Effects of Lower Battery Voltage on Performance and Economics of the Hyperdrive Powertrain

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ABSTRACT

The Hyperdrive™ is a hybrid-electric powertrain. It is unique among other hybrid systems because of its method of engine control, and the use of higher voltages in the electrical subsystem. The unique engine control restricts internal combustion engine operation to near maximum thermodynamic efficiencies, in either diesel or gasoline types. Higher voltages are used to not only increase efficiency but also to lower cost and weight of the electrical subsystem. In practice, the Hyperdrive is unique among hybrids because it provides both a substantial reduction in fuel consumption along with substantial improvements in acceleration. The component technologies of the Hyperdrive are very similar to those in conventional powertrains, which results in competitive costs. An analysis of Hyperdrive application in a European light commercial vehicle is represented, at two voltages, 600 V and 300 V. In a 4.500 kg gross combined weight vehicle with a 600 V system, the Hyperdrive reduces fuel consumption with a diesel engine by 27%. The acceleration is improved by about 30% and all gradeability requirements are met. The same system at a 300 V level raises estimated cost by 50%, increases fuel usage on the ECE schedule by 11% and increases CO_2 emissions by a like amount over the 600V system.

INTRODUCTION

Paice Corporation has designed, patented and tested a hybrid electric vehicle (HEV) powertrain called the Hyperdrive.

The Hyperdrive, a unique series/parallel hybrid electric powertrain for automobiles and light trucks, delivers a previously unattainable combination of fuel efficiency and vehicle performance at cost premiums that are reasonable when compared to conventional powertrains. Moreover, the Hyperdrive is well suited for a wide range of passenger vehicles, including SUVs, light trucks, and minivans.

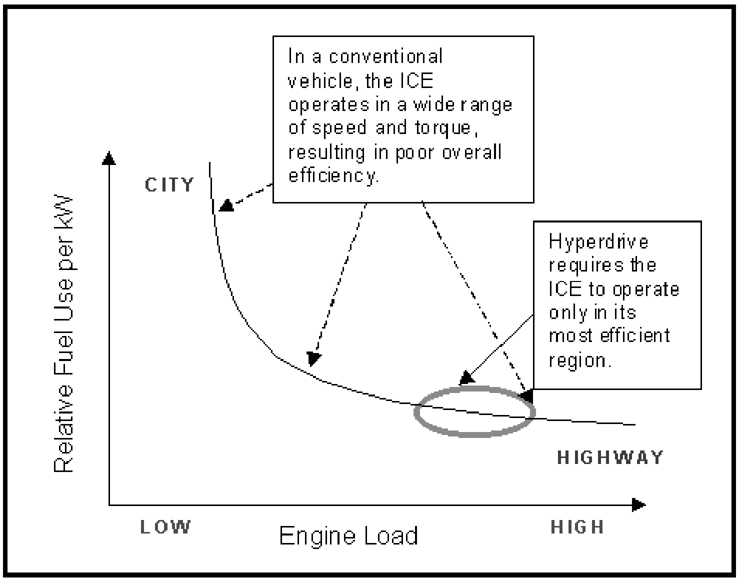

Fig. 1. Use of the ICE in the Hyperdrive

We have successfully demonstrated the benefits of the Hyperdrive on a full-scale prototype powertrain on a dynamometer.

This report is divided into several topics: first, an overview of the characteristics of the Hyperdrive powertrain and test results; second, a version of the Hyperdrive powertrain in a popular European light commercial vehicle platform, with both diesel and gasoline engines; third, components selection at two different battery voltages: 600 V and 300 V; and fourth, modeling results and economics.

I. The Hyperdrive System

Fundamental Principles

To compete against current and future powertrains, any HEV as well as the Hyperdrive HEV must be at least equal, and even superior to existing powertrains in all respects. Only this will result in market forces choosing the adoption of fuel saving powertrain technology. Accordingly, our development of the Hyperdrive was guided by the following fundamental considerations:

- The system should run on readily available gasoline or diesel fuel, but be compatible with alternate fuels should the logistics require them.
- The internal combustion engine (ICE) should be used to convert chemical energy into mechanical energy, as it is the most efficient means yet discovered. The system should use the ICE only in its most efficient operating region; that is, under those load conditions where Brake Specific Fuel Consumption (BSFC) is minimized, or thermodynamic efficiency maximized. In Figure 1 we present graphically how the ICE is used in the Hyperdrive in comparison with current powertrains.

- Use of the ICE in this way will result in increased fuel efficiency as well as improvements (i.e. reductions) in exhaust emissions. Emissions can further be reduced by use of advanced computer control of the engine air-fuel ratio, catalyst preheating and a simplified engine operating cycle (eliminating ICE transients). While a number of current production vehicles are already meeting California's Ultra-Low Emission Vehicle (ULEV) requirements (40% of all Honda's cars in 2002), the Hyperdrive can not only overachieve these levels of emission control but do it over a much wider range of vehicles and at lower cost.
- Sophisticated software control algorithms must be employed to control the powertrain components, without any need for an increase in driver skills or driver awareness.
- Customer expectations must be satisfied without compromise. Present levels of acceleration, convenience of operation, and operating/ownership cost must be equal to or be better than those offered by present powertrains.
- Manufacturing material requirements must be satisfied by using the same readily available materials already used in present high-volume automotive production, i.e. iron, lead, copper, aluminum and silicon. Special material needs, such as catalytic agents, must be no more critical than they are today. System flexibility and cost must be applicable over a wide range of vehicle weights and sizes to allow the benefits to be achieved over the entire passenger vehicle market.
- Restrictions imposed on design flexibility by vehicle space, weight, drag and architecture requirements should be reduced to allow freedom for design variations.
- Physical size and arrangement of the drive components must be flexible enough to allow installation in existing body and chassis to avoid costs, lead times and investments in plants and equipment that new vehicle programs would require.
- Vehicle, powertrain and fuel system service requirements must be compatible with the skills, training and diagnostic capability available at the retail level.

Testing and Test Results

Based on these principles, Paice Corporation built and tested the Hyperdrive system on a dynamometer load representing a typical American 4,250 lb. large passenger car. In Figure 2, we present arrangements and rating of components in the Hyperdrive powertrain as tested and in Figure 3 we present some photographs from the testing site.

