still reliant on the ICE for propulsion, and have limited regenerative braking ability when compared to a full hybrid. To accommodate the more capable motor, a larger battery pack typically limited to 1 kWh is used [7]. The larger electric components play a greater role in vehicle operation and can boost fuel efficiency by 20-25% [8].

2.3.3 Full Hybrid

Full hybrid systems can vary greatly, but generally consist of a larger more powerful electric motor and battery pack, with sophisticated vehicle control systems to maximize fuel economy. Larger electric components allow for electric-only propulsion at lower speeds, greater regenerative braking capability, and downsized combustion engines. Vehicle accessories like power

steering and air conditioning are typically electric as well, to enable ICE-off driving and further reduce fuel consumption. All of these improvements result in a 40-45% increase in fuel economy over a comparable non-hybrid vehicle [8]. Full hybrids typically excel in stop-and-go city traffic when the vehicle is able to take advantage of the efficiency benefits of a high torque electric powertrain.

2.3.4 Plug-in Hybrid

Plug-in, or grid connected hybrids have even larger electric powertrain components and are also considered range extended EVs. This is because the larger motor and battery capacity enable the vehicle to operate in all-electric mode until the battery capacity is depleted to a point determined by the VCU. This provides a considerable advantage over traditional hybrid systems because no fuel is used on trips within the vehicle's battery capacity.

CHAPTER 3

METHODOLOGY

3.1 Project Scope

While hybrid vehicles are widely available in current markets, they represent a very small portion of the 246 million registered cars in the United States [9], [5]. Outfitting an existing vehicle with basic hybrid technology may serve as a viable short-term substitute for a newer, more efficient car or truck. Replacing every non-hybrid vehicle with a newer, more fuel-efficient vehicle is not a viable option and consumes additional energy and resources in the process. Although advanced powertrain vehicles have come to market in response to fears of greenhouse gas emissions or dependency on foreign oil, the average age of vehicles is increasing [2]. Although the efficiency gains of a new or used manufacturer-developed hybrid will likely far exceed a hybrid conversion, the cost of a new vehicle in combination with the added cost of an OEM (original equipment manufacturer) hybrid powertrain exceeds customer willingness and ability to pay [3].

An aftermarket hybrid that is both straightforward in design and installation, capable of modest fuel efficiency gains, and (comparatively) inexpensive, may serve as a viable substitute for a new or replacement vehicle. This type of system is absent from today's market. Commercially available off-the-shelf parts will be used for a practical implementation of existing hybrid technology concepts using a 1998 Toyota Avalon XLS. A benchmark system cost of $2,000 and a desired 5 year payback period will be used. Development is centered on a system that the average "do-it yourself"

mechanic is capable of installing. A system that is easily adapted to different vehicles by only modifying the electric motor mounting bracket and the host vehicle's accessory belt drive is also desired. Additionally, the developed hybrid system will be independent of the host vehicle's drivetrain configuration (front, rear, or all-wheel drive).

3.2 Major Components

The mild hybrid system developed is largely defined by the components used. Component selection of the motor/generator (orange), motor controller (blue), and battery bank (black), is as follows; accompanied by relative installation information (Figure 5).
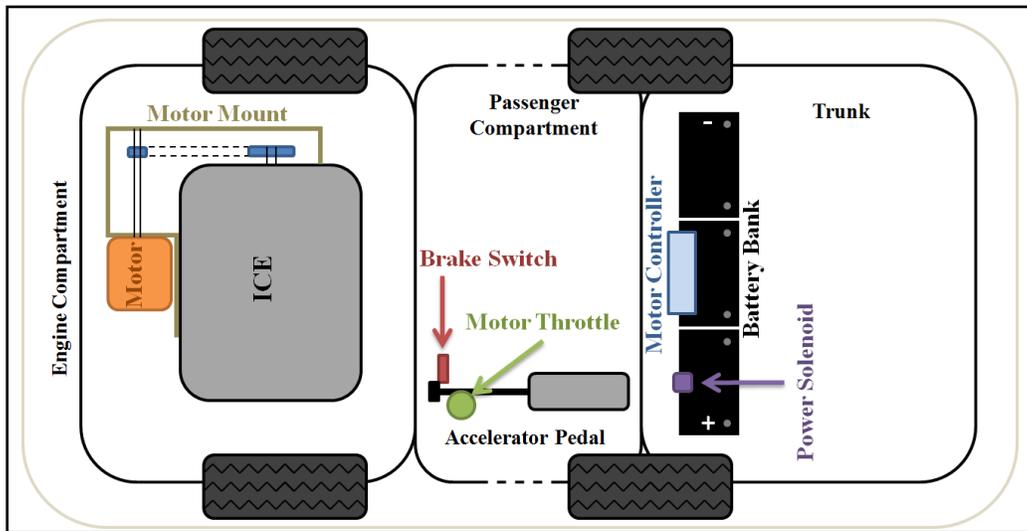
Figure 5. Component overview (not to scale).

3.2.1 Motor/Generator

A Mars ME0909 permanent magnet (PM) DC motor was ultimately chosen, based largely on available space, performance, and cost. Due to limited space, the motor was required to fit between the front valve cover and radiator, just above the front exhaust manifold without interfering with the

hood. This resulted in a usable vacant area of 11x8x7.5 inches, as depicted

below in Figure 6. The ME0909 was modeled in cardboard, and discovered to

be an ideal size within the 7.5 inch exhaust manifold-to-hood clearance limit.

Figure 7 below depicts the final mounting location. The Mars ME0909 may

not be suited for all applications due to varying space constrains.

Figure 6. Vacant space in engine compartment prior to installation.
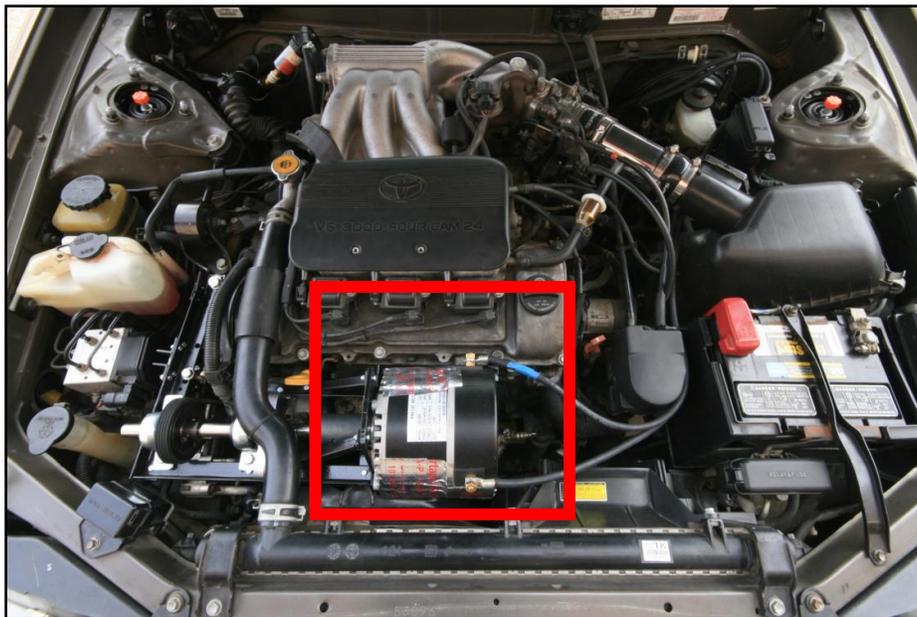
Figure 7. Mars ME0909 PM DC motor mounted above front exhaust manifold.

