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PROJECT TITLE: AN INTRODUCTION TO THE HYBRID ELECTRIC
VEHICLE CONTROL SYSTEM AND HYBRID COUPLER

I have reviewed this completed senior honors thesis with this student and certify that it is a project commensurate with honors level undergraduate research in this field.

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Comments (Optional):

An Introduction to the Hybrid Electric Vehicle Control System and Hybrid Coupler

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Abstract

Hybrid electric vehicles are growing in popularity because of the ability to achieve similar performance to a standard automobile while greatly improving fuel efficiency and tailpipe emissions. The University of Tennessee Future Truck, a highly modified 2002 Ford Explorer, is a useful example of parallel hybrid electric vehicles and what follows is intended to be an introduction to such vehicles for people without a technical background. The Future Truck is the focus of this paper because it, like the hybrid cars that are currently most prominent in the public, is of the parallel design. Specifically, the UT Future Truck's control system and hybrid coupler are addressed as they are the key to successful implementation of a hybrid vehicle.

Introduction

The automobile has undergone countless advances since its conception over 100 years ago. Improvements are still being made to the ways that cars are designed and perform and currently there is growing emphasis on a vehicle's fuel efficiency and tailpipe emissions. A sign of this change is the increasing number of hybrid electric vehicles. A hybrid electric automobile is any car or truck that has that has an electric motor in addition to an internal combustion engine. Hybrid electric vehicles take advantage of the characteristics of their two power sources and the fact that the majority of driving situations, such as cruising down the road, do not require high horsepower or torque. This means that smaller, less powerful engines are suitable for most conditions. Such

engines are more efficient than larger engines because of lower overall weight and less internal friction. The drawback to engines, both large and small, is that they are not as efficient at low engine speeds as they are at high engine speeds. This is why electric motors are implemented. Electric motors produce high torque, which is what gets a car moving from a stop, at very low speeds. This characteristic means that motors can be used to provide the initial motion to a vehicle and then, once the vehicle moving, the engine can take over as the primary power source while operating in its most efficient speed range, thus lowering emissions and increasing fuel efficiency.

The two main types of hybrid automobiles are series and parallel. Series hybrids use only an electric motor or motors to provide power to the drive wheels to move the vehicle and rely upon the internal combustion engine to keep the battery pack charged. This typically requires a single large motor or multiple small motors to match the performance of a standard car. Parallel hybrids are capable of using the electric motor and the engine in unison to move the vehicle allowing the use of a smaller electric motor than a series hybrid and a smaller engine than a standard automobile. They are also capable of operation using just the motor to provide motion or just the engine, in which case the motor acts as a generator to charge the battery pack. Since the two power sources have the capability of working together when necessary, standard car performance may be matched or exceeded with smaller, more efficient components. The most prominent hybrid cars today, the Toyota Prius and the Honda Insight, are parallel hybrids. Due to this success what follows is an introduction to parallel hybrid vehicles.

The University of Tennessee Future Truck, in particular the control system and hybrid coupler, is the focus of this paper because it is a useful example of many of the factors that must be taken into account when creating a parallel hybrid and shows one manner in which a parallel hybrid can be designed to operate. The truck itself is a 2002 Ford Explorer that has been modified over the past four years to compete in a Department of Energy and Ford sponsored event known as the Future Truck Competition. For 2004 the truck, known as *Evolution*, must meet the competition goals of achieving at least 25% better fuel economy while lowering the emissions to at least Ultra Low Emissions

Vehicle (ULEV) levels and maintaining the consumer acceptability of the product. These goals are accomplished by mating a 75kW (100 hp) motor and a 113kW (151hp) 2.3 liter 4-cylinder spark ignition engine in a pre-transmission parallel arrangement using a student designed hybrid coupler box. The combined output of the motor and engine is 188kW (251hp), which compares favorably with the original 4.0 liter 6-cylinder engine capable of producing 157 kW (210hp). It is the responsibility of the truck's control system to control the interaction of the motor and 2.3 liter engine to reap the benefits of a parallel hybrid design, and the responsibility of the hybrid coupler to allow such control to take place. *Evolution's* hybrid coupler and control system are the topics of the remainder of this document to illustrate how parallel hybrid vehicles are capable of achieving superior emissions levels and performance in comparison to standard vehicles.

