2001-01-2826

Fuel Economy and Performance Impact of Hybrid Drive Systems in Light Trucks, Vans & SUV's

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ABSTRACT

Fuel economy and emission improvements have been demonstrated with the application of hybrid electric drive systems to a variety of vehicle types. These include hybrid systems known as integrated starter alternator, mild hybrids, and heavy hybrids. The fuel economy and emission improvements for the integrated starter alternator and mild hybrid applications have been demonstrated through the Honda Insight and Toyota Prius.

Heavy hybrids applications consist of a significantly smaller engine assisted by a high peak power electric motor to provide additional power to the engine for acceleration and recovery of a higher degree of braking energy. Light trucks, vans, and SUV’s typically have a large difference between the gross combined weight of the vehicle and the fuel economy test weight. Heavy hybrid powertrains offer significant fuel economy and emission improvements in this type of application.

This paper will explore the application of heavy hybrid powertrains to light trucks, vans, and SUV’s.

INTRODUCTION

Light Trucks, vans, and SUV’s have become the dominant vehicle type in the US market today, selling more units annually than passenger cars. These vehicles range in test weight from 4000 lb to 6000 lb with gross combined weights (vehicle plus trailer) up to 14,000 lbs. Typically, powertrain components are sized to meet minimum automotive performance standards at the gross combined weight (GCW) of the vehicle. In order to meet the trailer towing and gradeability requirements at GCW, the automotive manufacturers have equipped this class of vehicles with large V-8 engines. The driving cycles of many of this class of vehicles includes a high proportion of operating time in an unloaded condition. This results in a significant amount of time and miles driven with the engine unloaded or lightly loaded.

Heavy hybrid powertrain applications typically allow engine downsizing, thereby allowing engine operation at a higher proportion of maximum engine power and increased fuel economy in both city and highway driving. Additionally, through the use of regenerative braking and engine off when the vehicle load requirement is low, a significant fuel economy improvement can be realized in city driving. The main question for the application of heavy hybrid powertrains for this class of vehicle becomes the ability to maintain all vehicle performance requirements, while employing the heavy hybrid system.

BASIC ENGINE OPERATING CONDITIONS- TYPICAL 5500LB SUV

In order to examine the fuel economy improvement capability of hybrid powertrain system applications to light trucks, vans, and SUV’s , we have chosen the typical 5500 lb SUV for analysis. The GCW (vehicle + cargo + trailer) studied is 13,500 lb and is typical of the trailer towing capabilities of this market segment.

Meeting minimum gradeability and 0 to 60 MPH performance criteria requires vehicles of this segment to utilize engines capable of producing in excess of 185 kW. We have chosen a 5.4L naturally aspirated 2 valves per cylinder V-8 engine and four speed automatic overdrive transmission as the baseline powertrain for study.

The typical engine maximum efficiency of today’s V-8 engines occur at 50% of maximum load and above with degradation in efficiency when lightly loaded. An efficiency map of a typical 5.4L, 16 valves V-8 engine is shown in figure 1. As can be seen in the figure, peak engine efficiency occurs in a narrow band of torque and engine speed, resulting in large fuel economy penalties due to the inability to operate at peak efficiency during most drive modes.

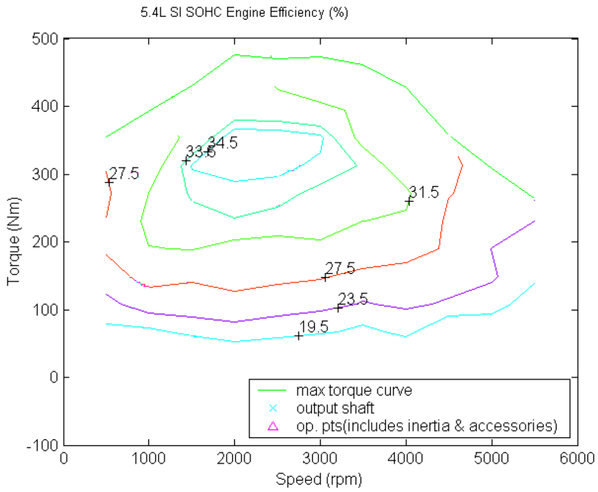

Figure 1.
Engine efficiency as a function of speed and torque.