The motor is rated at 4.8 kW continuous and 15 kW peak (for 30 seconds). At 36 V it is capable of roughly 4,000 rpm. With a resulting motor pulley (3.125 inches) to engine crankshaft pulley (6.22 inches) ratio of 1.99, the motor is capable of supplying additional power up to roughly 2,000 engine-rpm. This corresponds well to a typical shift point in normal driving, and a cruising speed of roughly 60 mph in top gear (see Figure 19 in chapter 3.6 for detailed shift points).

Additional Installation Points:

The motor was wrapped in Relectix® brand thermal insulation followed by Shurtape® aluminum foil tape with an applicable temperature range of up to 260°F to avoid excessive heat exposure. The front cylinder bank exhaust manifold was also wrapped with DEI© Titanium Exhaust Wrap, as seen directly below the motor in Figure 8 (and again in Figure 14).
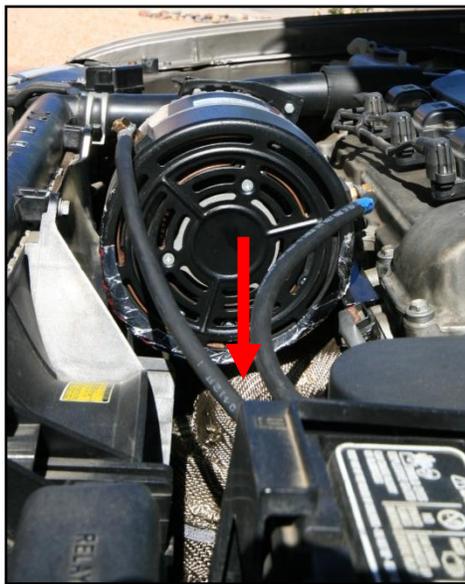
Figure 8. DEI© *Titanium Exhaust Wrap.*

3.2.2 Motor Controller

Based on a power-matched controller recommendation for the Mars ME0909 on the Kelly Controls website, a Kelly KDZ48401 motor controller was chosen. The KDZ48401 also provided regenerative capability and quick user programmability.

Additional Installation Points:

The motor controller is pictured below in Figure 9, mounted above the battery bank in the trunk. An ignition controlled 12 V source from the host vehicle is used to turn on and power the controller.
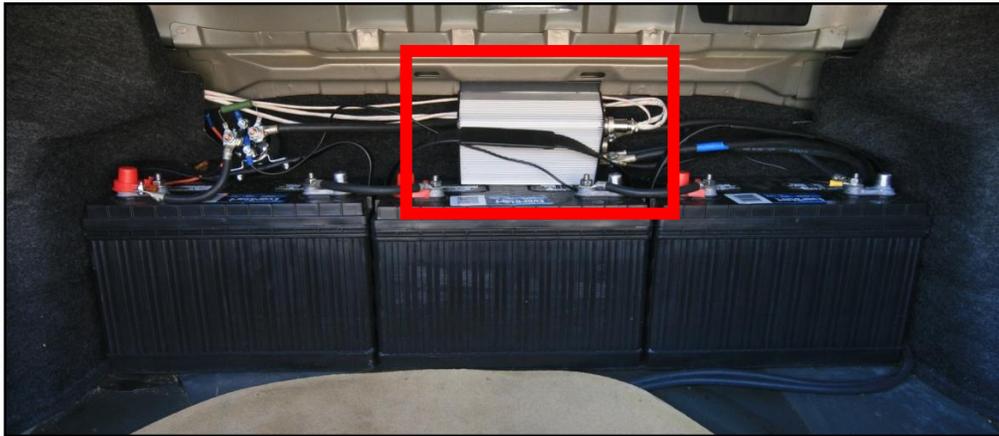
Figure 9. Kelly Controls KDZ48401 PM DC motor controller with regen.

3.2.3 Battery Bank

To reduce cost, three marine-grade 12 V, 125 Ah lead acid batteries were used. A system voltage of 36 V was chosen to reduce cost, weight, and occupied trunk space. Each EverStart® MAXX Marine 29DC battery measures in at 13 inches long, and 61 lbs. The resulting 4.5 kWh battery bank measures 39.5x6.75x10 inches and weighs a total of 183 lbs. It should

be noted that although the lead acid battery bank is capable of 4.5 kWh, its usable rating should be reduced by 50 percent (2.25 kWh) to extend cycle life.

True deep cycle lead acid batteries were initially considered (6 V, 200 Ah for golf cart applications), but the six batteries required for a 36 V system would have doubled the cost and exceeded 400 lbs.

Additional Installation Points:

The battery bank fits between the rear wheel wells as pictured below in Figure 10. The original usable trunk capacity of 15.4 cubic feet was reduced by approximately 2.1 cubic feet (including un-usable space above the batteries). The bank is supported on three sides, which isolates movement due to braking and cornering, and the host vehicle is not capable of accelerating rapidly enough to shift the battery bank in the direction of the unsupported side. The added 186 lb battery weight also resulted in a quarter-inch sag in the rear suspension.

Figure 10. The 36 V EverStart® MAXX battery bank (trunk carpet removed).

3.3 Additional Components

In addition to the major components, a DC power solenoid (purple) with switch , throttle potentiometer (green), regen brake switch (red), and associated wires/power cables were all necessary to complete the hybrid conversion (refer back to Figure 5).