Hybrid Coupler

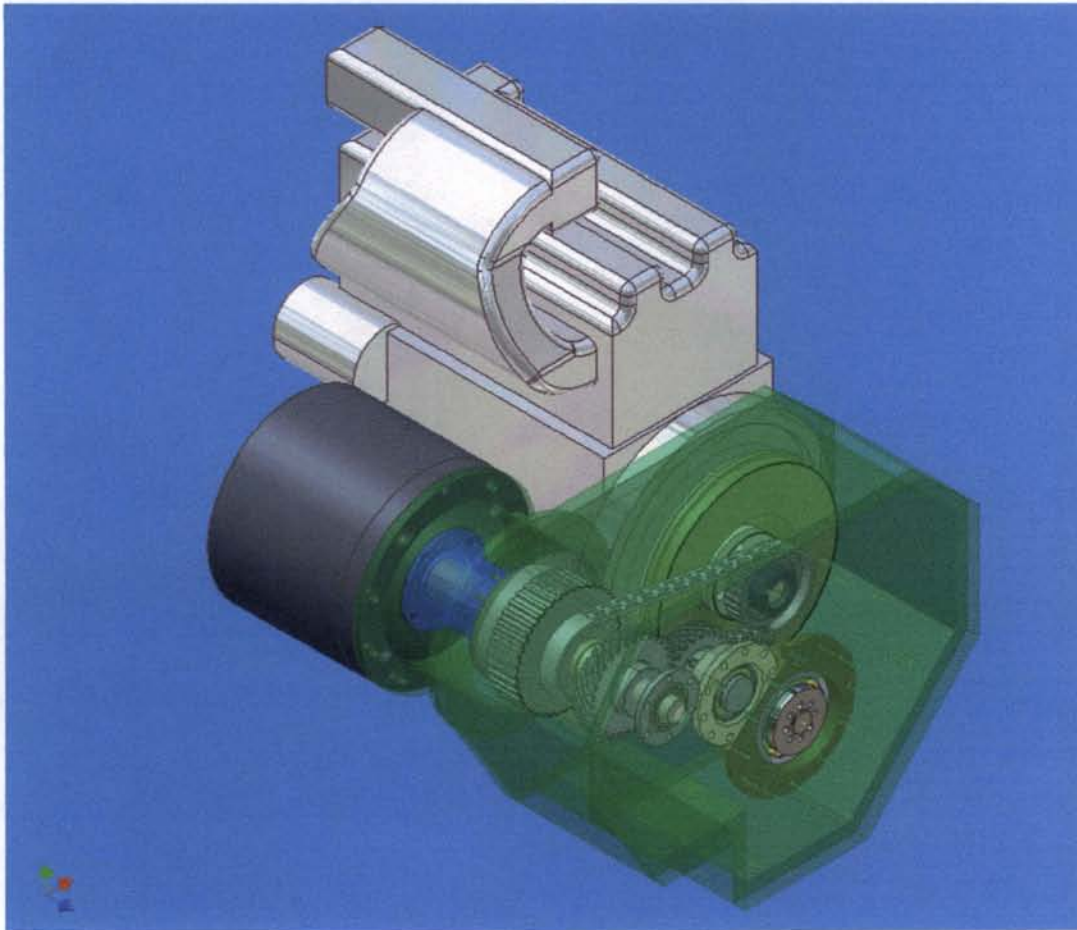


Figure 1: Hybrid Coupler with Engine and Motor (Team Tennessee)

In order for pre-transmission parallel hybrid electric vehicles to work there must be a coupling device that ties the electric and internal combustion power sources together. This hybrid coupler is what mechanically allows the motor and engine to simultaneously or independently power the drive wheels of the vehicle and charge the batteries as necessary. The coupler in a parallel hybrid must be designed to allow the engine and motor to operate as dictated by the control system in a reliable manner.

