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THE ENERGY FLOW MANAGEMENT AND BATTERY ENERGY CAPACITY DETERMINATION FOR THE DRIVE TRAIN OF ELECTRICALLY PEAKING HYBRID VEHICLE

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ABSTRACT

In this paper, the configuration of a parallel hybrid vehicle, called electrically peaking hybrid (ELPH) vehicle is introduced. Several operation modes of the engine and electric motor and different control strategies are analyzed. The results show that, with proper selection of the drivetrain parameters, the vehicle can satisfy the urban and highway driving with a small internal combustion engine, a small battery pack and a single gear transmission. Moreover, the vehicle does not need to charge the battery pack from the electricity network for keeping its battery SOC at a reasonable level.

INTRODUCTION

In recent years, increasing concern over air pollution, caused by tailpipe emissions of petroleum-based vehicles, and the dwindling petroleum resources have lead the automotive engineers and automakers to probe the possibility of the zero-emission (ZE) and ultra-low emission (ULE) vehicles. Among all kind possible schemes, electric vehicle (EV) seems to be the most attractive due to their zero emission, petroleum-free energy supply, control flexibility, and simple construction. However, pure electric vehicles suffer from other disadvantages[5, 6].

1. The heavy and bulky battery pack, with very limited energy storage, makes the EV limited in range, and load carrying capacity.

2. Long charging time limits the EV's availability.

Therefore, commercial success of the EV depends entirely on development of advanced high energy batteries. However, progress in batteries over the past several decades has not been adequate.

Hybrid configurations, in which two power sources are applied to propel the vehicles, are now holding the greatest promise. The hybrid electric-internal combustion engine drive train, if properly configured, can combine the advantages of both EV and ICE vehicles with no drawbacks.

The configuration of a parallel hybrid vehicle, called electrically peaking hybrid (ELPH) vehicle is shown in Fig. 1.[7,8,9,10] The internal combustion engine (ICE) and the electric motor are coupled by a set of match gear (or chain) into the input shaft of the transmission. The transmission would be multi-speed or single-speed depending completely on the performance requirement and drivetrain parameters selected.

When the vehicle operates on level road with constant cruising speed, relatively low power is required, but large amount of energy is consumed in a long trip. In this case, a small ICE alone is used to power the vehicle, resulting in an excellent fuel economy due to its operating point being close to the optimal point. When the vehicle experiences an acceleration or a steep hill climbing, the electric motor, functioning as a load leveling device, supplies supplementary power to the drive train to meet the performance requirement. The ELPH configuration has the ability to recover braking energy with the electric motor functioning in regenerating mode. Furthermore, when the vehicle operates with light load, such as at a relatively low constant speed or going down a slight hill, the engine can recharge the battery pack to maintain adequate state-of-charge. More beneficially, this enhances the engine load, for operation close to its optimal point. A well designed ELPH vehicle may never use a wall plug to charge its battery pack and can obtain an excellent fuel economy.

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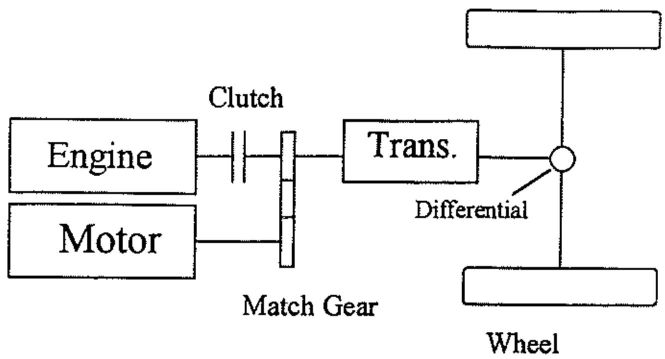

Fig. 1 The Configuration of the ELPH Vehicle

MANAGEMENT OF MOTOR AND ENGINE POWER

The operation of a vehicle can be divided into three basic modes: constant speed (cruising), acceleration (peak power) and deceleration (regeneration). In each mode, the engine and the motor operate with the appropriate behavior to meet the load power requirement and keep proper SOC on the battery.

CRUISING MODE - The cruising mode is the operation mode of the vehicle in which the engine alone can meet the load power requirement, such as operating on a level road with constant speed or with a slight acceleration or a slight hill climbing with constant speed. In this operation mode, the engine and electric motor have several operating status.

Motor-only Tractive Mode - When the speed of the vehicle is less than the speed that is limited by the minimum rpm of engine or greater than the speed that is limited by the engine maximum rpm, all the power required by the load of the vehicle is supplied by the electric motor. The engine must remain at standstill or in idling. In these cases, we have

$$P_e = 0 \quad (1)$$

$$P_m = P_l \quad (2)$$

$$P_b = \frac{P_m}{\eta_{bd}\ \eta_m} \quad (3)$$

where, P_e= power output of engine,
P_m = power output of electric motor,
P_l = load power of the vehicle,
P_b= discharge power of the battery pack,
η_{bd}= discharge efficiency of the battery pack,
η_m= efficiency of the motor.

In this operating mode. All the required energy must be supplied by battery pack.

Battery Pack Charging Mode - When the load power of the vehicle is less than the engine power with wide open throttle, engine has the extra power to charge the battery pack, if necessary. The electric motor functions in the regenerating mode to convert the engine power into electric power to recharge the battery pack. The electric motor power (as a generator), P_m, and battery pack recharging power, P_b, are

$$P_m = -(P_e - P_l) \quad (4)$$

$$P_b = P_m \eta_m \eta_{bc} \quad (5)$$

where; η_{bc}= the battery pack charging efficiency .

Negative P_m means electric motor functioning as generator.

Engine-only Mode - If the battery pack is not required to be recharged, for example, the SOC of the battery pack reaches its top line, the electric motor is idling and the engine power is equal to the load power of the vehicle, that is

$$P_e = P_l \quad (6)$$

PEAK POWER MODE - When the vehicle experiences an acceleration or a steep hill climbing, the load power is much greater than that the engine can produce. Consequently, the motor must work together with the engine to produce enough power to meet the requirement. In this case, the motor power output and battery power output are

$$P_m = P_l - P_e \quad (7)$$

$$P_b = \frac{P_m}{\eta_{bd}\eta_m} \quad (8)$$

REGENERATING MODE - When the vehicle experiences a deceleration or a hill descending, the engine is turned off or idles. The electric motor functions in regenerating mode. The electric motor (generator) power P_m, and battery charging power, P_b, are

$$P_m = \alpha P_l \quad (9)$$

$$P_b = P_m \eta_{tm} \eta_m \eta_{bc} \quad (10)$$

where α = fractional factor of power recovery,
η_{tm} = efficiency from motor to the drive wheels.

In equations (1) to (10), positive P_e, P_m and P_b mean that the engine, motor and battery pack supply powers to the vehicle. In contrast, negative P_m and P_b means that motor and battery pack absorb power from the engine or regenerating braking.

THE ENERGY CHANGE IN THE BATTERY PACK

As explained above, in the peaking power mode, the battery pack must supply energy to the vehicle. Consequently, the stored energy in the battery pack is decreased. On the other hand, when the vehicle operates at low load or in the braking mode, the battery pack absorbs energy from engine or regenerative braking. In a whole drive cycle, if the consumed energy and absorbed energy are balanced, the battery pack will never have to get energy from wall plug. Therefore the range of the vehicle is only limited by the fuel tank as in a conventional vehicle.