3.3.1 Power Solenoid

A White Rogers 36 V DC power solenoid rated at 100 A was used as a safety precaution to disconnect the positive (+) main power lead from the controller in the event of controller failure. As recommended by Kelly Controls, a 1 kΩ (10 W) pre-charge resistor was placed across the contactor poles and a 200 V (3 A) diode was placed across the solenoid coil leads. A wiring diagram of the contactor included by Kelly Controls with the motor controller is presented below in Figure 11. The contactor is activated by an on/off rocker switch accessible by the driver below the dashboard.
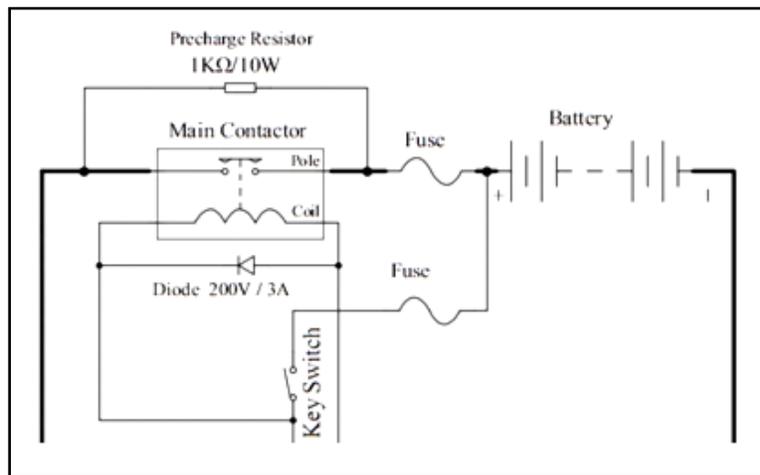
Figure 11. Power solenoid wiring diagram [10].

3.3.2 Throttle

A 0-5 V potentiometer based thumb throttle originally intended to be used on a bicycle handlebar was purchased from Kelly Controls and adapted for use. The throttle was mounted to a one-inch section of discarded handlebar end, which was then bolted to a four-inch piece of 1/16x1/2 inch flat aluminum stock. The resulting aluminum bracket was bolted to an existing location in the vehicle's firewall. A small hole was drilled in the thumb throttle, and wire was used to fasten the throttle to the arm of the vehicle's accelerator pedal. Cable ties prevented the fastening wire from sliding excessively on the accelerator pedal arm. Because the throttle was mounted parallel to the accelerator pedal arm, throttle adjustment only required simple rotation of the thumb throttle on the section of handlebar. Figure 12 shows the throttle in its "low" signal position.
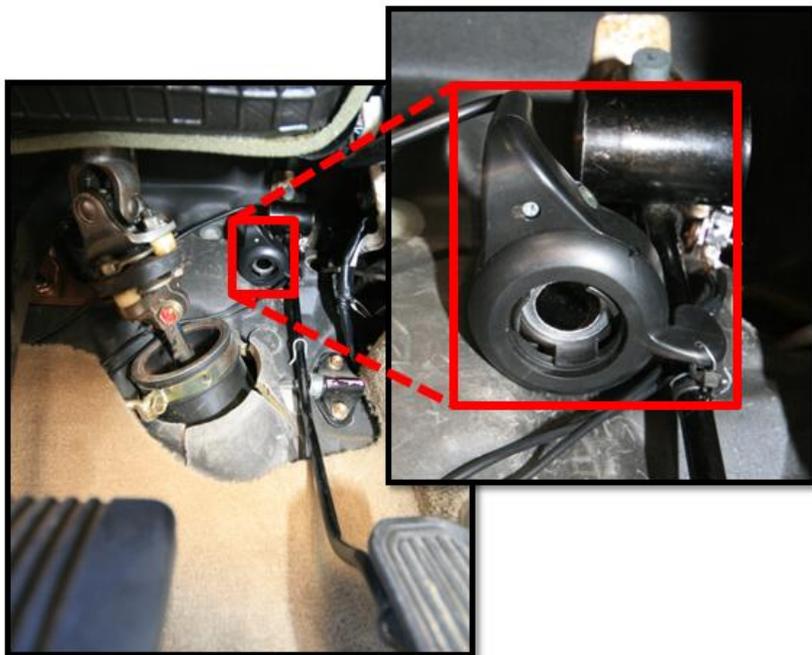
Figure 12. Thumb throttle potentiometer mounted to accelerator pedal.

3.3.3 Regen Switch

The regen activation switch can also be referred to as a controller "brake" switch due to programmable setting discussed later in section *3.5.3*. One side of a small lever activated SPDT (single pole, double throw) switch was used as an on/off sensor. The switch was mounted to an aluminum bracket bolted to the firewall in the same manner as the throttle. The switch can be seen in the open (off) position below in Figure 13, and in the closed position in the previous Figure 12.
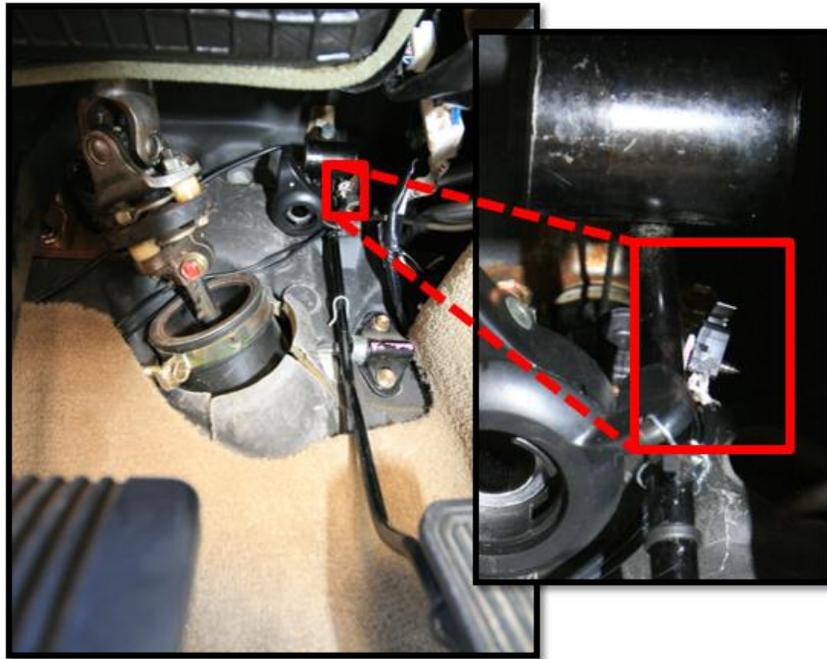
Figure 13. Regen/brake switch mounted behind accelerator pedal arm.

3.3.4 Wires & Power Cable

The power solenoid switch was wired using 14 gauge automotive wire and a 20 A in-line blade fuse. Both the brake switch and thumb throttle were wired with 16 gauge automotive wire. All switch and throttle signal wire was

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run through the interior of the vehicle underneath the driver side carpet and back seat, then into the trunk.