When reviewing the operating conditions of the typical light truck, van, and SUV on the EPA city fuel economy test cycle (FUDS), it becomes apparent that the engine loading on these test cycles is below the best efficiency load point.

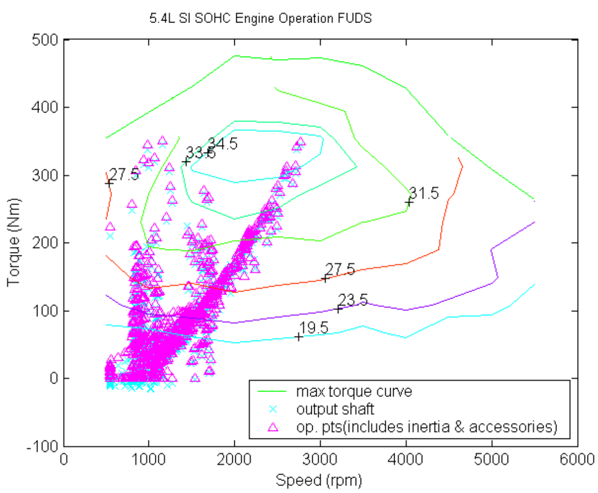

Figure 2.
Engine operating conditions on FUDS test at 5500 lb ETW.

Figure 2 represents the simulation results for the 5.4L V-8 conventional drivetrain on the EPA city fuel economy test cycle (FUDS) at the emission test weight (ETW).

As can be seen in the figure 2, city driving of this class of vehicles at the lightly loaded emission test weight results in the majority of time spent at light engine loads and poor fuel efficiency.

The typical loading on the EPA highway cycle (HWFET) shown in figure 3 demonstrates a higher engine loading than the city cycle, but still below the best engine operating load points.

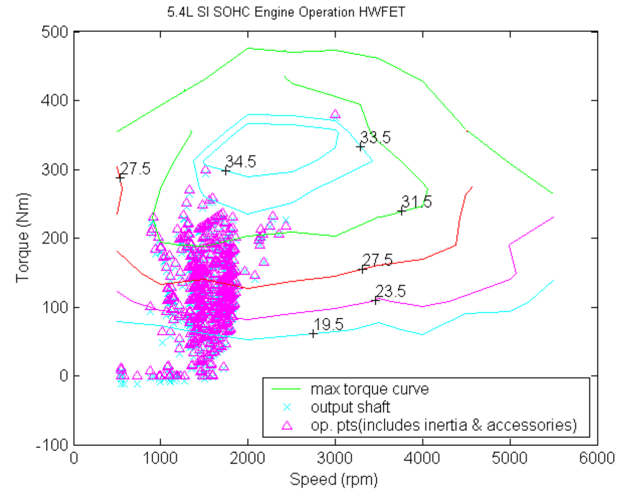

Figure 3.
Engine operating conditions on the HWFET at 5500 lb ETW.

Clearly, the challenge of any heavy hybrid system is to allow the hybrid system to control the engine to achieve maximum efficiency while maintaining the vehicle performance characteristics of this market segment.

SERIES, PARALLEL, OR SERIES/PARALLEL DRIVE CONFIGURATION

Typical series hybrid systems consist of an engine and generator decoupled from the drive wheels, a traction motor to drive the vehicle and an energy storage device to store engine and regenerative energy.