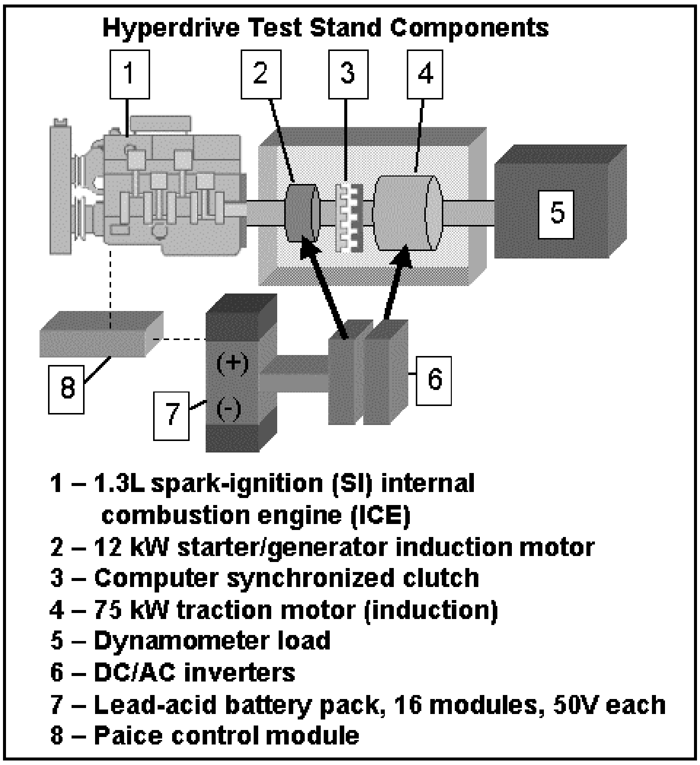

Fig. 2. Test prototype of the Hyperdrive

Table 1 presents a summary of the fuel economy test results. To verify these results, we have measured energy losses in all components of the Hyperdrive together with energy applied to the load, and compared this with the energy coming from the fuel. These results coincided within tolerances of measurements. This allowed us to calibrate our control software model, which we have used to determine the expected results of using the Hyperdrive system in other vehicles discussed below.

Table 1: Summary of Hyperdrive Test Results, mpg*

	Conventional	Hyperdrive
City Driving (FUDS)	19	**38**
Highway Driving (HWFET)	33	**54**
Combined	24	**44**

* mpg – miles per gallon

Key Technical Principle

The key technical principle underlying the Hyperdrive system is that it employs a unique method of control that optimizes the operation of the internal combustion engine in a hybrid electric vehicle [1-8]. This method of control results in the achievement of operational thermodynamic efficiencies within 1-2% of maximal attainable efficiency of either gasoline or diesel engines. Our improved overall operating efficiency is supported by the configuration of components in the Hyperdrive: a lead-acid battery system that stores the energy generated by the engine or regenerated while braking, and high-power electric motors that propel the vehicle when the engine cannot be used in its most efficient operating region.

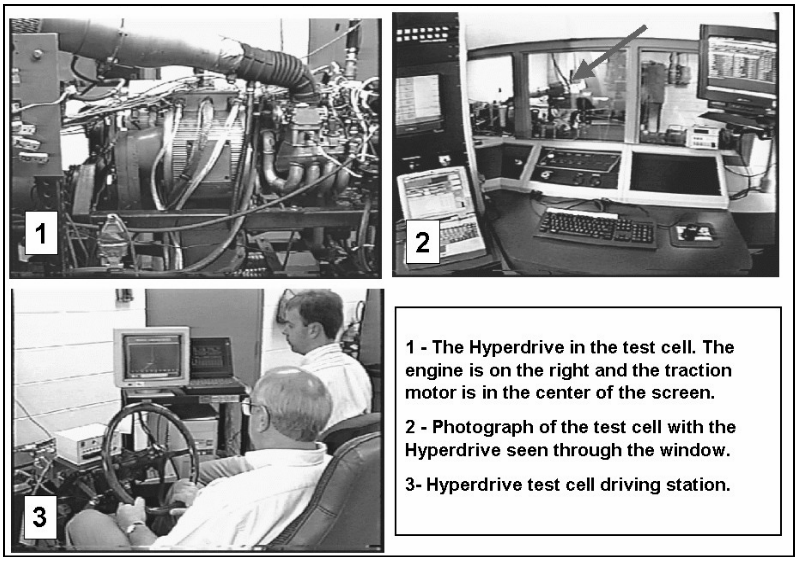

Fig. 3. Hyperdrive in the dynamometer test cell

Recent advancements in high voltage power semiconductors, coupled with positive experience in new lead-acid battery applications in HEV buses, have provided the practical basis for the commercialization of this technology.

How the Hyperdrive Powertrain Works

The internal combustion engine (ICE) of a conventional vehicle is required to deliver power under a wide range of loads as a function of driving condition. This results in an inefficient way of producing mechanical power from the energy in gasoline or diesel fuel. If the ICE were allowed to operate *only* in its optimal operating region, maximum fuel efficiency improvements would be possible. This is the fundamental principle behind the Hyperdrive as is illustrated in Figure 1.

The Hyperdrive achieves this high level of performance and fuel economy by introducing a battery system that captures the excess energy output of the ICE (when it is operated only in its most efficient range) and an electric motor that uses this stored electrical energy to power the vehicle when the ICE cannot be used efficiently or when power requirements are higher than can be delivered by the ICE alone. The motor also acts as a generator to recover energy from the vehicle during deceleration. The operation of all of these components and their function is managed by the Control Module, a DSP multiprocessor with associated control software and embedded proprietary control algorithms.

Other than the Control Module, the various hardware components in the Hyperdrive system already exist in one form or another in conventional vehicles. The differences lie in the relative sizes of components, their functional relationships and, most significantly, in the software incorporating proprietary method of control, which enables the components to function as a highly energy efficient system. Thus, the Hyperdrive represents an evolutionary step in automobile technology, and does not require advanced development efforts or dramatic changes in fuel delivery or manufacturing infrastructure.