The amount of energy change in the battery pack at time t in the drive cycle ($t=0$ represents the beginning of the drive cycle) is expressed by

$$E = -\int_0^t P_b d\tau \qquad (11)$$

The negative sign means that when P_b is positive (battery pack supplies power to the vehicle), the energy in the battery pack is decreased. If, at the end of the drive cycle, the value of E is the same as that at the beginning of the driving cycle, the battery SOC will be kept the same as at the beginning of the drive cycle. Consequently the vehicle will not need wall plug to charge the battery.

CONTROL STRATEGIES OF THE DRIVETRAIN

As explained above, at any time in driving, the sum of the engine power, P_e, and the electric motor power, P_m, should be equal to the vehicle load power P_l, (except in the braking mode, in which external braking power may be applied by brake system of the vehicle). In the actual operation, the control system of the drivetrain can determine the power output of each power unit in many ways, provided the total power output meets the requirement. Different control strategies will obtain different fuel economies and different battery energy capacities.

MAXIMUM BATTERY SOC CONTROL STRATEGY - The maximum battery state-of-charge control strategy is consistent with the principle that, at any time, except the battery SOC reaching its top line, the engine should operate with full load (wide-open throttle) to produce maximum power. One part of the engine power is used to counterbalance the vehicle load power, and the remainder is used to charge the battery. This control strategy is illustrated in Fig. 2. In this figure, the segments a and a' represent the battery charging power for high-speed and low-speed gears of the transmission respectively. Similarly, b and b' represent the battery discharging power for higher and lower speed gear of the transmission. *Fig. 2* also implies that a multi-speed transmission is helpful to reduce the size of battery pack. However the penalty is a complicated construction and control system.

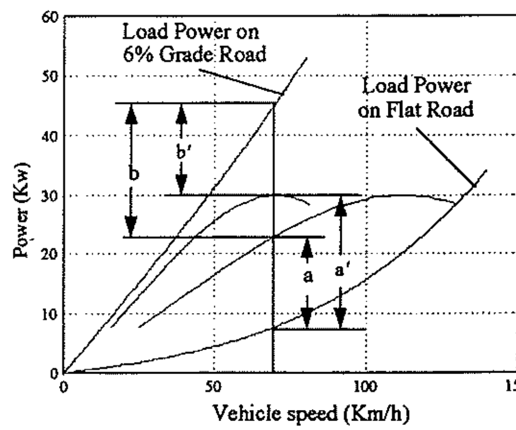

Fig. 2 Battery Charging and Discharging Power

OPTIMAL CONTROL STRATEGY - Fig. 3 shows the fuel consumption map of a typical SI engine with its optimal fuel economy operating line. If operating point of the engine is just on the optimal fuel economy operating line, the engine has a optimal operating efficiency. Fortunately, the power output corresponding to the optimal operating line is just a little smaller than the power output with a full load (wide-open throttle). This implies that, if the control system controls the engine operating on the optimal operating line, the vehicle can not only maintain the battery SOC at a certain level, but also have a good fuel economy, and generally, good emission characteristics.

Generally, the optimal operating line of engine is quite difficult to obtain analytically. It is approximately assumed that power on the optimal fuel economy operating line is proportional to the power output of engine with a wide-open-throttle in a large speed range (see Fig. 3). Thus

$$P_{eop} = \beta P_{e\,max} \qquad (12)$$

where P_{eop} = power output corresponding to the optimal fuel economy operating line,

β = fractional factor,
P_{emax} = power of the engine with wide open throttle.

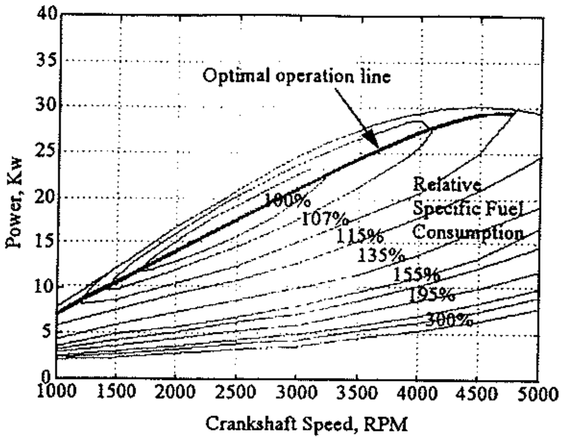

Fig. 3 Specific Fuel Consumption Map Of a Typical SI Engine with Its Optimal Operating Line

DETERMINATION OF BATTERY ENERGY CAPACITY

Proper selection for energy capacity of the battery pack is crucial for the design of the ELPH vehicle. Oversized battery pack would cause vehicle overload, and, undersized battery pack can not supply adequate energy and power for the needs of the vehicle.

The minimal value of E in equation (11) within a drive cycle represents the lowest SOC of the battery, $E=0$ represents the highest SOC of the battery pack

Fig. 4 shows a charge and discharge efficiency of a typical lead-acid battery along with its state -of-charge. This figure suggests that if the SOC of the battery pack is kept within the range of *40%* to *60%*, the cycle efficiency is optimal[1]. Therefore, we set the highest SOC of the battery pack being *60%* and the lowest *40%*..

Thus, we have

$$0.6C_{be} - 0.4C_{be} = |E_{min}| \qquad (13)$$

So,
$$C_{be} = \frac{|E_{min}|}{0.2} \qquad (14)$$

where, C_{be}= the energy capacity of the battery pack with *Kw.h*.

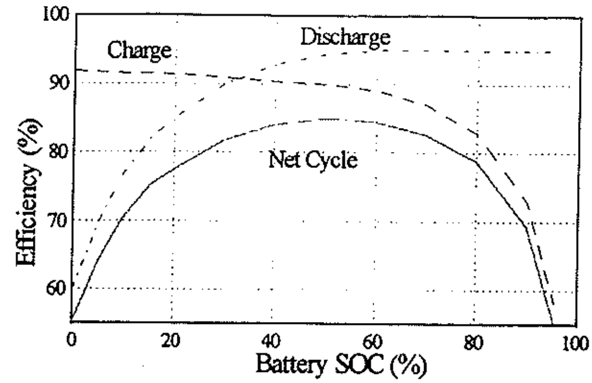

Fig. 4 Battery Efficiency Respect with Battery State-of-Charge [1]

A NUMERICAL EXAMPLE

The specification of the example ELPH vehicle prototype which is being developed at Texas A&M University is listed as below:

Total weight	*1700 Kg,*
Rolling resistance coefficient of tire	*0.013,*
Aero-dynamic drag coefficient	*0.29,*
Frontal area	*2.13 m^2*
Wheel radius	*0.2794 m.*

The following parameters are used in the calculations.

Engine power capacity	*30 Kw*
Differential gear ratio	*4.23*
Single gear transmission, gear ratio	*1.0*
Transmission efficiency from engine and motor to drive wheels	*0.9*
Motor efficiency	*0.85*
Battery charge and discharge efficiency	*0.85*

The engine speed-power characteristic is shown in Fig. 5.