Four gauge (4 AWG) welding cable rated at 150 A was used for DC power transmission. Welding cable was chosen based on its flexibility, durable insulation, and current/voltage handling ability. Motor power cables exited the trunk through an existing drainage hole in the vehicle's spare tire well. Cables were run next to the vehicle's brake lines along the undercarriage and cable tied in place. Special care was taken to ensure the power wires were protected from impact and isolated from excess heat in all locations.

3.4 Motor/Generator Mount

A prototype motor mounting bracket was first mocked up using 1/16x1 inch plastic angle stock. The prototype was constructed based on existing mounting locations on the ICE, and space requirements for the motor, shaft, and drive pulley. The motor had to be mounted directly to the engine to avoid variation in belt tension as the engine shifts on the engine mounts during normal operation. This was done using the front motor mount bolt (1), two vacant M8-1.0 threaded holes in the front cylinder head (2), and a vacant M10-1.5 threaded hole in the upper stabilizer support mount (3) as seen in Figure 14 on the following page.
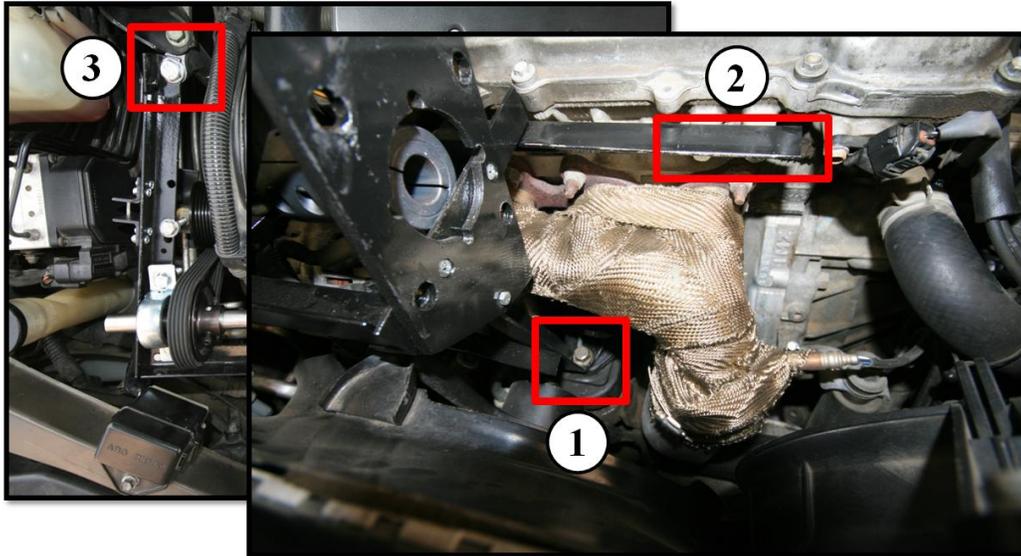
Figure 14. Motor/generator mount.

The plastic prototype was then used to transfer designs to 1/8x1 inch steel angle. The steel angle was bolted together using M5-.80x15mm hex head bolts with nylon lock nuts. Quarter-inch steel plate was fabricated into a mounting point for the motor, and also used as a drive shaft bearing support.

3.4.1 Mechanical Power Transmission

A 3/4 inch keyed steel shaft was used to transmit power from the motor to a 3.125 inch six-rib Vortech supercharger pulley. The 7/8 inch motor output shaft was stepped down using a machinable shaft coupler. The shaft was supported by two floating-mount, sealed ball bearings. To adapt the Vortech pulley to the shaft, it was bored out to accept a 0.7502 inch press-fit bushing. Allen-head bolts were also added to lock the pulley on to the shaft, and hold the 1/4 inch key-stock in place.

3.4.2 Belt & Tensioner

Mechanical power transmission was accomplished through an aftermarket serpentine belt, connecting the motor shaft pulley to the ICE crankshaft pulley. Tensioner design required multiple iterations due to the limited selection of two-sided six and five rib serpentine belts. No pre-existing two-sided six-rib belts were short enough for the required belt routing. Ultimately, the shortest available five-rib double-sided micro-v belt (Gates Belt # DK050565) was used. The belt was routed in a serpentine configuration with a fabricated tensioner to support a free spinning bearing-supported six-rib pulley. Serving as the original belt tensioner, the alternator was fixed in place at its lowest setting for added clearance. The final tensioner design is pictured below in Figure 15 followed by a belt routing diagram in Figure 16.
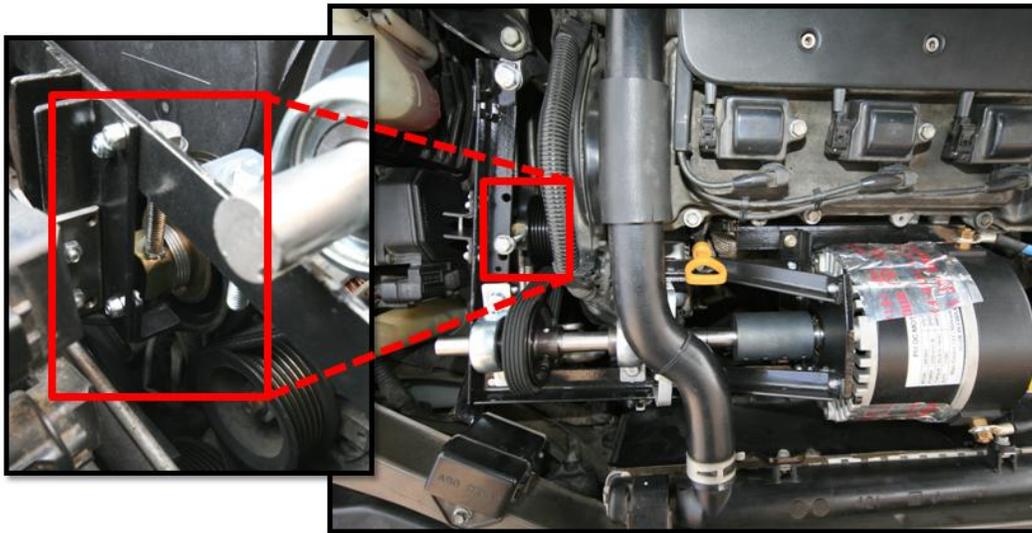
Figure 15. Serpentine belt tensioner.
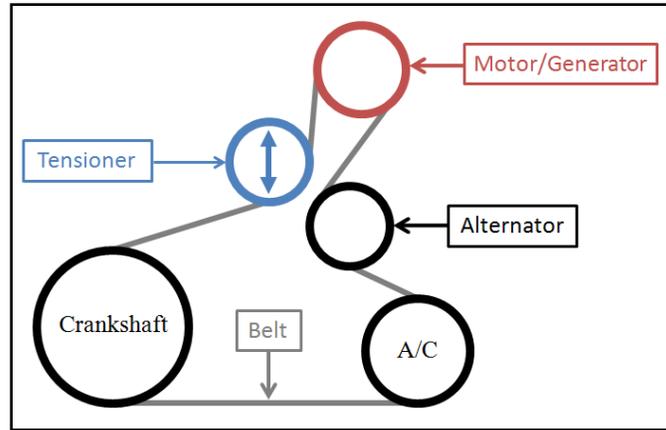
Figure 16. Serpentine belt routing diagram.