Modes of Operation

There are four typical modes of operation that illustrate the basic functionality of the Hyperdrive: 1 - city driving; 2 - recharging during city driving; 3 - acceleration; and 4 - cruising on the highway. In addition to these four, there are a number of other modes defined in the control algorithm.

The Hyperdrive system includes a clutch – essentially a synchronized coupling device that is either engaged or disengaged. The clutch must be engaged for mechanical power from the engine to be delivered directly to the driving wheels. The dominant condition controlling whether the clutch is engaged or disengaged is vehicle road load reflected on the engine shaft. If this load is sufficient for the engine to be used near its maximum efficiency, then the clutch is engaged. Otherwise, it is disengaged.

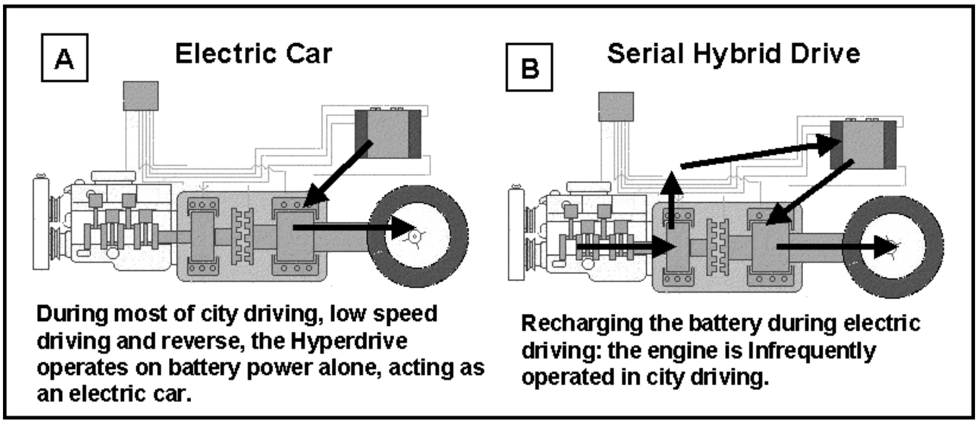

Fig. 4. Typical Hyperdrive operation in city driving.

Generally, the clutch *is not* engaged during city driving and *is* engaged during rapid acceleration and highway driving.

In Figure 4, the clutch is disengaged in city driving. In part A of Figure 4, the battery is above its minimum state of charge and the traction motor drives the vehicle. At this point, the vehicle is operating like an electric car. The battery is used in a very benign narrow range of state of charge, normally in 50% to 70% under partial state of charge (PSOC) condition. This assures low battery stress and long operating life. The amount of energy used in this electric-only mode is far below the definition of a "dual mode hybrid". The Hyperdrive HEV operates like an electric car upon initial starting of the vehicle and during the intervals between times in which the battery is being charged.

Part B of Figure 4, shows a time period in city driving after the battery has been used to power the traction motors. Once the battery has reached its minimum state of charge, approximately 50%, the starter/generator motor starts the engine. Upon starting the engine, a load is applied by the starter/generator motor, now operating as a generator, so that the engine runs close to its minimal BSFC operating region. The power produced by the starter and generator is split. One part of it is delivered to the traction motor, making the Hyperdrive operate as a serial hybrid. The balance of power is used to recharge the battery. Upon reaching the maximum level of battery charge, about 70%, the engine is stopped.

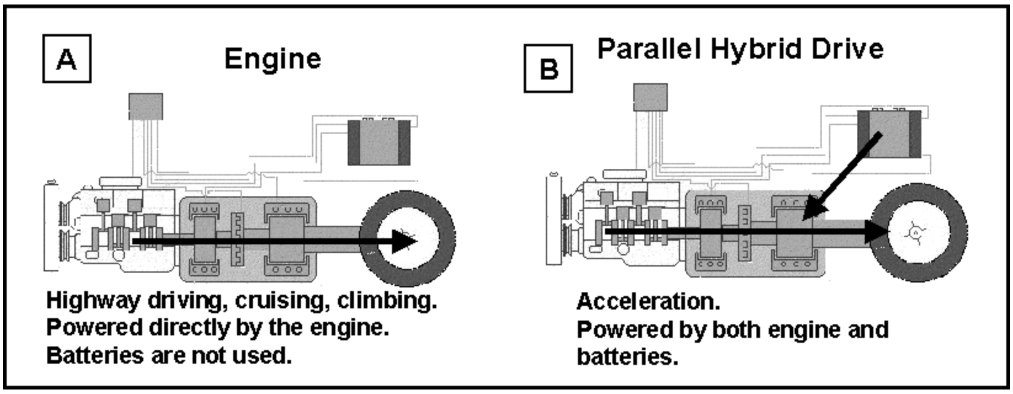

Fig. 5. Typical Hyperdrive operation in highway driving.

In Figure 5, the clutch is engaged to accelerate onto and cruise on the highway. When time-averaged road load on the Hyperdrive is sufficient to place the engine in a region close to its minimum BSFC, the clutch is engaged. If the engine was off, it is started and synchronized by the starter/generator motor, and then the clutch is engaged. At this point the engine begins to provide the average power demands of the vehicle. In this mode, the Hyperdrive acts as a conventional powertrain with its transmission in the direct drive position. This is depicted in Part A of Figure 5.

For vehicle acceleration or deceleration, all motors are used in a manner that minimizes energy loss in all electrical and electronic components. The Control Module can assure this on a millisecond-by-millisecond basis. Acceleration with only the traction motor is shown in Part B of Figure 5. This is a parallel hybrid mode. During transients, engine torque is controlled, lagging motor torque, to assure operation with the most efficient air/fuel mixture. This allows for substantial reduction of engine-out emissions, due to the elimination of transient fuel enrichment under any driving conditions. Because electric motors provide excellent torque response to the driver's command, new levels of car responsiveness become possible, even varying the shape of this response as a function of the driver history and driving condition.

II. The Hyperdrive in a European Light Commercial Vehicle

Fig. 6. Base light commercial vehicle

Using our calibrated modeling software and principles of the Hyperdrive, we have designed a version of a popular European light commercial vehicle with the Hyperdrive.

For a broader horizon of capabilities, we modeled two implementations: with diesel and gasoline engines.