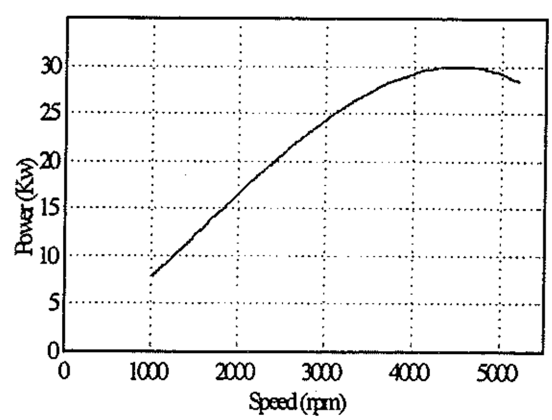

Fig. 5 The Speed-power Characteristic of Engine

Best Battery SOC Control Strategy - Fig. 6 shows the engine power, motor power, battery power and the change of battery energy along with driving time in the urban driving cycle FPT75.

Fig. 6 indicates that E has the same value at the beginning and end of the driving cycle. Therefore, the vehicle does not requires a wall plug to charge the battery pack in urban driving. Fig. 6 also gives a minimal E equal to *0.1421 Kw.h.* Using equation (14) , the energy capacity of the battery pack, $C_{be}=0.7105$ *Kw.h,* is obtained. This result means that, from the energy point of view, only a very small battery pack is needed.

While operating with highway driving cycle, the engine power, motor power, battery power and energy change in the battery pack are shown in Fig. 7. This figure indicates that engine alone can almost satisfy the requirement except for the transient acceleration at the beginning of the drive cycle. The minimal E is equal to *0.0431 Kw.h.* So, the $C_{be}=0.2155$ *Kw.h* is enough for this driving cycle.

Optimal Control Strategy - Fig. 8 and Fig. 9 show the time history of the engine power, motor power, battery power and the change in the battery storage energy corresponding to urban and highway driving cycle of FTP 75. The β (see equation (12)) is 0.87 The results show that, even with the frequent start-stop urban driving mode, the vehicle does not need a wall plug to charge its battery pack. The minimal E is equal to 0.1850Kw.h So, the $C_{be}=$ *0.925 Kw.h* This means that, with this control strategy , the battery size is also quite small.

The situation of highway driving with optimal control is quite similar to that with best battery SOC control. The engine alone can almost satisfy the power requirement.

CONCLUSION

The electrically peaking hybrid vehicle has a parallel configuration in which a small internal combustion engine and an electric power peaking motor cooperate. When the vehicle is operating with a light load, the engine can charge the battery pack with the remaining power. When the vehicle operates with high load , the battery pack can supply energy to the drivetrain to meet the requirement of the load power.

The calculation results show that, for a 1700 Kg passenger car ,the combination of a 30 Kw power capacity engine and a small battery pack with a single-gear transmission will satisfy the requirement in both urban and highway driving conditions. With the engine operating point being controlled on the optimal operating line by the optimal control strategy, the vehicle will achieve an excellent fuel economy, and generally good emissions characteristics.

ACKNOWLEDGMENT

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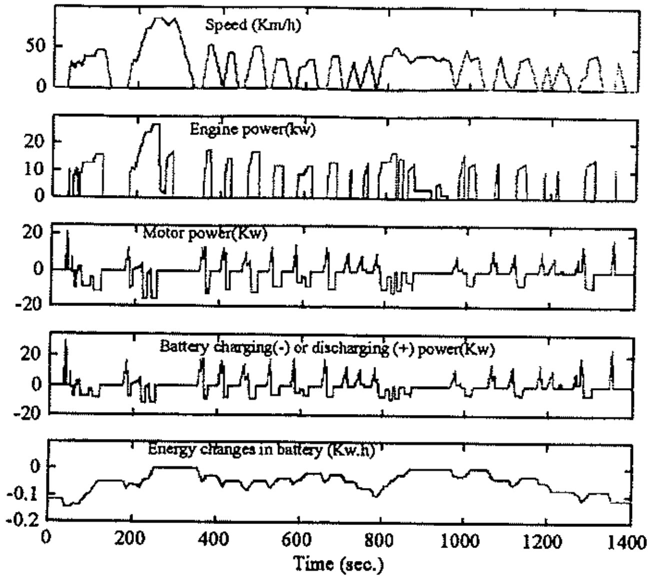

Fig 6. The Time History of Engine Power, Motor Power, Battery Power and Change of Battery Storage Energy Corresponding to FTP75 Urban Driving Cycle with Best Battery SOC Control Strategy

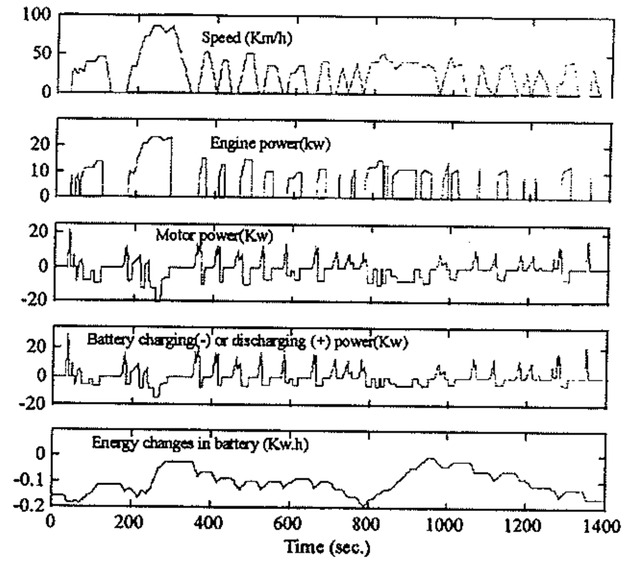

Fig. 8 The Time History of Engine Power, Motor Power, Battery Power and Change of Battery Storage Energy Corresponding to FTP75 Urban Driving Cycle with Optimal Control Strategy)

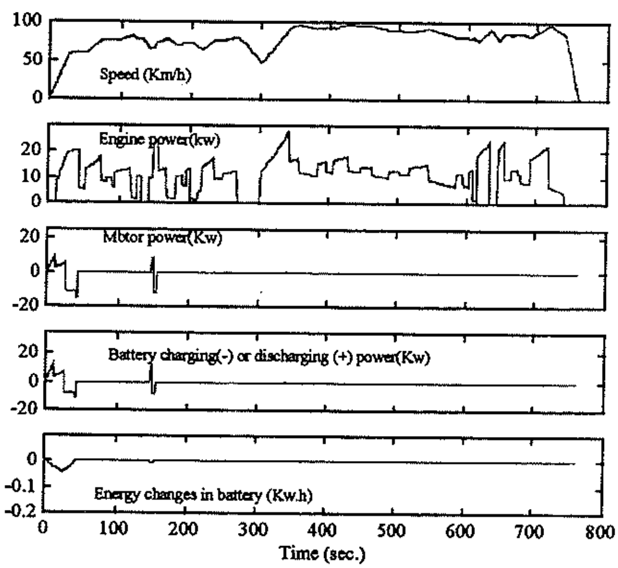

Fig. 7 The Time History of Engine Power, Motor Power, Battery Power and Change of Battery Storage Energy Corresponding to FTP75 Highway Driving Cycle with Best Battery SOC Control Strategy