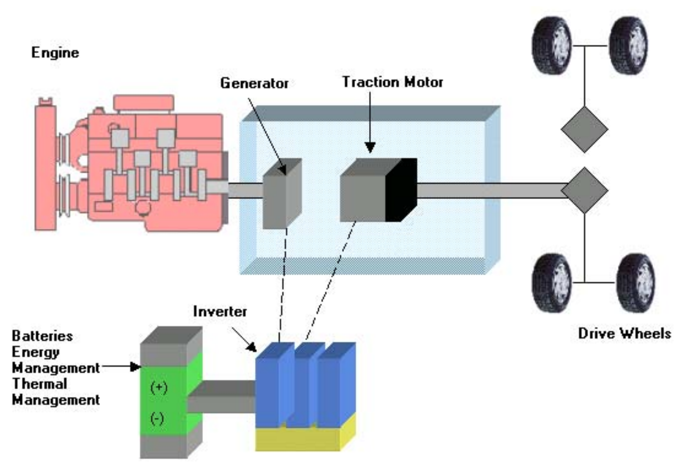

Figure 4
Typical Series Hybrid Drive System

The series system engine, generator and traction motor must be sized to maintain vehicle performance criteria at GCW. This results in high continuous power requirements of the generator and traction motor. The generator and traction motor continuous ratings are also inflated due to the requirement of transporting all the vehicle energy requirements through the generator, traction motor and battery storage with their associated losses. This results in an engine and generator power rating increase by 15% to 20% to make up for the inefficiencies in the generator and traction motor over a mechanical link from the engine to the drive wheels. High continuous power requirements for traction motors and generators result in extreme cost and weight penalties and will not be considered further for high GCW vehicle applications.

Typical parallel hybrid systems consist of an engine coupled to the drive wheels through a clutch, a traction motor to assist the engine in driving the vehicle and an energy storage device to store engine and regenerative energy. The parallel engine and traction motor must be sized to maintain vehicle performance criteria at GCW.

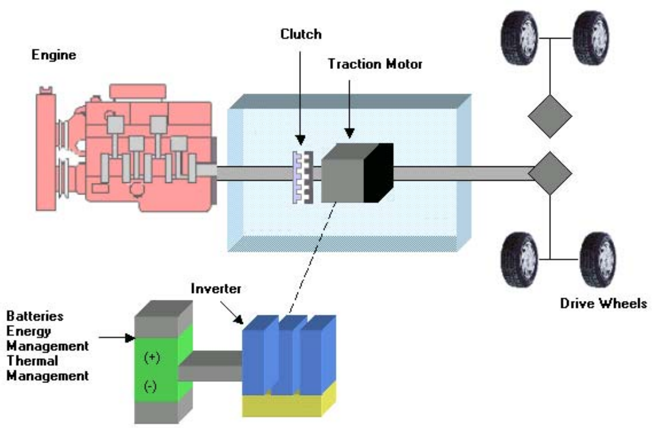

Figure 5
Typical Parallel Hybrid Drive System

This results in smaller power requirements of the traction motor than in a series drive configuration. The traction motor continuous ratings are reduced due to the engine providing a large portion of the continuous drive power mechanically while the transient peak power requirements are provided by the electric traction motor. The engine power ratings are also reduced because the continuous performance requirements at GCW can now be met by the engine with a direct mechanical link to the drive wheels.

While the parallel hybrid system has advantages over a serial drive in component size, weight and cost, the ability to operate the engine at the maximum efficiency during city driving is greatly reduced because the engine is mechanically linked to the drive wheels during periods of low load operation.

Employing the use of the series hybrid drive for city operation and parallel hybrid drive system for highway and high load driving appears to be the best solution for maximum fuel economy with minimum engine, generator, and traction motor power requirements. This leads to the series/parallel hybrid drive system, which will be referred to as the power amplified internal combustion engine (power amplified ICE) hybrid.

The power amplified ICE hybrid systems consist of an engine and generator coupled to the drive wheels through a clutch, a traction motor to assist the engine in driving the vehicle and an energy storage device to store engine and regenerative energy. The parallel engine, generator and traction motor must be sized to maintain vehicle performance criteria at GCW. A control strategy is required to select the mode of operation based on vehicle drive power requirements, state of charge of the storage device and engine efficiency. Several patents exist for this type of power amplified ICE control system. Please refer to the references for further details.

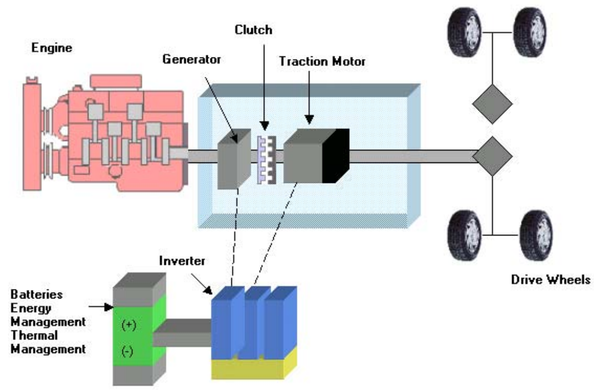

Figure 6
Power Amplified ICE Hybrid Drive System

The power amplified ICE arrangement yields most of the component sizing and highway fuel economy advantages of the parallel system without relinquishing the fuel economy benefits in city driving of the series system. The power amplified ICE system requires only the addition of a small generator over the parallel system to obtain the equivalent hybrid system benefits of the series system at light vehicle load requirements.