Table 2. Performance Characteristics of the Base Vehicle		
	Gasoline	**Diesel**
Engine		
Type	2,5L	2,5 L TDI
Peak Power	82 kW	75 kW
Gearing		
Transmission Type	Manual 5 Spd	Manual 5 Spd
Final Drive Ratio	3.55	3.55
Fuel Economy, L/100km		
Test Weight, kg	1.710	1.710
ECE	11	9,6
EUDC	8,1	6,5
Combined	8,9	7,7
W.O.T.[1] Performance @ 2.700 kg GVW[2], sec.		
Top Speed, km/h	144	144
0-100 km/h	27	22
65-100 km/h	14	12
Gradeability @ 4.500 kg GCW[3], %		
@ 88 km/h	5	4
@ 40 km/h	13	12
Starting Grade	> 30	> 30

[1] W.O.T. - Wide Open Throttle
[2] GVW - Gross Vehicle Weight
[3] GCW - Gross Combined Weight

A picture of one type of a body style of such a popular vehicle is presented In Fig. 7, and its typical driving performance characteristics in Table 2.

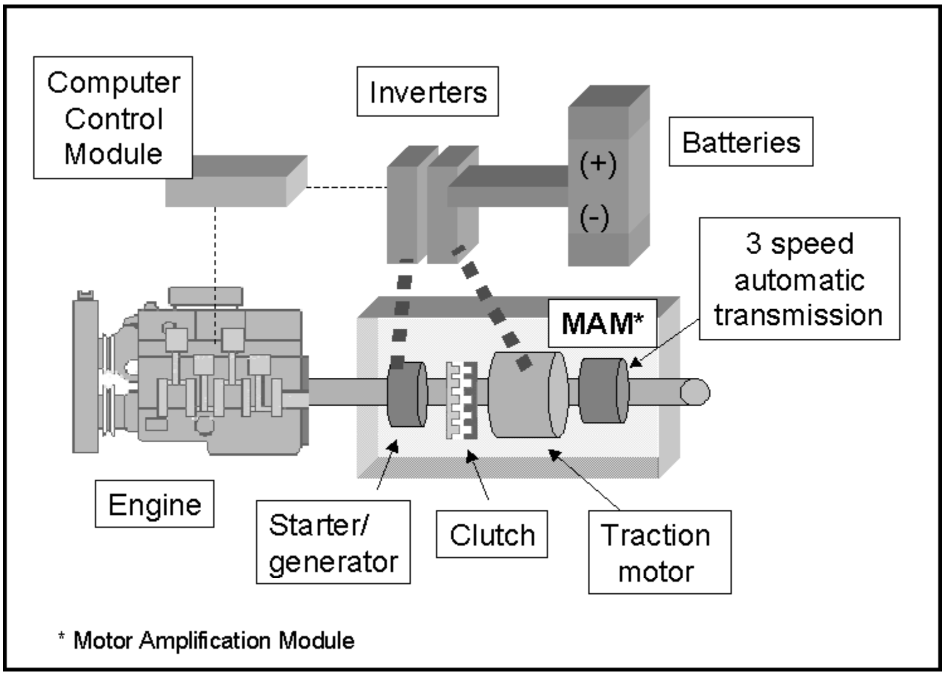

Fig. 7. The Hyperdrive powertrain in a light commercial vehicle

In Fig. 8, we present a version of the Hyperdrive in the base vehicle. Now, we will discuss a selection of components for two different battery voltages ,600 V and 300 V.

ENGINE

Both engines in the base vehicle are sized for grade climbing ability at gross combined weight of 4.50 kg. For this reason, we use them unmodified in the Hyperdrive.

TRANSMISSION

We replace the base vehicle 5-speed manual transmission with a 3-speed automatic, primarily to assure grade ability at starting and very low speed.

STARTER/GENERATOR MOTOR

This is an induction motor with 15 kW rating. It can be directly attached to the engine shaft or via a speed reducer. In the later case, the motor size, weight, and cost will be smaller. The key design characteristic of this motor is 92% efficiency when operated by the engine in charging mode. This efficiency is the same with either a 600 V or 300 V battery if its stator winding is geometrically the same. For example, the 300 V motor has a stator with two windings in parallel. Then, for 600 V, we just connect them in series, each one carrying the same current as in each of 300 V winding. So, the flux, the rotor current, and the stator wire currents all stay the same.

TRACTION MOTOR

This is also an induction motor with peak rating of 30 kW and continuous rating of 8 kW. It is attached to the output drive shaft via a speed reducer. The top motor speed is 16.000 rpm. Again, efficiency of this motor is independent of the battery voltage for the same reason as the starter/generator motor. In Fig. 8 efficiency maps for this motor are shown.

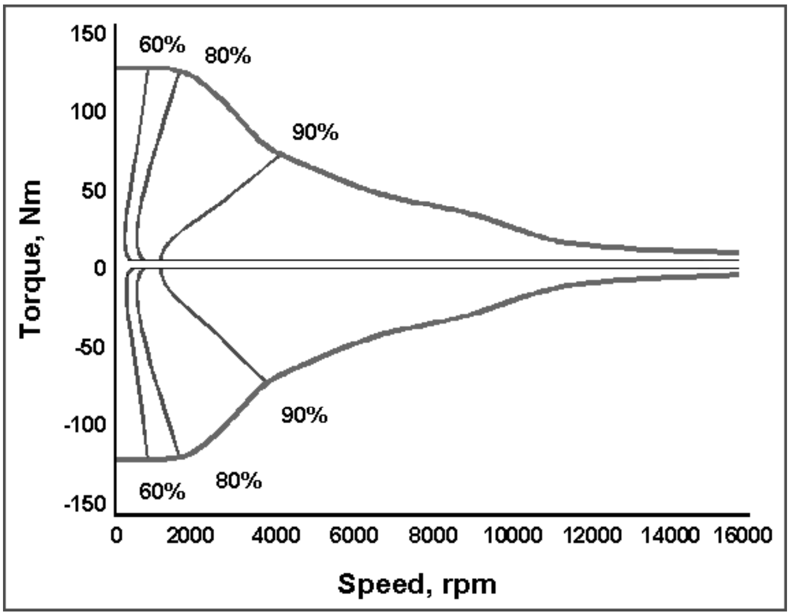

Fig. 8. Traction motor efficiency map, in %

It is important to note that this motor can be split in two, for 4x4 drive applications, with almost no penalty in weight. The electrical 4x4 drive can be made more controllable under variable road and load conditions than a mechanical drive. It also will have lower fuel consumption, especially in a stop-and-go city driving, due to the larger amount of recovered regenerative energy from the other set of wheels. In the modeling results below, however, we show the results for the vehicle with only one driving axle.