The UT Future Truck's hybrid coupler is a specially designed box that mounts the engine and motor on one side and a standard transmission on the other. The electric motor sends power directly to the transmission through a helical gear train (Team Tennessee). This direct path is used because the motor is the preferred power source for the drive wheels. The helical gear train is designed to be a simple, strong, and reliable means of transmitting power from the motor to the rest of the drivetrain. The output shaft of the motor contains an electric clutch, governed by the control system, capable of engaging or disengaging the internal combustion engine as necessary to meet driving and battery charging requirements of the vehicle. When the clutch is disengaged, *Evolution* is powered solely by the electric motor and does not have to overcome the internal friction of the engine (Holder). This allows the vehicle to operate in a zero emissions state, producing no emissions and using no fuel. When engaged, the clutch receives power from the engine via a high speed chain. This allows power from the engine to be added to that of the motor for high power demand situations such as passing or hard acceleration. The clutch also allows the engine to use the motor as a generator to charge the battery pack as required while simultaneously powering the drive wheels (Smith). The hybrid coupler assembly is seen in Figure 1.

Control System

The control system of *Evolution* is primarily responsible for coordination of the electric motor and internal combustion engine, maintaining a proper state-of-charge in the hybrid battery pack, and protecting the battery pack. Coordination of the engine and motor depends upon driver intent as communicated by the accelerator and brake pedals. Proper state of charge is maintained by employing either regenerative braking or by using the

motor as a generator taking power from the engine. The battery pack is protected by monitoring variables such as temperature and current and ensuring that the manufacturer specifications are never exceeded (Smith).

The basic parts of the UT Future Truck control system are the Vehicle System Control Module (VSCM), the Battery Control Module (BCM), the Traction Inverter Module (TIM), and the Electronic Throttle Control Module (ETCM). The VSCM is the core of the system and controls when and how the other systems in the vehicle interact. The battery pack specifications, state of charge, and outputs such as voltage and current are monitored by the BCM (Team Tennessee). The electric motor that helps power the vehicle is controlled by the TIM, which also protects it. The ETCM controls the throttle to transparently blend the motor and engine (Smith). An overview of the control system is seen in Figure 2.