Fuel economy and performance simulations for the power amplified ICE hybrid and conventional drive systems were performed. All systems were modeled using MatLab simulation software. Models were built to represent the drivetrain configurations and control system software was developed to optimize the performance and fuel economy of each configuration. Please refer to appendix 1 an 2 for model assumption, techniques and correlation to actual test data activities.

COMPONENT SIZING

Engines, motors and generators were sized based upon continuous duty requirements of the particular vehicle configuration studied. In general, continuous engine, motor and generator power requirements were established to meet the continuous grade requirements of the vehicle at the GCW's studied. Peak motor and generator power requirements were set from the maximum power performance requirements for the vehicle at performance test weight and launch grade requirements at GCW. The table shown below summarizes the vehicle performance of the power amplified ICE hybrid and base vehicle studied.

	Base SUV	Power Amplified ICE Hybrid SUV	Automotive Industry Targets (approximate)
0 to 60 mph	8.2 s	6.6 s	9.0 s
35 to 55 mph	3.6 s	2.7 s	4.0 s
55 to 75 mph	6.0 s	4.5 s	7.0s
Maximum Speed	> 106 mph	> 106 mph	106 mph
Maximum Starting Grade	> 30%	30%	30%
Continuous 80 mph Grade	4.2%	3.2%	3.0%
Continuous 45 mph grade	7.5%	9.5%	7.0%

Table 1.
Vehicle Performance

The power amplified ICE hybrid components were selected based on meeting the minimum performance requirements shown in table 1. The continuous grade requirement at 80 mph set the engine power rating requirement. The starting grade requirement of 30% at GCW sets the electric motor peak rating. The 30% launch grade must be achievable without the engine mechanically linked to the drive wheels. Continuous electric motor power ratings are based on time weighted power requirements of a variety of drive modes. A two speed automatic transmission was selected to reduce the peak electric motor requirement for vehicle launch at 30% grade at GCW. The base vehicle and power amplified ICE hybrid component ratings are shown in table 2.

	Base SUV	Power Amplified ICE Hybrid SUV
Engine Power	5.4L V-8 184 kW	3.0L Turbocharged V-6 200 kW
Electric Motor Power	N/A	75 kW Peak 15 kW Continuous
Starter/Generator Power	N/A	19 kW Continuous
Transmission	4 speed automatic overdrive	2 speed automatic
Motor Drive Ratio	N/a	2.8:1
Final Drive Ratio	3.73:1	4.1:1
Battery Pack	N/A	16 – 48 Volt modules 9 Ah rated/800 Volts

Table 2
Component sizing

The power amplified ICE drive system configuration studied is shown in figure 7. A turbocharged V-6 engine was chosen due to good engine efficiency in moderate load conditions and the ability to provide peak power only during continuous high load conditions of grade and maximum vehicle speed. The transient response shortfalls typical of turbocharged engines are easily overcome in the power amplified ICE drive by the addition of electrical power from the traction motor and starter/generator during peak transient load conditions.

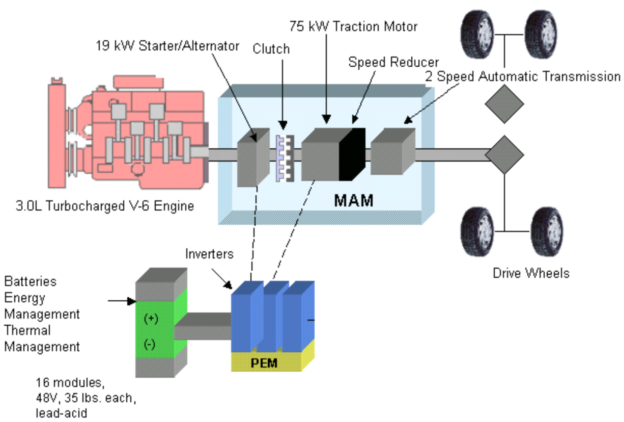

Figure 7
Power Amplified ICE Hybrid Drivetrain Components

City and highway fuel economy simulations were performed for the base and power amplified ICE hybrid systems. FUDS and HWFET simulation results are shown in table 3. Please refer to appendix 2 for drivetrain efficiencies generated in the modeling process.