CLUTCH

The clutch acts as a mechanical switch. It is either engaged or disengaged by the controller when the shafts are synchronized, when angular positions and first derivative over time are equal within an error of measurements, for example 1^o. Since the clutch is not required to absorb shift energy, it can be a low cost mechanical device.

INVERTERS

The inverters are key performance and cost components of the Hyperdrive. First, the choice of semiconductors is limited to IGBTs (insulated gate bipolar transistors), rated at 1.200 V for the 600 V system, and 600 V for the 300 V system.. Secondly, quasi-lossless snubbers are used to reduce switching losses. Thirdly, we use input and output filters. With the input L-C filter, pulsating currents caused by PWM to and from the batteries are reduced. The output filter reduces switching current losses in the motors. Both filters also allow reduced cost EMI compliance.

We have designed both inverters, for the 600 V battery and 300 V battery using our test data for other components in the system. Then, we calculated conduction and switching losses for each pulse in PWM (pulse width modulated) waveform. The summary of this analysis is presented in Table 3.

Table 3. Inverter Losses, %

Rated Power, %	600 V battery	300 V battery
100	3.4	7.3
50	4.9	7.3
10	5.2	11.5

BATTERY

The word "battery" may be misleading in this case. The system uses a Lead-Acid Battery System (LABS). It consists of several 50 V modules. Each module contains 24 lead-acid cells. The modules are connected in series and the electrical center point of this string is connected to the chassis, per Underwriter's Laboratories recommendation, as better solution from a safety-engineering standpoint. This allows the voltage rating of all components to be reduced to half of the total LABS voltage. Each module has an internal normally open disconnect with an air-gap. It assures absence of any voltage on the module terminal during shipment, assembly, service, or when the vehicle is turned off or in an accident. The module contains three important subsystems – a thermal equalizer, an electronic operational conditioner, plus a computer interface. Further details are too voluminous for this paper and will be reported separately. The module content is so different from a traditional battery that it is better designated a Hybrid Energy Module (HEM).

For this vehicle, the system needs approximately 5 Ah cells, and 12 modules with a total string voltage of 600 V. These cells will need to have an end-of-life power density of 600 W/kg. With existing manufacturing technology, this will result in minimum thickness of all layers in the cell.

For the 300 V string, there will be 6 modules. The capacity of the cell, however, will have to be greater than10 Ah, to sustain the same cycle life as in the 5 Ah cell. The reason is that the cell internal resistance changes with temperature, similar to an effect observed in bipolar transistors. The cell internal resistance is reduced approximately in half for each 10^{o}C temperature rise. Such behavior creates a so-called “current crowding” effect, which was the main cause of failure of initial SCRs circa 1960.. Current crowding will cause only a part of the electrode surface to be utilized, resulting in a much larger swing in the state-of-charge over portions of the electrode than expected.. To ameliorate this problem, cell current density must be reduced. Following the experience from paralleling bipolar transistors, this dictates de-rating the current density by 1/3. This calls for 50% proportionally more surface area than expected to achieve a satisfactory 10 Ah cell cycle life. Without the possibility of reducing layer thickness, this will dictate a nominal 15 Ah cell, with 50% more weight.

We have tested the efficiency of the closest available prototype of the needed cell, the Hawker Energy Product’s Genesis 13 Ah battery, using currents actually experienced in our tests. We found through two different measuring techniques that the roundtrip energy efficiency is 88-90% while coulombic efficiency is close to 100%.

In summary, in high power density application of lead-acid cells as required in HEVs, we need approximately 50% larger size, weight, and cost of a battery system at 300 V than at 600 V.

COMPUTER CONTROL MODULE

The computer controller takes the place of the current Engine Control Module (ECM) but is even more important. The existing ECU becomes a peripheral device along with each motor controller, each HEM, and other peripheral controllers customary in vehicles. The controller hardware must support extensive parallel DSP computation. The key element of the Hyperdrive that allows it to deliver advantages in both performance and cost is in the control algorithms.

III. MODELING RESULTS

We have modeled performance and fuel economy of the base vehicle with two engines, diesel and gasoline. The results of modeling with the diesel engine are presented in Table 4.

Table 4. Hyperdrive with Diesel Engine, Performance Comparison			
	Base	**600 V**	**300 V**
Fuel Economy, L/100 km			
Test Weight, kg	1.710	1.850	1.900
ECE	**9,6**	**5,2**	**6,2**
EUDC	**6,5**	**5,8**	**6,2**
Combined	**7,7**	**5,6**	**6,2**
W.O.T.[1] Performance @ 2.700 kg GVW[2] , sec			
Top Speed km/h	144	144	144
0-100 km/h	22	16	16
65-100 km/h	12	9	9
Gradeability @ 2.700 kg GVW, %			
@ 88 km/h	7	8	8
Starting Grade	> 30	> 30	>30
Gradeability @ 4.500 kg GCW[3], %			
@ 88 km/h	4	4	4
@ 40 km/h	12	12	12
Starting Grade	> 30	> 30	>30

[1] W.O.T. – Wide Open Throttle
[2] GVW – Gross Vehicle Weight
[3] GCW – Gross Combined Weight

Fuel consumption comparisons were made on the ECE, on the EUDC, and on a combined cycle. At 600 V, the Hyperdrive lowers fuel consumption from 7,7 L/100 km to 5.6, or 27%.

At 300 V, it lowers fuel consumption only by 19%. This is due to larger inverter losses and higher battery weight.

The Hyperdrive also provides a major performance improvement, reducing the 0-100 km/h acceleration time from 22 sec to 16 sec.

Top speed and gradeability remain practically the same, unlike in any other HEV so far reported.