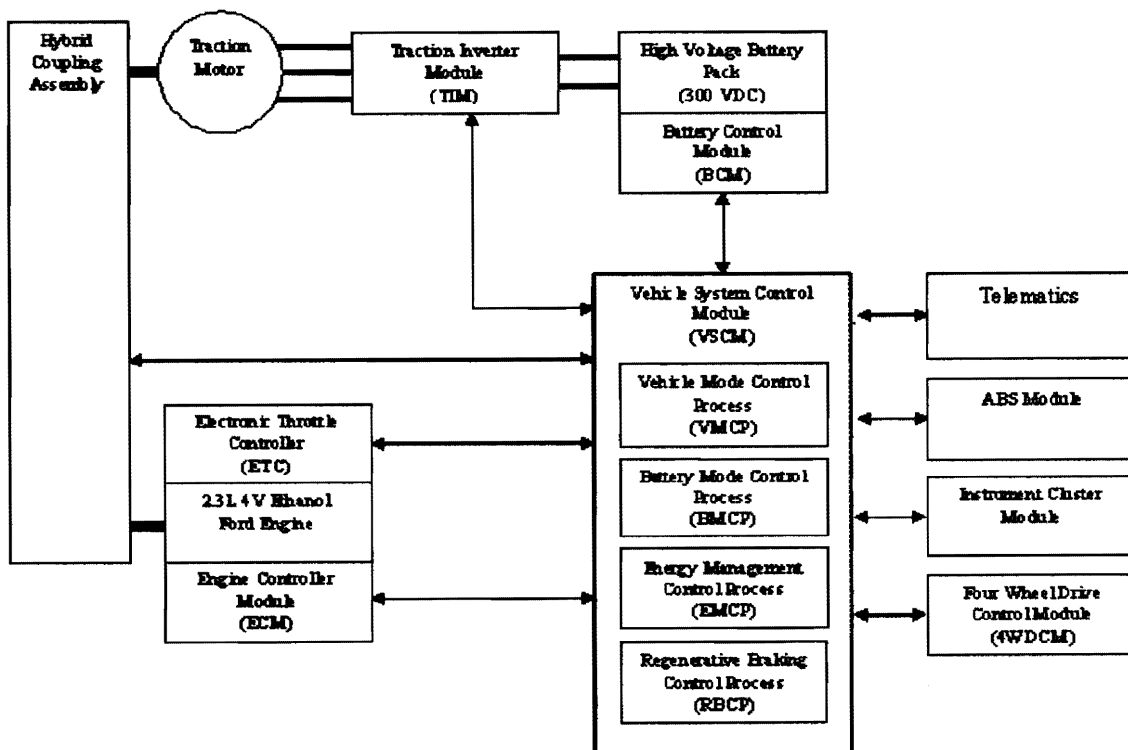


Figure 2: *Evolution* Control System Overview (Team Tennessee)

Vehicle System Control Module

The VSCM coordinates the systems that allow the Future Truck Explorer to operate as a hybrid electric vehicle. The four subsystems that are part of the VSCM are the Vehicle Mode Control Process (VMCP), the Battery Mode Control Process (BMCP), the Energy Management Control Process (EMCP), and the Regenerative Braking Control Process (RBCP). The VMCP monitors the status of the key, governs the initial power up of the vehicle, and translates the driver intent to determine what power source or sources should be used. The BMCP is an extension of the BCM and works with the VMCP to provide information to the EMCP. The EMCP is in control of engine and motor interaction. The RBCP translates driver intent to blend regenerative and normal braking (Smith).

Vehicle Mode Control Process - *Evolution's* VMCP decides when to power up the vehicle by monitoring the position of the key in the ignition. When the truck is being activated (the key is turned "on") the VMCP communicates with the BCM to close the contactors and energize the high voltage system. The BCM responds to the VMCP upon completion of the tasks and the VMCP then contacts the TIM. Once the TIM has been activated the high voltage system of the UT Future Truck is operational. At this point the VMCP is capable of telling the electric motor to start the internal combustion engine. The engine is started by the motor due to the absence of a traditional starter unit. The VMCP couples the engine and motor together via the electric clutch in the hybrid coupler and the motor then spins the engine to an appropriate starting speed, at which point it sends a signal to the ignition system to start the engine. As soon as the engine is running, the clutch in the hybrid coupler disengages and the engine operates independently of the high voltage system and is controlled by the Engine Control Module, which is no different from what is present in standard automobiles. The VMCP and VSCM determine when to run the engine, not how to run the engine. The only other input the system has is through the electronic throttle assembly (Smith).

The VMCP also translates driver intent via the accelerator and brake pedals. Signals from the pedals are transmitted to the VSCM where they are sent to the VMCP. When the VMCP has received the necessary input, it looks at data generated from dynamometer

testing to determine how much torque is available to move the vehicle. Since the motor is the preferred power source for the vehicle, the calculations controlling the Explorer are based off of the motor's speed. This means that the motor never actually stops spinning while the truck is in use because the VMCP and VSCM need a usable, or greater than zero, engine speed to operate the truck. Therefore, when the truck is not moving the motor is still spinning at as slow a speed as can be reliably mapped by the data programmed into VMCP. This leads to the following equation showing that power available to the driver is a function of motor speed, pedal input and motor and engine torques (Smith).

$$P_{drv} = \omega_{motor_min} * pedal_demand * (\tau_{mot_max} + \tau_{eng_max})$$

Battery Mode Control Process - Another subsystem within the VSCM is the BMCP. The BMCP calculates the battery pack power limits and passes the information to the EMCP. The BMCP determines if the battery pack requires charging and what amount of power is required from the engine to maintain an appropriate state of charge in the battery pack. This is accomplished the use of a table that can be calibrated to the specific Future Truck application. The power required to maintain the charge, P_{soc} , depends solely upon the state of charge of the battery pack, as seen in Figure 3 . The BMCP has the additional task of gathering data from the BCM and correcting it for conditions that are present in the battery pack such as high or low state of charge and high or low battery temperature (Smith).