	Base SUV 5500 lb ETW	Power Amplified ICE Hybrid SUV 5500 lb ETW
FUDS	13.6 mpg	27.8 mpg
Highway	22.6 mpg	27.1 mpg
Combined	16.6 mpg	27.5 mpg
FUDS Average Cycle Efficiency	22%	30%
Highway Cycle Average Efficiency	27%	32%

Table 3
Simulated Fuel Economy

The power amplified ICE hybrid offers the best fuel economy potential of the systems studied. City fuel economy of the power amplified ICE hybrid system is improved by over 100% over conventional drive. This improvement is the result of operating the engine at a more efficient load (refer to figure 8), recouping some of the braking energy and stopping the engine during low load portions of the test.

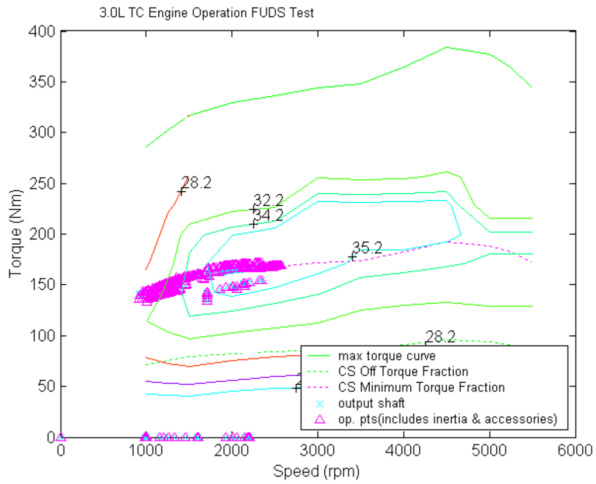

Figure 8
Engine Torque, Speed and Efficiency - City Driving

Highway fuel economy was improved by over 19% with the power amplified ICE hybrid drive over the conventional powertrain. This improvement was realized by operating the engine at a better efficiency point (refer to figure 9) and recouping a small amount of braking energy.

The power amplified ICE hybrid arrangement allows the engine to be operated as a steady state device while using the electric motor to maintain the engine load by either increasing the engine load when the vehicle drive load is below optimum or decreasing the engine load when the vehicle drive load is greater than optimum.

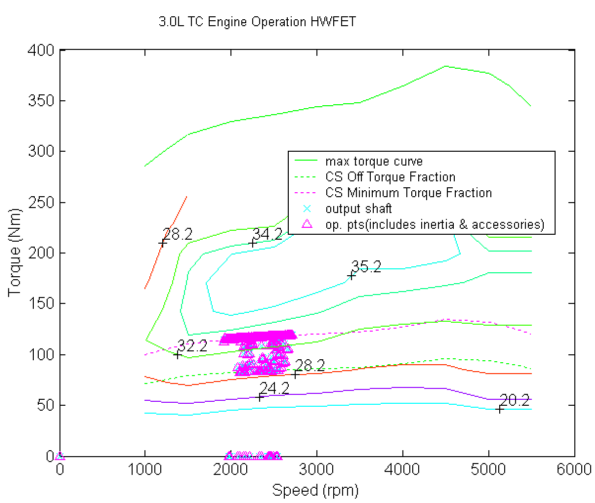

Figure 9
Engine Torque, Speed and Efficiency - Highway Driving

The power amplified ICE hybrid control strategy maintains the engine torque in a very narrow range on the city and highway cycle. Figure 10 shows the drivetrain torque requirements on the highway driving cycle. As can be seen in the figure, the torque requirements vary greatly during the cycle.