Now we present how different components are utilized. In Figs. 9A and 9B, we present diesel engine efficiency maps on both, ECE and EUDC, cycles. During the ECE cycle, the engine has to operate only to recharge the battery. Operation is only at one operating point at 38% efficiency. During EUDC cycle, the engine is operated over a wider range, but in the torque range between 38 and 36% efficiency. This is how the Hyperdrive method of control is implemented. It allows utilizing the engine at much higher thermodynamic efficiency than in a conventional powertrain.

Not only is the method of engine control important to achieve substantial improvement in fuel consumption, the electrical components must also be utilized

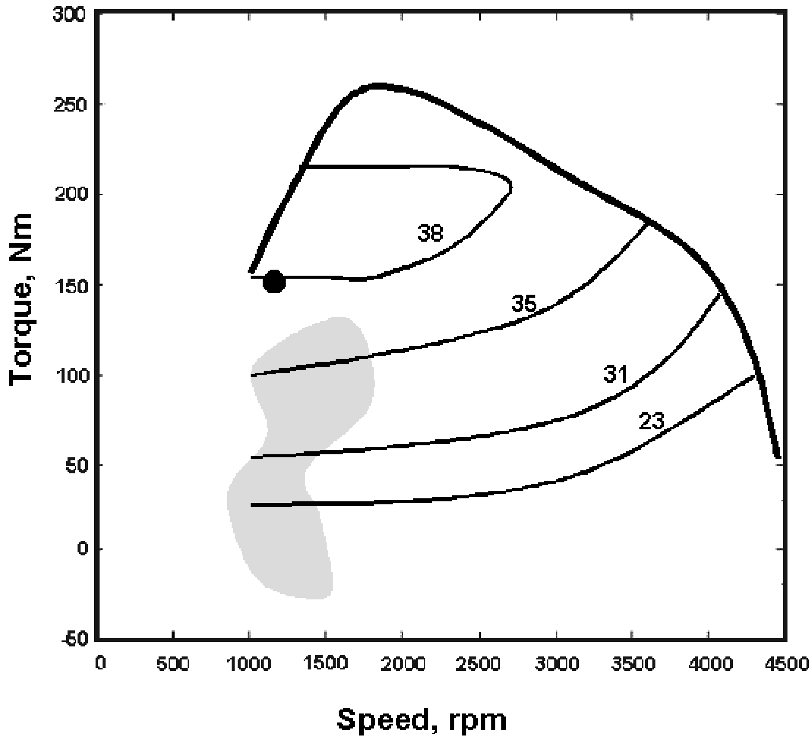

Fig. 9A. Utilization of the diesel engine on the ECE cycle.

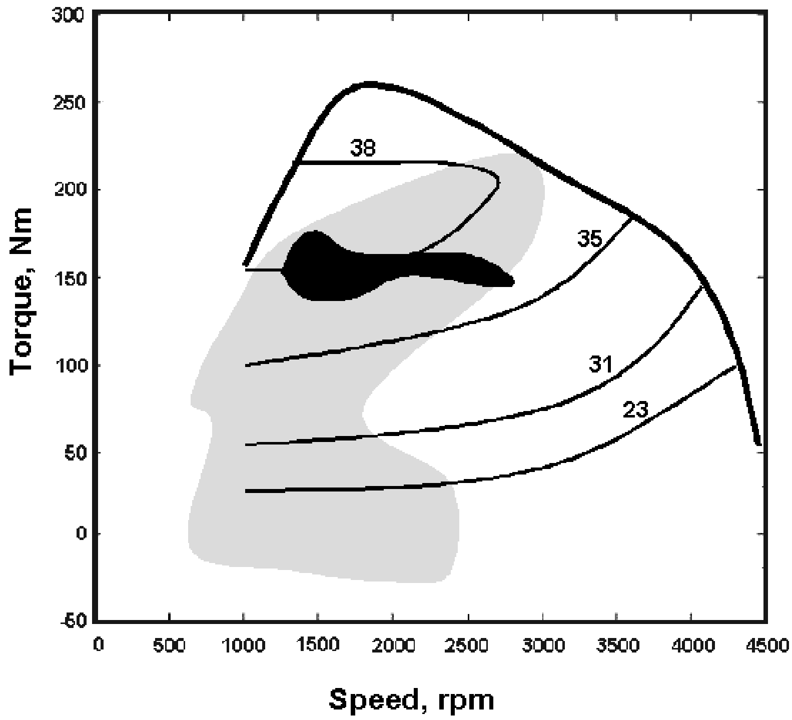

Fig. 9B. Utilization of the diesel engine on the EUDC cycle.

- Contoured lines are for equal thermodynamic efficiency, in %
- Black dot / area depicts utilization in the Hyperdrive powertrain
- Gray area depicts utilization in the base vehicle

efficiently. In Fig. 10 we present traction motor and its inverter combined efficiency maps for both voltages, and superimpose on both the operating points on ECE cycle. As one can see, most of the time efficiency of the 600 V system is around 90%, but in the 300 V system efficiency is 85% and below. This is mostly due to lower efficiency of the inverters at lower voltage.