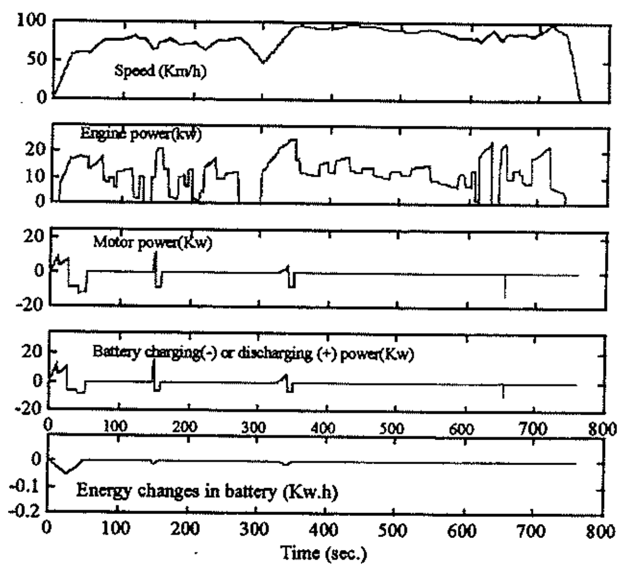

Fig. 9 The Time History of Engine Power, Motor Power, Battery Power and Change of Battery Storage Energy Corresponding to FTP75 Highway Driving Cycle with Optimal Control Strategy

APPLICATION OF ELECTRICLLY PEAKING HYBRID (ELPH) PROPULSION SYSTEM TO A FULL SIZE PASSENGER CAR WITH SIMULATED DESIGN VERIFICATION

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Abstract

An electrically peaking hybrid electric (ELPH) propulsion system is being developed that has a parallel configuration. A small engine is used to supply power approximately equal to the average load power. The operation of the engine is managed by a vehicle controller and engine controller such that the engine always operates with nearly full load – the optimal economy operation. A induction AC motor is used to supply the peaking power required by the peak load (electrically peaking). The motor can also absorb the excess power of the engine while the load power is less than the peak. This power, along with the regenerative braking power, can be used to charge the batteries on board to maintain the battery state-of-charge at a reasonable level.

With the electrically peaking principle, two control strategies for the drive train have been developed. One is called MAXIMUM BATTERY SOC, by which, the engine and electric motor are controlled so that the battery SOC is maintained at its top level as much as possible. This control strategy may be used in urban driving, in which, accelerating and decelerating driving is common. The other control strategy is called ENGINE TURN-ON AND TURN OFF control, by which, the engine is controlled to operate in turn-on and turn-off manner. This control strategy may be used in highway driving.

Based on the ELPH principles and the drive train control strategies, a drive train for a full size, 5-seat passenger car (1700 kg of gross weight) has been designed and verified using the V-ELPH computer simulation package developed at Texas A&M University. The results show that the ELPH car can easily satisfy the performance requirements and the fuel economy can be improved greatly over conventional vehicles.

Introduction

In vehicle development and design, the major issues are the marketability and the impacts on the environment. Conventional gasoline and diesel fueled vehicles possess the advantages such as, good performance, long driving range, ease in refueling, light-weight energy source. These advantages have enabled the conventional vehicles to dominate the market. However, conventional vehicles have serious disadvantages in regard to energy sources and environment protection, primarily the very inefficient usage of the petroleum sources and serious air pollution. The electric vehicles, which have been under development for many years, are considered to be important substitutes of the conventional vehicles that can overcome their disadvantages. But the acceptability of the electric vehicles in the automobile market has encountered major obstacles. Due to the heavy and bulky batteries on board, the electric vehicles usually have sluggish performance, limited loading capacity, short driving range and long battery recharging time and high manufacturing cost.

Hybrid electric vehicles under development in recent years, are considered to be the best trade-off between conventional and electric vehicles. In a hybrid vehicle, two power plants are available which commonly are an internal combustion engine and electric motor. The inclusion of two power plants provides flexibility to use either internal combustion engine or electric motor or both together for traction, according to their operation characteristics and driving requirement. This configuration increases the potential to optimize the overall drive train operation. It also, however, increases the complexity in the management of the powers supplied by the both engine and motor. Therefore, the control strategy of the power plants is a crucial aspect in the development of hybrid electric vehicles.

In this paper, a hybrid electric propulsion system, with a parallel configuration, referred to as ELectrically Peaking Hybrid (ELPH) propulsion system, is introduced. The principle is illustrated through simulations performed using the V-ELPH software simulation program developed at Texas A&M University[1]. The power plants available in the system are a spark ignition internal combustion engine and an AC induction motor. The power plants are managed (controlled) with electrically peaking manner[2,3,7,8]. The objectives of the application of the ELPH propulsion system to a full size car are: (1) comparable performance to conventional vehicles that have similar space and loading capacity, (2) similar mass production to that for corresponding conventional one, (3) the same operation as driving conventional vehicle, (4) two to three times fuel economy over the conventional vehicles, and (5) self sustained battery SOC.

ELPH Principle

For a full size vehicle, the required acceleration performance usually constraints the reduction of the power capacity of the power plants. For instance, for a vehicle with 1500kg gross weight, the average power needed to accelerate the vehicle from zero speed to 100 km/h (62.5mph) in 10 seconds is about 60kW, and the peak power of the engine needed would reach about 90 to 100kW. However, in normal driving, the average load power is only 15 to 20kW. Such low load power results in very low engine fuel efficiency. This conflict between the performance and fuel economy requirements pushes the conventional vehicle design into a dilemma.

Actually, in normal driving, the load power of the vehicle varies randomly as shown in Fig.1. This power profile can be resolved into two components: one representing the average power demand and other representing the dynamic power demand which has a zero average value. With the ELPH principle, an internal combustion engine, which has optimal steady-state operating region in its speed-power characteristics map, is used to supply the average load. The electric traction system (electric motor and batteries) is used to produce the dynamic power[7,8]

With the ELPH principle, engine size can be reduced greatly and the engine can operate almost in its efficient region, thus resulting in much high operating efficiency. The electric traction system operates in a dynamic manner, producing the peaking power to meet the peak power demand in acceleration and hill-climbing driving. The storage energy within the batteries can be maintained in a balanced state by two battery charging approaches. The first approach is to charge the battery by recovering the kinetic energy in decelerating driving and potential energy of the vehicle in down-hill driving. The second approach is to charge the batteries by the access power of the engine when the load power demand is less than the power the engine can produce. These two battery-charging approaches can be implemented by using the motor controller to operate the traction motor as a generator. With these approaches, the batteries only function as an energy reservoir. With proper design, the battery state-of-charge can possibly be maintained at a reasonable level in the driving, and the battery size (energy capacity) can be small[2].

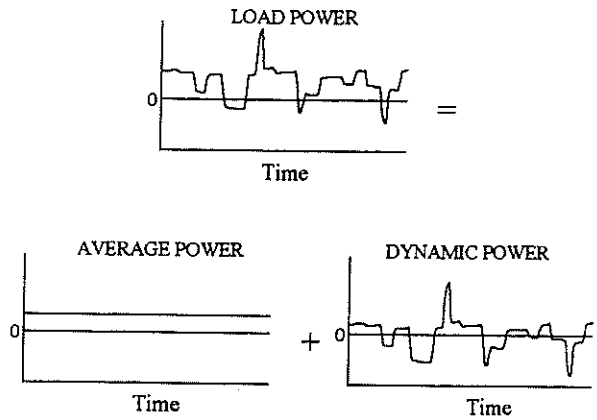


Fig.1 The load power demand and its steady and dynamic components

Configuration and Operation Modes of the Propulsion System

The ELPH prolusion system proposed has parallel configuration as shown in Fig.2 and Fig.3[7,8]. The configuration shown in Fig.2 is the two-shaft configuration, in which, the engine torque, modified by the transmission, and motor torque are added together by a torque summer which may be a set of gears, or chain. The configuration in Fig.3 is single-shaft configuration, in which, the rotor of the motor functions as the torque summer. However, both configurations have the same operation principle, and which is more suitable in physical design depends on the engine and motor characteristics, performance requirement, and convenience to developing the propulsion under hood.