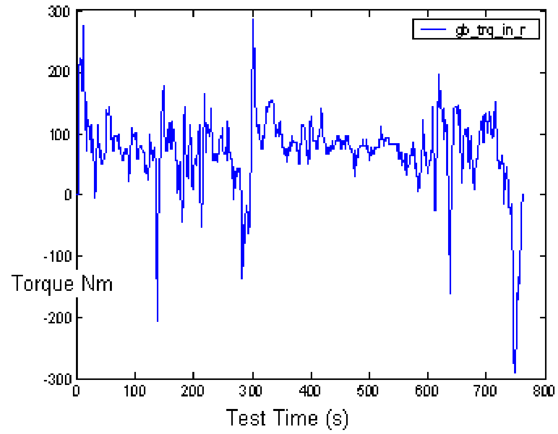

Figure 10
Torque requirements Highway Driving Cycle

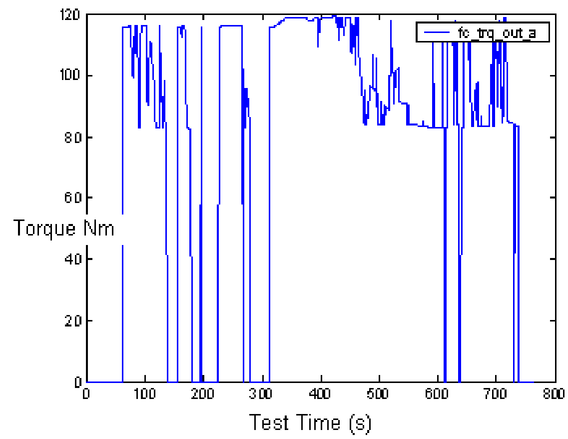

Figure 11
Engine Torque Highway Driving Cycle

The control strategy maintains an even, efficient torque level for the engine while meeting the varying torque requirements of the vehicle with the electric motors. Figure 11 and 12 show the output torque of the engine and electric motor during the highway cycle.

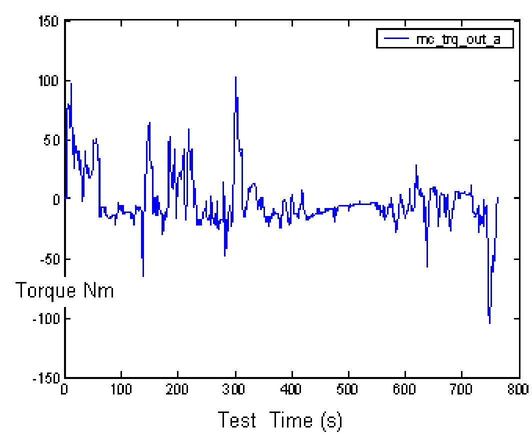

Figure 12
Motor Torque Highway Driving Cycle

PROLONGED GRADE DRIVING AT GCW

Light Trucks and SUV's are not only required to meet continuous grade criteria, but must also be able to successfully negotiate a variety of grades over prolonged periods through mountainous regions of the country. In order to verify the power amplified ICE hybrid studied is capable of meeting prolonged grades without degradation in vehicle performance, a drive cycle simulation from Golden, CO to the city of Vail, CO at GCW was performed. The route is an interstate highway (I-70) with typical speed limits ranging from 45 - 65 MPH and grades ranging from -6% to 6%. As can be seen in figure 13, the power amplified ICE hybrid system was capable of maintaining highway speeds throughout the cycle. Minimum state of charge was 40% during the cycle, ensuring sufficient battery energy to maintain performance levels.