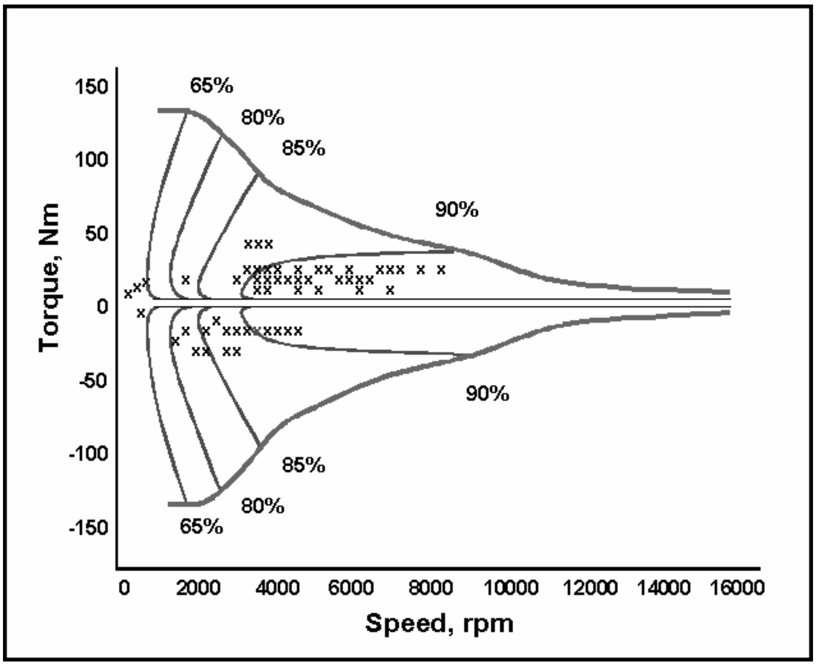

Fig. 10a. Traction Motor/Inverter utilization on ECE cycle with 600 V battery

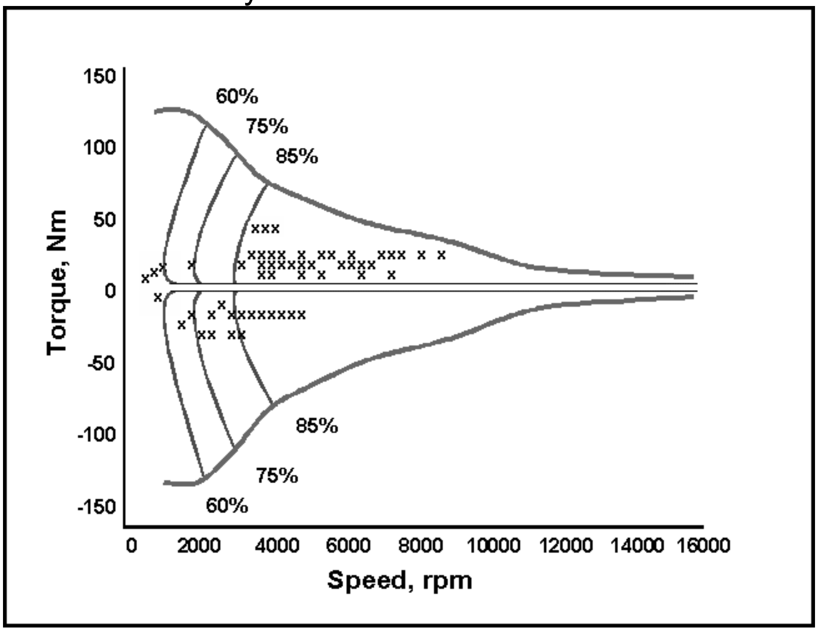

Fig. 10b. Traction Motor/Inverter utilization on ECE cycle with 300 V battery

- Numbers represent efficiency in percent
- "x" coordinates represent operating points on the ECE cycle

The efficiency, durability and SOC of the HEM is also critical. In Fig. 11 we present changes in the state-of-charge of cells on both driving cycles. When the engine is operating, cells are replenished.

As one can see, in this implementation of the Hyperdrive, the engine is operated every other ECE cycle, and only one time on EUDC cycle. The major changes in the state-of-charge of cells are: two changes on ECE cycle totaling 15% and one change totaling 10% on EUDC cycle. In total, 25% for 11 km, or 2.3% per km. If the desired cycle life of the HEM without any performance degradation is 150,000 km, this defines a cell with capability to withstand 42,000 cycles of 8% discharge/recharge at a partial state-of-charge in the range of 50-70%.

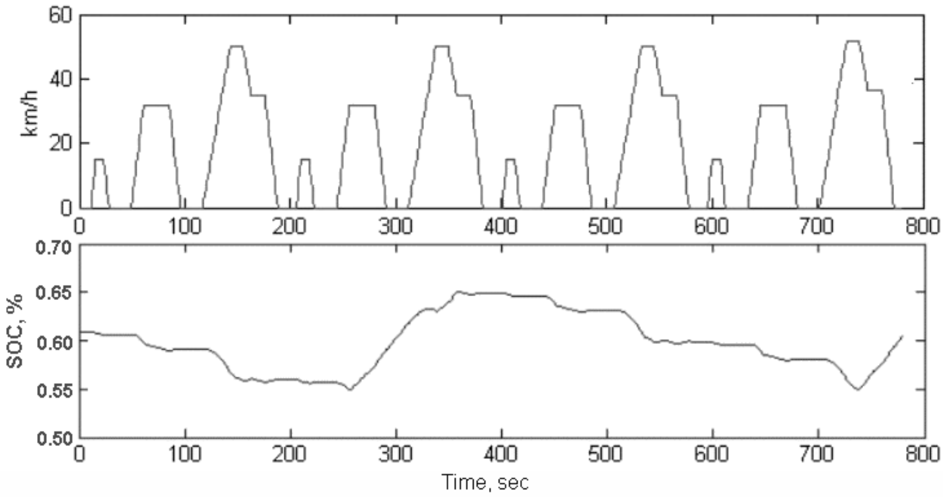

Fig. 11a. Utilization of cells on ECE cycle in a 600 V battery

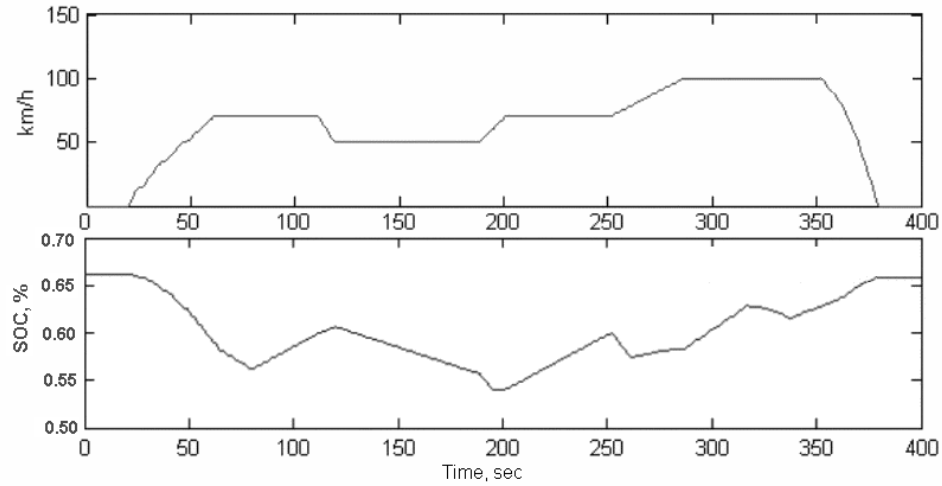

Fig. 11b. Utilization of cells on EUDC cycle in a 600 V battery

The results of modeling with the gasoline engine are presented in Table 5.