The transmissions in both configurations are used to modify the torques so as to properly match the requirement of the driving. The transmissions may be multi-speed or single speed, depending on the engine and motor size, operation characteristics and performance requirement. Actually, due to the favorable characteristics of the electric motor as a traction power plant, a sing-gear transmission may satisfactorily serve the propulsion[2].

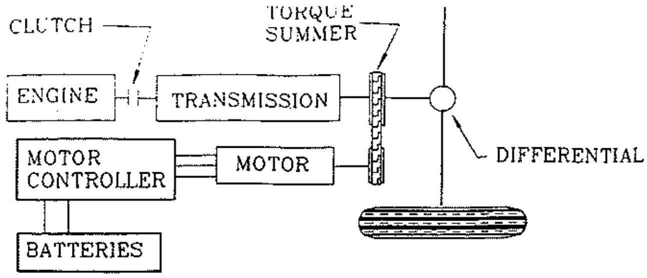


Fig.2 Two-shaft configuration of ELPH propulsion

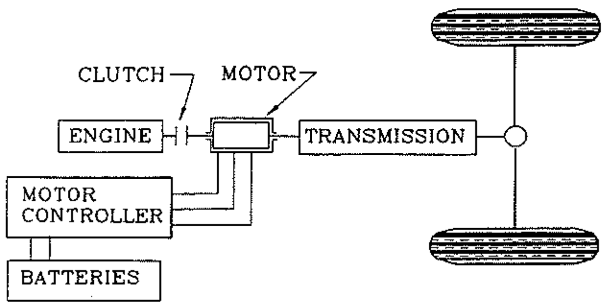


Fig.3 Single-shaft configuration of ELPH propulsion

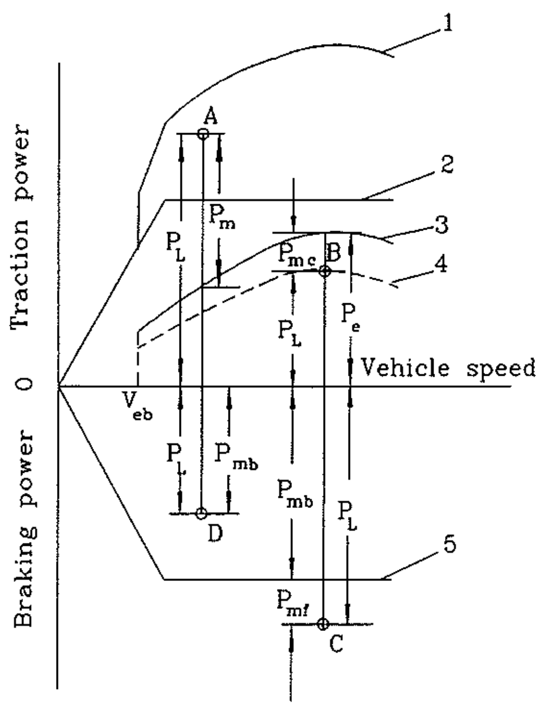
The ELPH propulsion can potentially realizes several operation modes such as: (1) motor-only mode, (2) engine-only mode, (3) hybrid traction mode (engine plus motor), (4) regenerative braking mode, and (5) battery charging from the excess power of the engine. The motor-only operation mode is used when the speed of the vehicle is very low such that the engine can not operate steadily and the battery is fully charged in highway driving. The engine-only operation mode may be used in the case that the battery is fully discharged (if this occurs accidentally). However, this operation mode should be avoided as much as possible. Hybrid traction operation mode is used in a case where the peak power is required, such as acceleration and hill climbing driving. The regenerative braking operation mode is used in braking driving. In this case, the electric motor functions as a generator to recuperate the kinetic or potential energy of the vehicle into electric energy to charge the batteries on board. The battery charging mode from the excess power of the engine is used when the batteries are not fully charged and the engine has excess power after propelling the vehicle.

A micro-processor based vehicle controller is applied to regulate the engine and motor operations to optimally use the above operation modes according to the driving requirement, engine and motor operation characteristics, battery state-of-charge information. The control target of the control strategies in the vehicle controller is (1) to meet the tractive effort required by the driver, (2) to maintain the battery SOC at reasonable level, (3) to operate the engine efficiently, and (4) to recover the kinetic and potential energy as much as possible.

Control Strategies

Maximum Battery SOC Control Strategy

The control target of the maximum Battery SOC control strategy follows the principle that high battery SOC should be maintained in driving as much as possible. This control principle results in that the engine should be used as much as possible and the electric traction system should be used as less as possible. The details of this control strategy are illustrated in Fig. 4.



1--Maximum power with hybrid mode
2--Maximum power of the electric motor in traction mode
3--Power of the engine corresponding to its optimum economy line
4--partial load of the engine
5--Maximum power of the electric system in regenerative braking

P_L --Load power, including traction and braking power
P_e --Engine power
P_m --Motor traction power
P_{mb}--Regenerative braking power of the motor
P_{mf}--Mechanical braking power
P_{mc}--Battery charging power

Fig. 4 Illustration of the Maximum battery SOC control strategy

In Fig.4, point A represents the traction power that is greater than the power that the engine can supply (this may occur in acceleration and hill-climbing driving), In this case, the engine and electric motor must supply their power to meet the power requirement. The power distribution between the engine and the motor is to operate the engine at near full load (full throttle, which usually is the optimal fuel economy operation), and to control the electric motor to supply its power equal to the remaining load power. Point B represents the traction power that is less than the power that the engine can produced with near full throttle. In this case, the engine can be controlled depending on the battery SOC. If the battery SOC dose not reach its top level, the engine should be operated at near full load. The power remaining after propelling the vehicle is used to charge the batteries. If the battery SOC reaches its top level, the engine should be controlled to produce its power that is equal the load power. Point C represents the braking power which is greater than the power that the electric system (electric motor and batteries) can absorb. In this case, to recuperate the braking energy as much as possible, the electric motor, functioning as a generator, should be controlled at its maximum power. The remaining braking power is taken by the frictional brake system. Point D represents the braking power required by the driver, which is less than the power the electric system can handle. In this case, the electric regenerative braking alone is used. Reference [3] has given the mathematical description in detail.

The Maximum Battery SOC control strategy may suitably match the urban driving, in which, the frequently accelerating–decelerating driving would discharges the batteries quickly. Therefore, Maintaining the battery SOC at high level is crucial for the operation of the vehicle.

Engine Turn-on and Turn-off Control Strategy

When vehicle drives on the highway, the power and energy supplied by the electric system is much smaller than driving in urban and the load power is usually less than the full-load power capacity of the engine. The batteries, in this case, can easily be fully charged. For avoidance of the inefficient engine operation, the engine should operate in a turn-on and turn-off or duty-cycle manner.