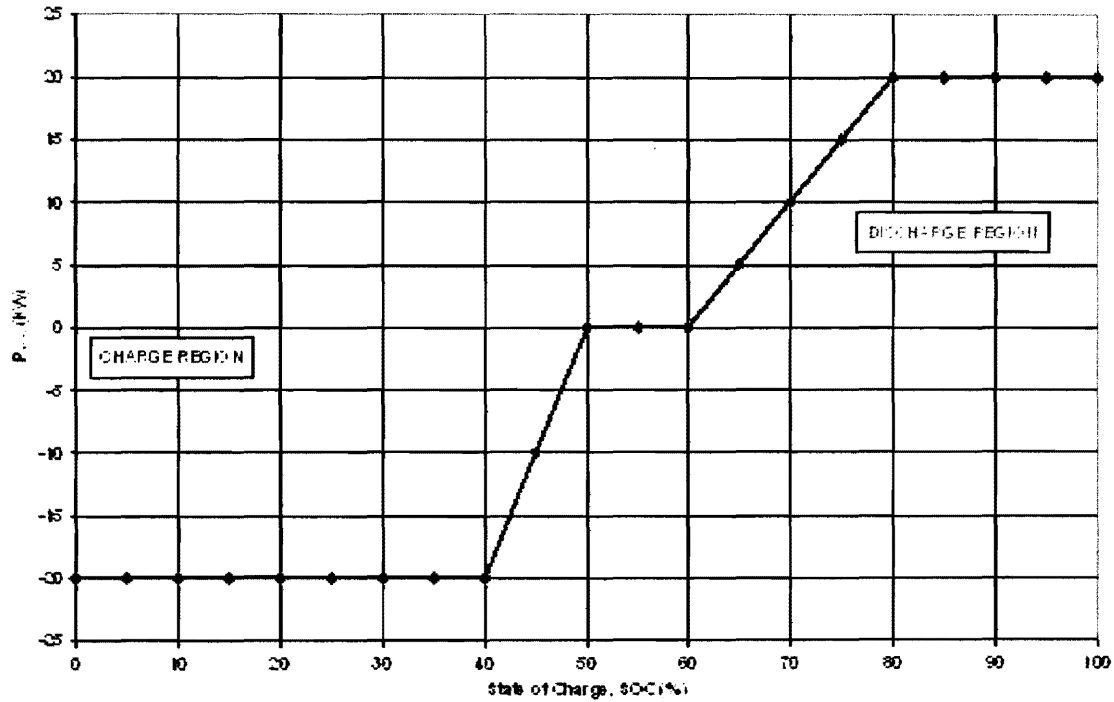


Figure 3: Determination of battery state of charge for BMCP (Smith)

Energy Mode Control Process - The EMCP is the subsystem within the VSCM that is most critical to the successful operation of the Explorer's hybrid system. The EMCP coordinates the motor and engine to meet driver demanded power while simultaneously meeting the constraints imposed by other systems in the vehicle and maintaining the battery pack's state of charge. Additionally, protection of subsystem components, especially the high voltage system and battery pack, is dealt with by the EMCP (Smith).

To successfully coordinate the two power sources in *Evolution*, the EMCP receives data from the BMCP and the VMCP. The outputs of these two subsystems, P_{SOC} and P_{drv} respectively, are combined to determine the total power required from the engine, P_{tot} . The total power is found from the following equation.

$$P_{tot} = P_{drv} - P_{SOC}$$

When the vehicle is operating using the electric motor as the only source of power P_{soc} is ignored. The EMCP also compensates for power lost in converting electrical energy to mechanical energy by calling for more power from the engine or motor (Smith).