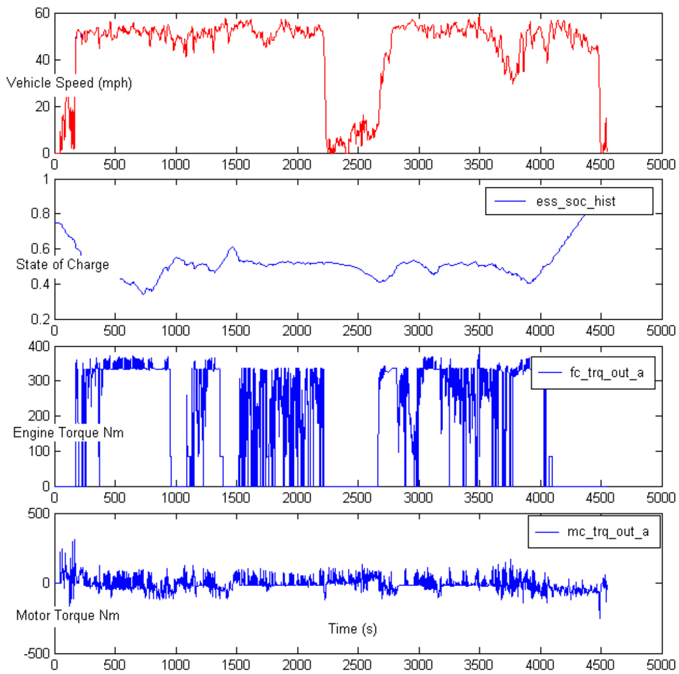

Figure 13
Mountain Trailer Towing Driving Cycle

COST CONSIDERATIONS

Although system cost was not addressed in this paper, component selection was driven by system cost considerations. Lead acid battery systems, and high voltage, low current motors and controllers have shown to have significant cost advantages over other types of hybrid components. A complete cost analysis of the series/parallel hybrid system studied is in process and will be presented in a future paper.

OPPORTUNITIES

It is in this area where the power train engineer will find the most interest, since the engine is used much differently in the power amplified ICE hybrid than today. The need for engine transient response is eliminated. The engine can be operated at stoichiometry at all times and the control system assures that the engine will always operate at a minimum of 30% of peak torque or higher (typically 50%). We must now re-examine how we can best use such technologies as compression ratio, variable compression, variable displacement, variable valve timing and lift control, induction and exhaust modulation and direct injection to suggest a few.

Although two wheel drive vehicles were studied in this analysis, four wheel drive systems offer additional advantages in fuel economy in city driving and better traction on slippery road surfaces. Four wheel drive can be accomplished electrically with the addition of a 15kw peak electric motor driving the front wheels and reducing the peak power of the main traction motor to 60 kW (75 kW). This allows the regenerative braking factor to increase to 85% of the total braking energy available, thereby increasing fuel economy an additional 10% to 15%. The cost impact of four wheel drive series/parallel hybrid drive systems is very favorable due to the cost offset of deletion of the typical mechanical transfer case while maintaining the vehicle stability advantages of four wheel drive.

CONCLUSION

Light trucks, vans and SUV's pose a significant challenge for hybrid drive system applications due to the impact of high GVW and GCW on hybrid component sizing. However, they also offer significant opportunity in fuel economy improvements due to their use of large displacement engines , which are operated at fractional loads during a significant amount of unloaded driving situations. Combined corporate average fuel economy (CAFÉ) improvements of over 65% can be realized with the application of series/parallel hybrid drive systems without degradation of vehicle performance or utility.

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APPENDIX 1

MODELING AND SIMULATION ASSUMPTIONS

All systems were modeled using MatLab simulation software. Models were built to represent the drivetrain configurations and control system software was developed to optimize the performance and fuel economy of each configuration.

Base 5.4L V-8 fuel economy projections were correlated to 2001 EPA results for 5500 ETW SUV published fuel economy data.

3.0L V-6 Turbocharged engine data was generated by scaling 1.9L DOHC Saturn engine data to reflect increased displacement and turbo charging.

Induction motors and generator characteristics were scaled from PAICE motor testing.

Lead Acid battery characteristics were derived from Optima valve-regulated spiral-wound lead-acid battery.

Accessory load were set at a constant 350 Watts for all hybrid configurations studied.

Regenerative braking factors were 45% of available braking energy to storage for 2WD.

APPENDIX 2

AVERAGE CYCLE EFFICIENCY

	Base 5.4L V-8		3.0L TC V-6 Power Amplified ICE Hybrid	
	FUDS	HWFET	FUDS	HWFET
Engine Efficiency	22%	27%	30%	32%
Torque Converter Efficiency	74%	98%	N/A	N/A
Clutch Efficiency	N/A	N/A	98%	99%
Starter/Generator Efficiency	N/A	N/A	95%	95%
Battery System Cycle Efficiency	N/A	N/A	88%	88%
Transmission Efficiency	97%	96%	98%	98%
Traction Motor Efficiency	N/A	N/A	82%	88%
Wheel/Axle/Final Drive Efficiency	94%	96%	95%	96%