In the engine turn-on and turn-off control strategy, the duty cycle of the engine operation is depends on the battery SOC. Fig.5 shows the relationship between the engine duty cycle and the battery SOC. In the engine turn-on period, the engine alone propels the vehicle and the excess power is used to charge the batteries. Then the battery SOC goes up until reaching its top line. In this way, the engine would operate always near full load. After the battery SOC reaches its top level, the engine is turned off and the vehicle is propelled by the electric system alone. With the engine turn-on and turn off operation manner, the propulsion system would obtain maximum overall efficiency

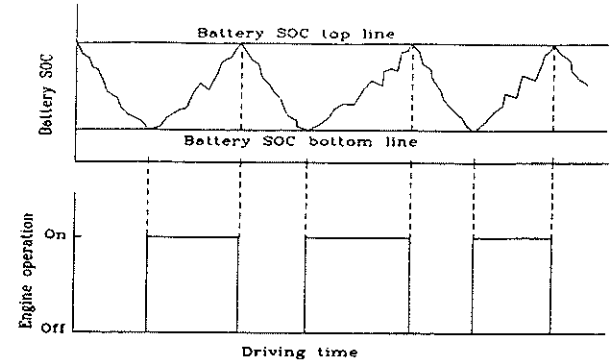


Fig.5 Illustration of the engine turn-on and turn-off operation

Application of the ELPH Propulsion System to Full Size Passenger Car

Below are the specifications of the full-size ELPH passenger car. It is expected that the car has the similar performance and load capacity to conventional gasoline fueled passenger cars with self-sustained battery SOC property. The fuel economy is expected to be two to three times that of conventional cars.

Vehicle Type: *4-door, 5-seat passenger car, front engine/moor and front drive*

Overall dimension:

Overall length:	*4.70 ~ 4.80 m*
Overall width:	*1.70 ~ 1.80 m*
Overall height:	*1.40 ~1.45 m*
Wheel base	*2.65 ~ 2.8 m*
Tread width	*1.55 ~ 1.75 m*

Estimated weight

Curb weight:	*1500 kg (include traction batteries)*
Load	*Two person (2×70 kg) + luggage (60 kg)=200 kg*

Total weight; 1700 kg
Weight on front/rear axle:62% / 38%

Main components:

Engine:	*Spark ignition, gasoline fueled internal combustion engine.*
Traction Motor:	*Electronically controlled induction AC motor.*
Batteries:	*Lead/acid traction batteries*
Transmission:	*Single gear, mechanical transmission*

Performance specification

Acceleration 12±1 sec. (from 0 to 96 km/h or 60 mph)

Max. gradeability:>30% and >5% @ 100km/h

Maximum speed;

Engine only: 140 km/h

Hybrid traction 160 km/h

Range: Free from battery energy storage and only rely on fuel tank volume

Estimate of Propulsion Parameters

Engine size – As mentioned in the ELPH operation principle, the engine power capacity can be determined by the load power for steady driving, which can be expressed as

$$P_e = \frac{V}{1000\eta_{t,e}}\left(mgf_r + \frac{1}{2}\rho_a C_D A_f V^2\right) \quad (kW), \qquad (1)$$

where, m is the vehicle gross mass in kg, $\eta_{t,e}$ is the transmission efficiency from the engine to driven wheels, f_r is the rolling resistance coefficient, ρ_a is the air density with $1.205 kg/m^3$, C_D is the aerodynamic coefficient, A_f is the front area of the vehicle in m^2, and V is vehicle speed in m/s. The values of above parameters used in this paper are as follows.

Vehicle mass	*1700 kg*
Rolling resistance	*0.01*
Transmission efficiency	*0.92*
Aerodynamic drag coefficient	*0.3*
Front area	*2.25m²*

The power demand along the vehicle speed is shown in Fig.6. This figure indicates that about 33 kW is needed for the vehicle speed of 140km/h (87mph). This value is quite much smaller than the power of engines used in conventional passenger cars[2]. Considering the power consumed in accessories, such as lights, audio, power steering, air conditioner and so on, a 40 kW engine is needed. Here a maximum power of 35 kW is assumed being used in traction. The speed – power and speed torque characteristics of the engine are shown in Fig.7.

Estimate of Electric Motor Size – Based on the ELPH principle, the electric motor is used to handle the dynamic load of the vehicle. Therefore, determination of the electric motor size depends on the acceleration and gradeability. In practice, the acceleration is the first consideration in the design of passenger cars.

As the initial estimate, an assumption would be made that the steady-state load is handled by the engine and the dynamic load is handled by electric motor. In this way, the maximum electric motor power needed in the acceleration can be expressed as[4]

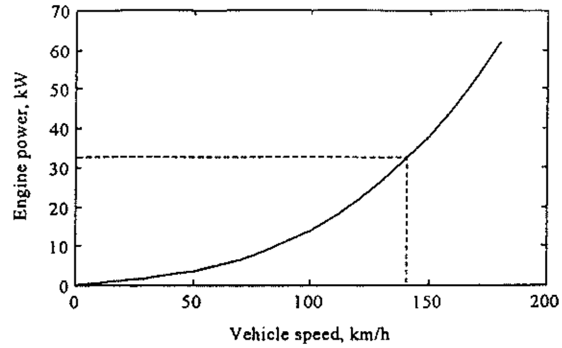


Fig.6 Engine power demand versus vehicle speed in steady driving

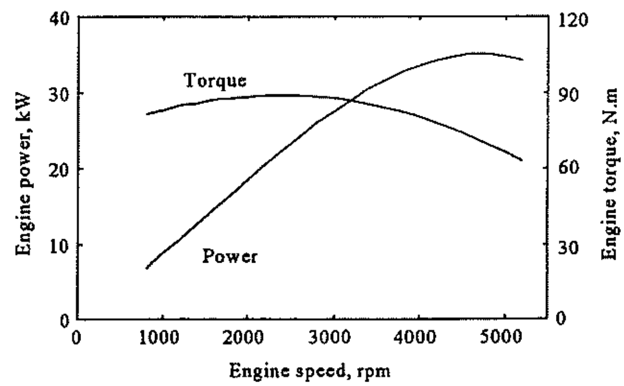


Fig.7 Speed-power and speed-torque characteristics of the engine

$$P_{m\,max} = \frac{30m\delta}{9549\pi t_f}\left(\frac{V_b^2 + V_f^2}{2}\right) \quad (kW), \qquad (2)$$

where, δ is the mass factor of the rotating components in the drive train, V_b is the vehicle speed corresponding to the motor base speed in m/s, V_f is the vehicle speed at the end of the acceleration in m/s, and t_f is the acceleration time in second. The following parameters are used in the in the estimate of the maximum power of the electric motor.

Final speed of acceleration:	*96km/h (60mph)*
Acceleration time:	*12 Sec.*
Mass factor	*1.02*
Vehicle speed corresponding to motor base speed	*37.5 km/h (23.4mph)*

The maximum motor power of about 65 kW is calculated using equation (2) and the parameters above. It should be noted that the engine has, actually, some excess power to help the electric motor to accelerate the vehicle as shown in Fig 8. This excess engine power to assist the electric motor in acceleration is assumed to be about 10 kW. Thus the maximum power of the electric motor will be

55kW. It should be noted that this motor power is the peak power needed. The rated power of the electric motor is much smaller that this value (one third or half of the peak power). Fig 9 shows the speed power characteristics of the electric motor.