Another function of the EMCP is controlling the engine in such a way that the driver is not aware when the battery pack is being charged. This is accomplished through closed loop idle speed control. This control setup allows the engine to spin at a predefined torque output and while the motor spins at a constant speed. This system allows the battery pack to be charged without noticeable engine speed or accelerator pedal feedback to the driver (Smith).

Regenerative Braking Control Process - The final subsystem in the VSCM is the RBCP. The RBCP determines the braking intent of the driver by monitoring a brake line pressure sensor and, when appropriate, implements regenerative braking through the motor to charge the battery pack. This subsystem also monitors vehicle speed via a sensor attached to the truck's driveshaft and reduces regenerative braking at low vehicle speeds. This reduction occurs due to drivability and noise, vibration, and harshness concerns. The UT Future Truck uses parallel regenerative braking. Unlike series regenerative braking, in which the electric motor absorbs all energy from the wheels, the parallel system uses the motor and standard brakes simultaneously to slow the vehicle. Parallel regenerative braking was chosen for *Evolution* because it is much easier to implement than series regenerative braking (Smith).

Battery Control Module

The BCM monitors the physical variables of the Explorer's battery pack. These variables, such as voltage, and data about the battery pack's state of charge are passed to the BMCP. The battery pack's state of charge is calculated using the open circuit voltage, the voltage that is present before the contactors are closed and the vehicle is started. These calculations are based in modeling of the battery pack to determine the correlation between open circuit voltage and state of charge. The open circuit voltage is

updated every time the ignition key is cycled. This also aids in the protection of the high voltage battery pack (Smith).

Electronic Throttle Control Module

The ETCM implements the throttle commands from the driver. The UT Future Truck is a true “drive by wire” system, meaning there is no physical connection between the accelerator pedal and the throttle body on the front of the engine, just wires. The pedal sends data to the throttle body where the butterfly is opened or closed according to driver input (Team Tennessee). This lack of a physical connection is one way in which the engine and motor are able to change speeds as directed by the EMCP to keep the battery pack charged without any feedback to the driver through the pedal.

Traction Inverter Module

Control of the motor is maintained via the TIM. The TIM receives information and inputs from the other systems of the vehicle and directs the motor accordingly. This direction is limited by built in safety protocols that are meant to prevent motor failure (Smith).

Results

In practice the control system and hybrid coupler produce fuel economy improvements and a reduction in tailpipe emissions. The largest fuel economy gains result from the control system shutting down the engine during times when the vehicle would be idling in traffic. According to a test in which a two-wheel drive Ford Escape with a 3.0 liter V-6 engine was driven through the Federal Urban Driving Schedule (FUDS), fuel economy gains of approximately 18.5% resulted from shutting the engine off during times when the vehicle was not moving. By shutting the engine down during the FUDS cycle, which simulates city driving conditions, fuel efficiency increased from 23.2mpg to 27.5mpg (Smith). By combining these engine shutdown gains with a smaller more efficient engine and *Evolution's* ability to use the electric motor to accelerate from a stop places fuel economy gains around 25%, one goal of the Future Truck Competition (Holder). This increase in fuel economy yields a corresponding decrease in tailpipe emissions since 25%

less waste is being produced. More fuel economy gains and emission reduction result from the fact that the Future Truck can be powered solely by the motor as long as the battery pack is sufficiently charged.

Conclusion

The hybrid coupler and control system in parallel hybrid electric vehicles make great improvements in tailpipe emissions and fuel efficiency possible. These systems are the heart of a parallel hybrid and are the key to consumer acceptable hybrid powertrain vehicles. A smoothly functioning control system and coupler ensure that the hybrid powertrain functions at its most efficient state while being transparent to the driver.

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