3.5 System Tuning

System tuning took place using a combination of motor controller programming and switch position adjustment. Tuning procedures proceeded as follows:

3.5.1 Brake Switch

The controller brake (regen) switch was set so that only a slight amount of pressure on the accelerator pedal deactivated the braking signal. With the accelerator pedal in its resting position, and no applied pressure (ICE at idle), the brake switch reported an "on" signal. As soon as any pressure was placed on the accelerator pedal (ICE still at idle) the switch reported an "off" signal to the controller.

3.5.2 Thumb Throttle

As mentioned previously in section *3.3.2*, throttle switch adjustment only required the simple rotation of the thumb throttle on the handle bar section to modify initial and final throttle position. With the vehicle's accelerator pedal in its resting position (no pressure applied), the thumb

throttle was set at roughly one quarter activated. To determine this setting, the vehicle was started with the hybrid system on. As the brake switch was disengaged without increasing engine rpm, the thumb throttle was slowly rotated to increase the throttle position. As soon as the power being transmitted to the crankshaft pulley (from the motor pulley) exceeded the friction capabilities of the serpentine belt, the throttle was backed off very slightly. The brake switch was then cycled to ensure that the belt was not slipping on the motor pulley, and locked in place.

3.5.3 Controller Programming

The controller was programmed so that the brake switch both deactivated the motor throttle and activated regenerative charging. This was done by setting "Braking Switch" to "Enable," and "Regeneration" to "Enable," respectively. To decrease rapid fluctuations in bi-directional loading on the belt, which resulted in slippage, the "Regen Current by Brake Switch On" setting was reduced to 10%. This also reduced regenerative load on the engine when the accelerator pedal was not depressed. A software screenshot including all of the above controller settings can be seen below in Figure 17.
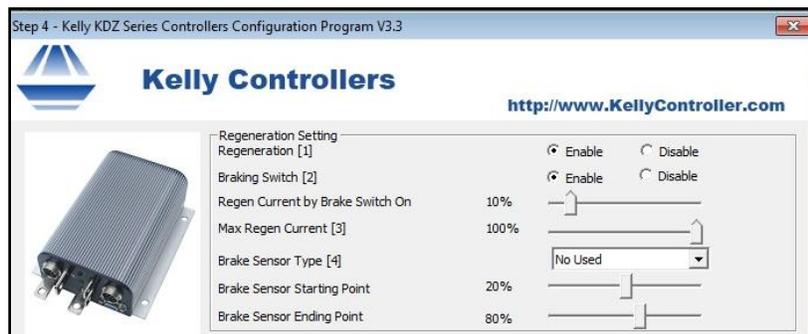
Figure 17. Brake switch regeneration settings.

To allow the motor controller to turn on with the throttle signal at one quarter (and prevent a fault code), "Power On High Penal Disable" was set to "Disable." To prevent a separate fault code when the brake switch is deactivated and the throttle signal is at roughly one-quarter, "Releasing Brake High Pedal Disable" was also set to "Disable." These program settings can be viewed in the screen shot below (Figure18).
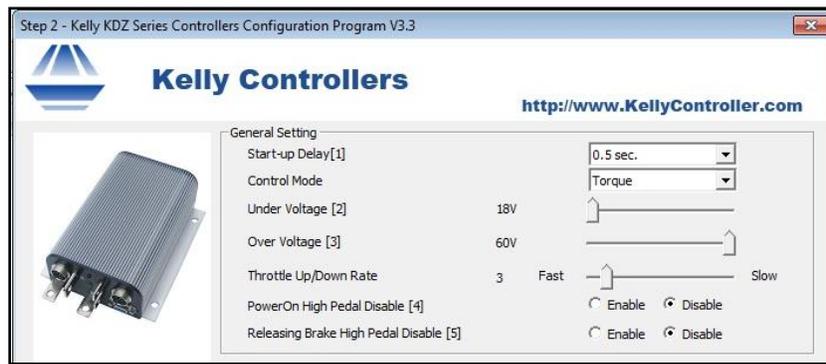
Figure 18. Power on and brake release settings.

3.6 System Operation

With the switches set and motor controller programmed, hybrid operation is as follows:

Prior to starting the vehicle, the power solenoid switch is flipped in to the "on" position. The key is then placed in the ignition and rotated to the ACC (accessory) position, which turns on the motor controller. The vehicle can then be started as usual.

When the vehicle is idling or moving with no pressure of the accelerator pedal, the regen switch is activated and regenerative charging of the battery bank is taking place. If the vehicle's brake is pressed, regen is unaffected, and is still active (assuming that there is still no pressure on the

accelerator pedal). Transmission position (P R N D 2 L) also has no effect on switch activation.

As soon as pressure is applied to the accelerator pedal, the brake switch is disengaged and the motor throttle is at one quarter. This corresponds to a 200 rpm increase at idle, which is attributed solely to the DC motor. Depressing the accelerator pedal just enough to deactivate the brake switch does not affect the position of the engines throttle body.

As the accelerator pedal is depressed further, power to the motor is increased in conjunction with air and fuel to the ICE as the throttle body opens. The motor is capable of adding power and assisting in acceleration up to roughly 2000 rpm. This corresponds to shift points at approximately 15 mph in first gear, 25 mph in second gear, and 42 mph in third gear, with a cruising speed of 60 mph in overdrive (fourth gear). An outline of motor and engine duty cycles is displayed below in Figure 19.
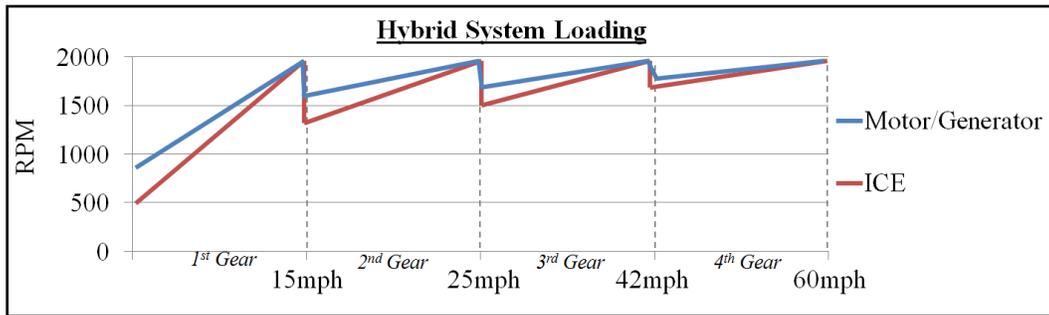
Figure 19. Hybrid system loading under normal acceleration.