Transmission – Due to the favorable traction characteristics of the electric motor, a single transmission would meet the performance requirement. Reference [2] has described the principle, with which, the proper gear ratios from the engine and the electric motor to the drive wheels can be chosen. With the engine characteristics shown in Fig.6 and the maximum vehicle speed specified in the design specification, the gear ratio from the engine to the driven wheels are chosen as 3.90. Similarly, the gear ratio from the electric motor to the driven wheels is also chosen as 6.58.

Performance Prediction

The predication of the vehicle performance has been performed using the V-ELPH Simulation Package, which yielded the parameters such as the acceleration performance, gradeability and maximum speed.

Acceleration Performance -- The acceleration performance that resulted from the simulation is shown in Fig 10. This figure shows that the acceleration time and distance covered from 0 to 96km/h (60 mph) are about 12 seconds and 180m respectively. These results perfectly coincide with acceleration performance specified in the design specification.

Gradeability and Maximum Speed – The gradeability and the maximum speed of the vehicle can be obtained from the diagram of vehicle traction effort and resistance versus vehicle speed and road slope angle, as shown in Fig.11. In this figure, the maximum traction effort of the propulsion and the vehicle resistance (rolling resistance and aerodynamic drag), are plotted against vehicle speed for different road slope angles. This figure indicates that the maximum gradeability of the vehicle is about 18.5° (33.5%) and the gradeability at speed of 96km/h (60mph) is about 9° (15.8%). The maximum speeds with engine alone traction and hybrid traction reach 140km/h (87.5mph) and 160km/h (100mph). These results meet the requirements specified in the design specification.

Driving Simulation under EPA FTP75 Driving Cycles

Using the V-ELPH simulation package developed by Hybrid Electric vehicle Research Group, Texas A&M University, data relating the driving of the vehicle to certain driving cycles can be obtained, such as the engine and motor operation states (speed and power versus driving time), battery charging and discharging energy, and fuel

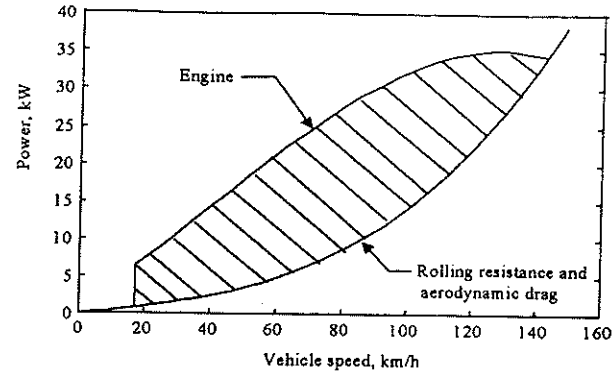


Fig.8 Illustration of the excess power of the engine used in acceleration

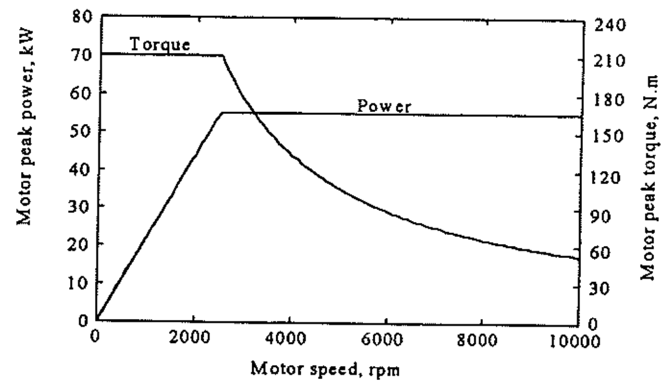


Fig.9 Electric motor characteristics

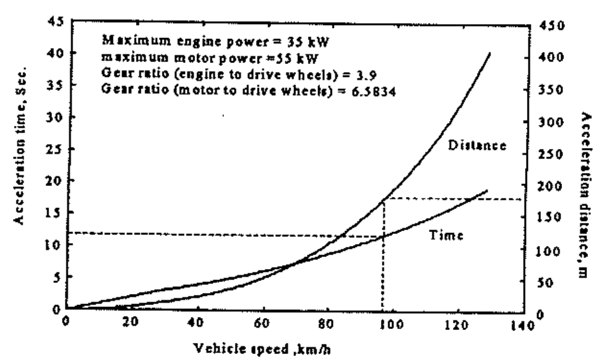


Fig.10 Acceleration performance of ELPH

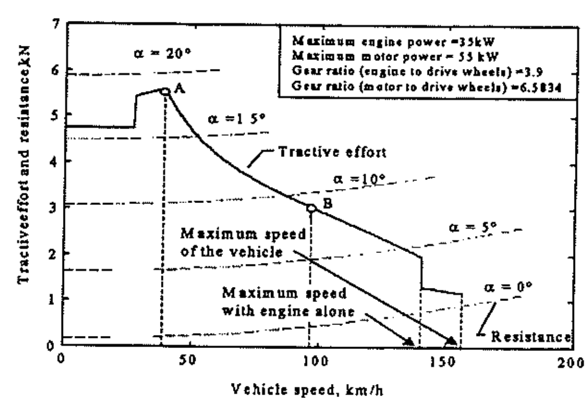


Fig.11 Diagrame of vehicle tration effort and resistenace versus vehicle speed and road angles

consumption. All data related to the operation of the components can be used to verify the design, determine the battery size, etc..

Simulation studies were based on the ELPH control strategies mentioned above. For the simulation of urban driving, the Maximum Battery SOC control strategy was used and for the highway driving, the Engine Turn-on and Turn-off control strategy was used. The regenerative braking was utilized in both urban and highway driving simulations.

Urban Driving Simulation

The EPA FTP75 urban driving cycle, which is described by the profile of vehicle speed versus driving time, is used to emulate the real driving of passenger car in urban area. The simulation program applies the driving cycle second by second, and calculates the engine speed, engine power, motor speed, motor power, regenerative braking power, and the change in the battery storage energy. Fig. 12 shows the simulation results generated by the studies using the urban drive cycle with the Maximum Battery SOC Control strategy. Fig. 13 shows the engine operation points on its fuel characteristic map.

Fig. 12 indicates that with the Maximum Battery SOC control strategy, the battery storage energy can be balanced at the beginning and end of the driving cycle by charging the battery from the excess power of the engine and the regenerative braking. This result shows that the batteries on board do not need to be charged from outside of the vehicle, and the vehicle driving range is limited only by the volume of the fuel tank.

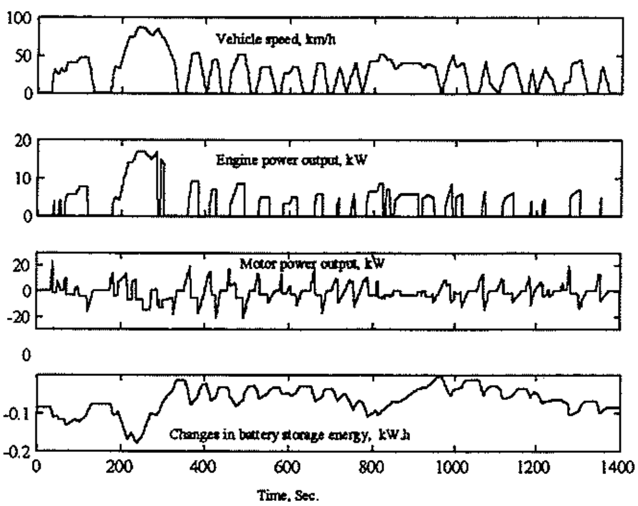


Fig. 12 Time history of vehicle speed, engine power output, motor power output and change in the battery storage energy in EPA FTP urban driving cycle.