As one can see, driving performance improvements are practically the same as with a diesel engine. The fuel consumption improvements are similar but smaller. The combined improvement is from 8,9 to 7.1 L/100 km at 600 V, or 20%, and 11% at 300 V. The reason for a lower level of improvement with the gasoline engine is that it is already more efficiently utilized in the base vehicle than in the diesel one. For example, compare acceleration of 27 sec with the gasoline engine versus 22 sec with a diesel during 0-100 km/h test. This shows that the gasoline engine is less powerful for acceleration, but this is why it runs more loaded on both ECE and EUDC cycles. In turn, larger loading of the engine improves its fuel efficiency.

Table 5. Hyperdrive with Gasoline Engine, Performance Comparison			
	Base	**600 V**	**300 V**
Fuel Economy, L/100 km			
Test Weight, kg	1.710	1.850	1.900
ECE	**11**	**6,4**	**7,7**
EUDC	**8,1**	**7,5**	**8,0**
Combined	**8,9**	**7,1**	**7,9**
W.O.T. Performance @ GVW , sec			
Top Speed (km/h)	144	144	144
0-100 km/h	27	16	16
65-100 km/h	14	9	9
Gradeability @ 2.700 kg GVW , %			
@ 88 km/h	9	9	9
Starting Grade	> 30	> 30	>30
Gradeability @ 4.500 kg GVW, %			
@ 88 km/h	5	4	4
@ 40 km/h	13	13	13
Starting Grade	> 30	> 30	>30

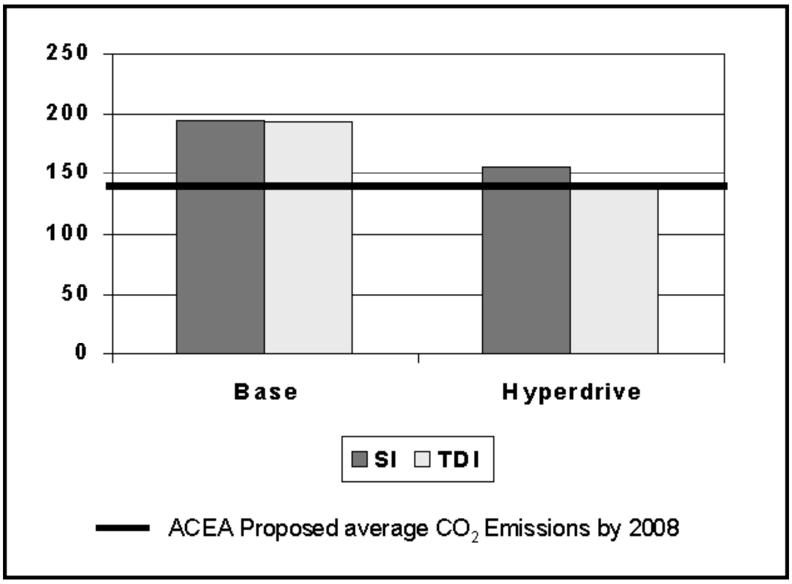

Fig. 12. Carbon dioxide emissions

Utilization of other electrical components is essentially the same as in the case of a diesel engine.

Because of concerns about carbon dioxide, a comparison of these emissions for this vehicle with different powertrains is shown in Fig. 12.

It is clear that the lowest CO_2 emissions are from the diesel version of the Hyperdrive.

III. COMPARATIVE ECONOMICS OF THE HYPERDRIVE AT 600 V AND 300 V

Table 6. Comparative Cost of Inverters, in Relative Units of Cost		
Major parts/assemblies	**600 V battery**	**300 V battery**
Power Semiconductors	**1,0**	**2,5**
Power Capacitors	**1,0**	**2,0**
Filter Inductors	**1,0**	**2,0**
Snubbers	**0,5**	**1,0**
Controls	**1,0**	**1,0**
Cooling	**0,3**	**3,0**
Packaging	**0,5**	**1,0**
TOTAL	**5,3**	**12,5**

The main cost elements of the Hyperdrive are the inverters. In Table 6 we present comparative cost of inverters at two different voltages.

The relative costing of major components came out of our design for the drive at two different voltages. It is important to note that one can use air-cooling at 600 V, but liquid cooling is required at 300 V. This is because of substantially higher losses at 300 V. In summary, the low voltage inverters will cost approximately 2.4 times more than the high voltage ones.

The next cost element is the HEM. In a low voltage system, we need 50% more cell capacity to assure cycle life. This causes a proportional increase in cost.

Table 7. Relative Costs of the Electrical System		
	600 V battery	**300 V battery**
Inverters	**1,0**	**2,4**
Motors	**1,0**	**1.0**
LABS	**1.0**	**1,5**
Wiring, safety	**0,5**	**1,5**
Total	**3,5**	**5,4**

Next is wiring and electrical safety disconnects. As power dissipation is proportional to the square of current, we will need four times more material content to control heat during peak performance. For comparison, there will be approximately 200 A current in lower voltage system versus 100 A in a 600 V one. We estimate that the resulting increase will be at least three (3) times in cost for lower voltage system.

In Table 7 these estimates are summarized.

Based on our prior experience in cost estimates for Hyperdrive components, we placed their relative costs in the 600 V column. For the 300 V column, we factored in considerations presented above. In this example, the total cost of a low voltage system will be approximately 50% larger than that of the high voltage system.

CONCLUSIONS

European light commercial vehicles can be built with the Hyperdrive to not only meet gradeability requirements, but acceleration performance improves significantly over the base vehicle. Expected reduction of fuel consumption at high voltage with a diesel engine is 27%. The 600 V battery offers 8% more reduction in fuel consumption versus the 300 V battery, mainly due to lower inverter losses.

In terms of cost, the 300 V electrical system is expected to cost 50% more than the 600 V one.

A greater price premium can be justified on the 600 V system because of the larger reduction in fuel consumption, 27% versus 19%. At the same time, the 600V system costs significantly less than the 300 V one, which makes it the better choice for the Hyperdrive.

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