When cruise control is activated, and pressure is removed from the accelerator pedal, regen is still activated. In this situation, it is possible to drive at highway speeds for long distances without worrying about battery capacity, because the battery will be charging.

3.7 Limitations

The simplicity and reduced cost of the system result in minor limitations when comparing the developed mild hybrid, to a fully integrated OEM hybrid of the same scale.

3.7.1 Energy Monitoring

The first limitation is the lack of any energy monitoring systems. This means that the driver is unaware of the battery's state of charge (SOC). If a driver is unaware of the system's basic functions, they will have no knowledge of when the DC motor is applying power or when regen is taking place. There is no display of any information to the user.

3.7.2 Range

Due to the lack of energy monitoring, an exact hybrid mode operating range is unknown. It is estimated based on battery bank voltage (a poor indication of SOC) that the system will operate for roughly 1.5 hours in normal stop-and-go traffic. In this situation the motor is drawing a load for extended periods, with short periods of regen when stopped and when coasting.

To increase hybrid operating range cruise control can be used which activates regen. Otherwise, long highway based trips would quickly deplete the battery. A consequence of this scenario is reduced fuel economy when cruising due to the added regen load on the engine.

3.7.3 Charging

Unlike a traditional mild hybrid that would not have to be plugged in, the developed system must be charged every night under normal driving

conditions. This assumes that long highway trips using cruise control, which recharges the battery, are not taking place. A mild hybrid will typically regulate and monitor battery SOC with the VCU, but this exceeds the limitations of a low cost system. To maintain battery SOC, the bank was connected to a Save A Battery™ 36 V Charger/Maintainer.

3.7.4 Serpentine Belt

Power transmission must be reduced due to friction limitation with the 5-rib belt. This results in one of the largest reductions in system performance. The limited power transmission ability of the belt results in reduced motor throttle and regen application. More power could be applied when accelerating, and more regen power could be harvested if belt slippage was remedied.

3.7.5 Idle-off

The largest limitation of the developed mild hybrid system in comparison to a typical mild hybrid is the lack of idle-off technology. Idle-off technology requires dedicated communication between the hybrid system and the vehicle's engine control unit (ECU). This requires extensive research, complex connections, and an added VCU; all of which exceed the uncomplicated and low cost goals of the developed system. It is also unknown if engine wear, carbon build up, or a reduction of catalytic converter life will result in an engine not originally designed for increased start-stop cycles [1].

3.8 User Transparency

User transparency plays an important role in any hybrid system. The vehicle must always operate in the same manner (to the user) as a

traditionally powered vehicle. In this category, the developed system excels.
In the process of adapting the system, no permanent modifications were
made to the host vehicle. This means that the system is completely
removable, returning the car to its original state. The only aspects visible to
the user are the small power solenoid switch in the main cabin, and the
battery bank/controller in the trunk, *if* one is looking from a low enough
angle. The battery bank is largely hidden by the vehicle's trunk carpeting
and is barely visible when standing directly behind the vehicle as seen in
Figure 20. On the following page, Figure 21 displays the trunk prior to
system installation.

Figure 20. Battery bank and controller with trunk carpet in place.

Figure 21. Trunk prior to battery and controller installation.

During vehicle operation, the hybrid system also feels the same to the driver as the original vehicle. Acceleration assist and regen are seamless in activation and do not cause any abrupt motion, vibration, or audible changes in engine noise.

3.9 DOH

The Toyota Avalon is equipped with a 3.0-liter V6 engine, and a four-speed automatic transmission. The V6 ICE is originally rated from the factory at 200 hp, or 149.14 kW. The Mars ME0909 electric motor is rated at a peak of 15kW. Using the degree of hybridization equation from Figure 3, and plugging in the respective power values; P_{ice} = 149.14 kW and P_{em} = 15 kW, yields a DOH value of 0.0914 or 9.14%.

3.10 Type Definition

Based on the degree of hybridization and a motor rating of less than 20 kW, the electric power potential of the developed hybrid system would be classified as a micro hybrid. Based on configuration, battery capacity, and system features like acceleration assist, the system is more accurately

classified as a mild hybrid. Although mild hybrid systems that are fully integrated into the initial vehicle design and VCU typically see fuel economy gains of 20-25%, a more modest gain of 10-15% is expected. This is largely due to lack of system integration with the host vehicle's ECU, an absence of a VCU, and the lack of start-stop capability.

3.11 Performance

A vehicle's fuel economy is the result of an extremely wide range of uncontrollable factors in real world testing. These include but are not limited to: outside temperature, constant or gusting wind, road surface roughness, road grade, traffic volume, and traffic patterns [1]. The only way to isolate the vehicle from these influences is to conduct controlled testing on a highly monitored closed course, or even better, a dynamometer using fuel economy drive cycles developed by the EPA [11]. Ideally, a vehicle's exhaust gasses are captured and the amount of expelled carbon dioxide is used to calculate gallons of gasoline burned [1]. More controllable factors effecting fuel economy are altered aerodynamics, added weight, accessory use, and driver attentiveness to speed, throttle/ brake application, and traffic patterns [1].

Due to the difficulty of establishing a consistent drive cycle on public roads and the lack of advanced data acquisition tools, tracking charts were developed to capture a limited number of factors affecting fuel economy. This serves as a basic approximation of the vehicle's driving cycle. Data recorded by a Garmin nüvi® 260 portable GPS (position accuracy within 15 meters) includes: trip duration, distance, average speed, and stop time. Air conditioning (A/C) use, the number of passengers, and special conditions

affecting aerodynamics (driving with the windows down, or bicycle(s) on the roof) were also recorded. Distance traveled per tank was captured by the vehicle's odometer. A sample of these charts can be seen below in Table 1.

Table 1. Sample of drive cycle tracking chart.

1998 Toyota Avalon Base MPG Performance Tracking (Using Garmin GPS)						
Date	Trip Duration (min.sec)	Distance (miles)	Avg Speed (MPH)	Stop Time (min.sec)	A/C (ON/OFF)	Number of Passengers	Special Conditions
19-Aug	18.01	6.4	21.0	4.01	ON	1	Note: Tank Filled
	13.4	6.2	26.7	1.01	ON	1	
	16.30	10.8	38.6	2.00	ON	1	
20-Aug	15.49	10.7	40.1	2.00	OFF	1	Windows Down
	21.48	9.1	24.8	3.35	ON	1	1 bike on roof
	23.50	9.1	22.7	5.22	ON	1	
	52.33	24.2	27.7	10.15	OFF	1.5	Windows Down

The Toyota Avalon is equipped with an aftermarket roof rack capable of holding two bicycles. This results in additional aerodynamic drag at all times that adversely affects fuel economy. The rack was not removed during testing to retain the vehicles utility purposes. When one or two bicycles are placed on the roof, fuel economy will be increasingly affected. The same can be said for added passenger weight, the use of vehicle accessories (namely A/C), and driving with the windows down. For consistency, the air conditioning was not used if the windows were down, and all four windows were placed in their fully retracted position.

Added weight increases vehicle loading and subsequently reduces fuel economy. The batteries (186 lbs), motor (30 lbs), motor mount (10 lbs), 4 AWG cable (9 lbs), and controller (4 lbs) add a total of 239 lbs of additional weight to the vehicle's 3,404 lb curb weight [12]. This also reduces total cargo capacity to 665 lbs. The percentage of weight change in a vehicle is inversely

proportional to the resulting percentage of fuel economy change [1]. So a weight increase of 239 lbs results in a fuel economy decrease of 7% (239 lbs/3,404 lbs).

CHAPTER 4

RESULTS

4.1 Baseline Results

Prior to hybrid system installation, baseline fuel economy performance in mpg was tracked over four fueling cycles for a total of 1,366 miles (59.562 gallons). Fuel consumption per fueling cycle was determined using the same gas station and the same pump (the last fill up required the use of a different pump at the same station) with a [(R+M)/2] gasoline rating of 87 octane. The first "auto-stop" of the pump to indicate a full fuel tank was used consistently. A summary of fuel economy performance by fuelling cycle is displayed below in Table 2.

Table 2. Fuel economy performance in mpg per fueling cycle.

Tank	Average Temp (degrees F)	% A/C on	% Windows Down	Average Occupancy	Bike on roof %	Avg Trip Length (miles)	Average Speed (mph)	Avg Trip Time (min.sec)	% Idle (Stopped)	Fuel Economy
1	98	61.55	38.45	1.135	5.87	9.2	30.86	17.81	17.55	21.45 mpg
2	91	57.37	42.63	1.238	30.04	7.8	31.77	15.11	15.25	22.05 mpg
3	91	49.34	50.42	1.064	14.39	8.1	35.14	13.83	17.91	24.60 mpg
4	79	34.14	48.25	1.182	0	6.1	28.89	12.76	19.75	23.59 mpg

"Average Temp" corresponds to monthly averages in Phoenix, AZ calculated by AccuWeather, based on the month of travel with the highest number of days [13]. The columns "% A/C on" and "% Windows Down" were calculated using a sum of the number of miles traveled with the air conditioning on (or windows down), over the total number of miles traveled per fueling cycle. The "Bike on roof %" was calculated using the same method as the A/C and windows down percentages. The "% Idle" column was calculated using a sum of the "Stop Time" over a sum of the "Trip Time" (see

Table 1). Fuel economy performance for fueling cycles 1-4 corresponds to 21.45 mpg, 22.05 mpg, 24.60 mpg, and 23.59 mpg, respectively. These figures represent an average of GPS recorded miles and odometer recorded miles, over the number of gallons of gasoline per fueling cycle.

The same methodology as above was used to calculate the overall baseline results, using data from all four fueling cycles over 1,366 miles traveled, as presented in the following section in Table 3. The vehicle established a fuel economy baseline of 22.93 mpg.

4.2 Hybrid Conversion Results

After hybrid conversion and tuning took place, performance data was recorded and calculated using methods presented in the previous section for one fueling cycle (326.75 miles). Fuel economy performance for the converted vehicle was 26.58 mpg. This corresponds to a 3.65 mpg or 15.92% improvement in fuel economy performance. A comparison of overall baseline and overall hybrid data in included below in Table 3.

Table 3. Overall baseline and hybrid performance.

Overall Baseline (1,372.60 miles)									
Average Temp (degrees F)	% A/C on	% Windows Down	Average Occupancy	Bike on roof %	Avg Trip Length (miles)	Average Speed (mph)	Avg Trip Time (min.sec)	% Idle (Stopped)	Fuel Economy
89.75	50.42	45.11	1.534	12.31	7.7	31.63	14.55	17.71	**22.93mpg**
Overall Hybrid (326.2 miles)									
69	3.39	62.05	1.128	0	8.4	30.71	16.4	14.78	**26.58mpg**

4.3 Basic Financial Analysis

A basic financial analysis that does not account for inflation, fluctuating gas prices, or maintenance costs was completed to determine the economic feasibility of this aftermarket hybrid system. The total cost (C_T) of

the developed hybrid system was $1866.07. A breakdown of system costs by major part is presented below in Table 4.

Table 4. System cost breakdown.

Part	Quantity	Unit Price	Vendor
Mars ME0909 PM DC Motor	1	$385.00	Electric Motorsport Inc.
Kelly KDZ48401 Motor Controller	1	$299.00	Kelly Controls, LLC
Thumb Throttle	1	$19.00	Kelly Controls, LLC
Keyed 1045 Steel Drive Shaft 3/4" OD, 3/16" Keyway Width, 12" Length	1	$20.57	McMaster-Carr
Stamped-Steel Mounted Ball Bearing--ABEC-1 2-Bolt Base Mount, for 3/4" Shaft	1	$11.78	McMaster-Carr
Machinable-Bore One-Piece Clamp-on Coupling 7/8" X .235" Bore, 1-7/8"	1	$33.71	McMaster-Carr
Vortech Supercharger Pulley VOR-2A036312	1	$73.00	Summit Racing
EverStart MAXX-29 12V Battery	3	$96.74	Wal-Mart
Gates Belt DK050565	1	$73.99	O'Reily Autoparts
25ft 4 AWG Welding Cable	2	$46.69	Grainger
DC Power Solenoid, 36V, 100 Amps	1	$86.80	Grainger
additional misc. hardware, materials, tax, and shipping costs		$479.56	
Total cost		**$1,866.07**	

With initial system costs known, annual fuel costs with and without the hybrid system can be compared, and a payback period can be established. Annual fuel cost calculations were developed using the following equation (Figure 22):

$$C = \frac{(D, \ mi/year)(G_\$, \ \$/gal)}{F_E, \ mi/gal}$$

Where:
C = annual fuel cost ($/year)
D = miles driven per year (mi/year)
$G_\$$ = cost of gasoline ($/gal)
F_E = fuel economy (mpg)

$C_T = \$1,866.07$
$D = 13,476 \ mi/year$
$G_\$ = \$3.941/gal \ (87 \ octane)$
$F_{EO} = 22.93 \ mpg$
  ➤ $C_O = \$2,316.13/year$
$F_{EH} = 26.58 \ mpg$
  ➤ $C_H = \$1,998.08/year$

Figure 22. Annual fuel cost (C) equation.

For miles driven per year (D), the national average established by the Federal Highway Administration of 13,476 mi/year was used [14].

For the cost of gasoline ($G_\$$) (regular, 87 octane), the U.S national average of $3.941/gal on April 2, 2012 was used as reported by the U.S. Energy Information Administration [15].

Fuel economy for the Toyota Avalon prior to conversion (fuel economy original) is F_{EO} = 22.93 mpg, and fuel economy for the Toyota Avalon after the hybrid conversion (fuel economy hybrid) is F_{EH} = 26.58 mpg.

Plugging in the values, the annual cost to drive the vehicle prior to conversion (annual fuel cost original) in C_O = $2,316.13/year, and the annual cost the drive the vehicle after hybrid conversion (annual fuel cost hybrid) is C_H = $1,998.08/year. This corresponds to an annual fuel savings of $318.05/year ($C_O - C_H$).

Dividing the total system cost by the annual fuel savings per year [$C_T/(C_O - C_H)$] yields a payback period of roughly 5.87 years (6 years for simplicity). The payback will shorten or increase if the $/gal cost of gasoline increases or decreases respectively. Although it is difficult to estimate system life, the age and condition of the vehicle must also be taken in to consideration to justify hybrid conversion.

CHAPTER 5

CONCLUSIONS & RECOMMENDATIONS

5.1 Conclusion

In summary, it can be concluded that a simple aftermarket hybrid system is feasible and capable of substantially improving fuel economy for an initial cost of less than $2,000. However, a fuel savings of 15.92% may not be justifiable if the expected remaining life of the vehicle is less than 7 years.

Real world testing on public roads provides insight into the performance of an aftermarket hybrid conversion, but the results are variable and influenced by too many factors to completely address.

5.2 Recommendations

Recommendations for suggested system improvements and further study are presented as follows:

5.2.1 System Improvements

The power transfer and bi-directional loading capability of the five-rib two-sided serpentine belt was far exceeded by the power capabilities of the ME0909 motor. As a result, a significant amount of hybrid acceleration assist and regen was lost. Replacing the DC motor to engine crankshaft coupling with a more capable toothed drive belt would enable increased acceleration assist and regen loading on the motor, and subsequently increase fuel economy.

The addition of an energy monitoring system would greatly benefit both data collection and vehicle operation. A heads up display would inform

the driver of hybrid system power usage and regen. At a minimum, the driver should be informed of the remaining battery capacity.

To reduce system weight and/or increase operating range more advanced battery technologies (Ni-MH, Li-ion, LiPo, etc) could be used. Smart battery technology would also aide in the development of a battery management system with heads up usage and SOC display.

While the long-term effects on engine wear are largely unknown, the hybrid system discussed may be capable of idle-off technology if equipped with an upgraded drive belt. This may also require the addition of a basic VCU to manage the system.

5.2.2 Further study

While the performance results in this study are promising, they are far from a finite conclusion. If a hybrid conversion system is brought to market, a more thorough account of drive cycle variables and other parameters affecting fuel economy should be conducted. This requires the use of energy monitoring feedback sensors, and real time data acquisition. At a minimum, hybrid system should be applied to a vehicle and tested with strict adherence to EPA fuel economy testing procedures on a dynamometer.

REFERENCES

[1] Allen E Fuhs, *Hybrid Vehicles and the Future of Personal Transportation*. Boca Raton, United States of America: CRC Press, 2009.

[2] Polk. (2012, January) Polk Company News. [Online]. https://www.polk.com/company/news/average_age_of_vehicles_reaches_record_high_according_to_polk

[3] John M German, *Hybrid Powered Vehicles*. Warrendale, United States of America: SAE International, 2003.

[4] Chevrolet. (2012, April) The first electric car that runs on more than electricity. [Online]. http://www.chevrolet.com/volt-electric-car/

[5] Tom Libby. (2011, October) Polk Blog: One Reason for Toyota's "Green" Image. [Online]. http://blog.polk.com/blog/blog-posts-by-tom-libby/one-reason-for-toyotas-green-image

[6] Mashadi Behrooz and David Crolla, *Vehicle Powertrain Systems*. Chichester, United Kingdom: John Wiley & Sons Ltd, 2012.

[7] Steven M. DeMers, "Mechanical and Regenerative Braking Integration for a Hybrid Electric Vehicle," University of Waterloo, Ontario, Thesis 978-0-494-43632-5, 2008.

[8] Dr. Robert E Urig, "Using Plug-in Hybrid Vehicles to Drastically Reduce Petroleum-Based Consumption and Emissions," *The Bent of Tau Beta Pi*, pp. 13-19, Spring 2005.

[9] Sebastian Blanco. (2010, January) Auto Blog. [Online]. http://www.autoblog.com/2010/01/04/report-number-of-cars-in-the-u-s-dropped-by-four-million-in-20/

[10] Kelly Controls LLC. (2012, April) Manual & Software. [Online]. http://kellycontroller.com/mot/downloads/KellyKDZUserManual.pdf

[11] U.S Environmental Protection Agency. (2012, April) fueleconomy.gov. [Online]. http://www.fueleconomy.gov/feg/fe_test_schedules.shtml

[12] Insurance Institute for Highway Safety. (2010, April) iihs.org. [Online]. http://www.iihs.org/ratings/rating.aspx?id=88

REFERENCES

[13] AccuWeather. (2012, April) AccuWeather.com. [Online].
    http://www.accuweather.com/en/us/phoenix-az/85003/april-
    weather/346935?view=table

[14] U.S. Department of Transportation - Federal Highway Administration.
    (2012, April) Average Annual Miles Driven per Driver by Age Group.
    [Online]. http://www.fhwa.dot.gov/ohim/onh00/bar8.htm

[15] U.S Energy Information Administration. (2012, April) Petroleum &
    Other Liquids. [Online]. http://www.eia.gov/petroleum/gasdiesel/