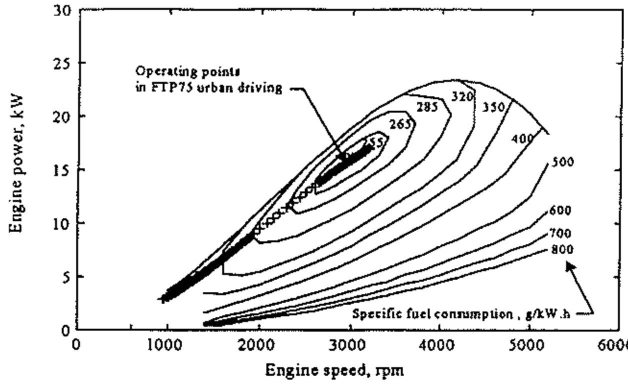


Fig. 13 Engine operating points on the fuel characteristic map of the engine

Fig. 13 indicates that, with the Maximum battery SOC control strategy and proper selection of the engine size, the engine can almost operate on its optimal operating line. This result is the major reason why the ELPH propulsion can improve the fuel economy greatly. The fuel consumption predicated from the simulation for this design is about 4.66L/100km (50.7mpg). This fuel economy is almost 2.5 times that of conventional passenger car that has a similar performance and load capacity.

Highway Driving Simulation

The EPA ftp highway driving cycle is used to emulate the real driving of passenger cars on highway. Comparing with the urban driving cycle, the highway cycle has a higher average speed and less acceleration–deceleration driving. The Engine Turn-on and Turn-off control strategy is a better control strategy for the highway driving. Using the V-ELPH simulation package, the simulation results generated by the studies using the highway drive cycle with the Engine Turn-on and Turn-off control strategy are shown in Fig. 14 and Fig. 15. From these two figures, it can be seen that the battery storage energy can be maintained balanced at beginning and end of the driving cycle and the engine operates almost in its optimal operating region. The fuel economy obtained from the simulation are 4.74 L/100km (50mpg). This value is almost twice the fuel economy of conventional passenger cars with similar performance and load capacity.

Determination of Battery Size

The battery size is determined by two factors, one is the power demand and the other is the storage energy demand. The batteries must be able to supply sufficient power to the electric motor in accelerating driving which means that the peak power the batteries supply must be greater than, at least equal to the peak power of the electric motor (*55kW*). The modern lead/acid traction batteries show the average specific power of *280W/kg* and power volume density of *470W/dm*^{3}[9], Thus, the total battery weight needed is about *200kg* $(55\times10^3/280)$ and the total battery volume is about $120dm^3$ $(55\times10^3/470)$.

The batteries must store sufficient energy to maintain the state-of-charge at a reasonable level during driving. Refer to Fig.12 and Fig.14, the maximum change in the battery storage energy is about *0.3kW.h*. The battery storage energy capacity of the batteries can be obtained by

$$C_b = \frac{\Delta E_b}{SOC_{top} - SOC_{bottom}} \quad , \qquad (4)$$

Where, ΔE_b is the maximum change in battery storage energy, SOC_{top} and SOC_{bottom} are the top and bottom values of the battery SOC, respectively, which are expected to be maintained in driving.

The battery operating efficiency (discharging and charging) is closely related to the battery state-of-charge as shown in Fig.16. This figure indicates that the range 40% to 60% of the battery state-of-charge is the optimal operating range. Thus, the battery storage energy capacity can be obtained as $C_b=0.3/(0.6-02)=1.5kW.h$.

The specific energy capacity and energy density of modern lead/acid are typically *40 W.h/kg* and $68W.h/dm^3$. Thus the total weight and total volume of the batteries required by the storage energy are about *37.5kg* $(1.5\times10^3/40)$ and $22dm^3$ $(1.5\times10^3/68)$ respectively, which are much smaller than those which are required by the peak power. This result implies that in ELPH propulsion, the batteries are used as power source more than as energy source.

Conclusion

This paper presents an alternative to conventional passenger cars, hybrid electric vehicle with an Electrically Peaking Hybrid (ELPH) propulsion system. Two control strategies, Maximum battery SOC and Engine Turn-on and Turn-off, are discussed for applicability in urban and highway driving, respectively. A full-size hybrid electric passenger car was simulated using the V-ELPH simulation program developed at Texas A&M University. Performance parameters were verified by studies using urban and highway driving cycle.

With parallel configuration and the electrically peaking principle, full size passenger cars can obtain comparable performance and loading capacity to the conventional cars, and the fuel economy of ELPH cars would be increased by 2-3 times. The ELPH cars do not need to be charged from outside of the vehicle. The cost of mass production is expected not to be much higher than that for conventional cars, since all the components in the propulsion are available in industry.

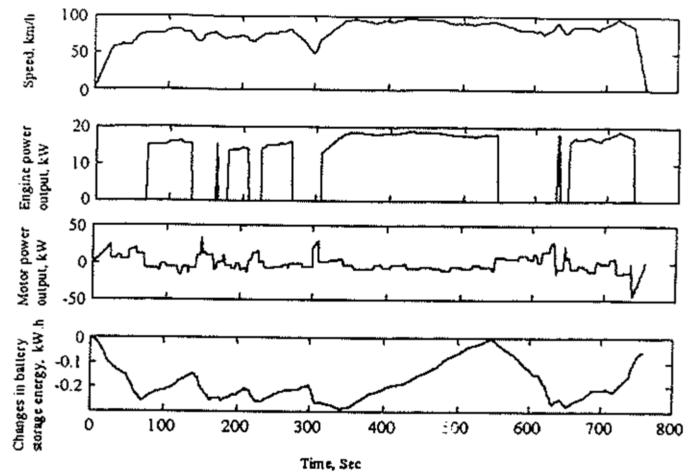


Fig.14 Time history of vehicle speed, engine power, motor power and changes in battery storage energy with the engine Turn-on and Turn-off control strategy in EPA FTP75 highway driving cycle

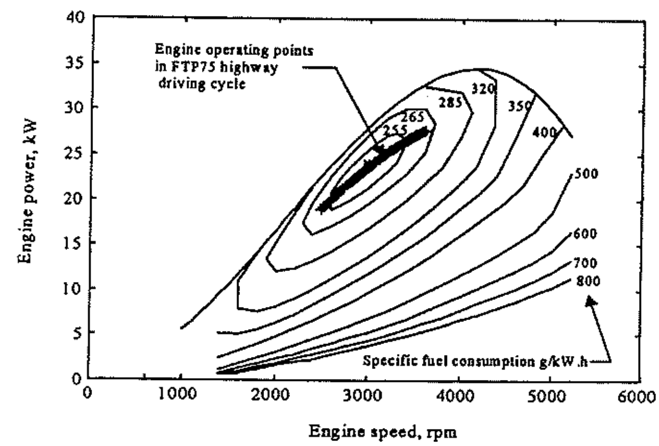


Fig.15 Engine operating points on the engine fuel consumption map in highway driving

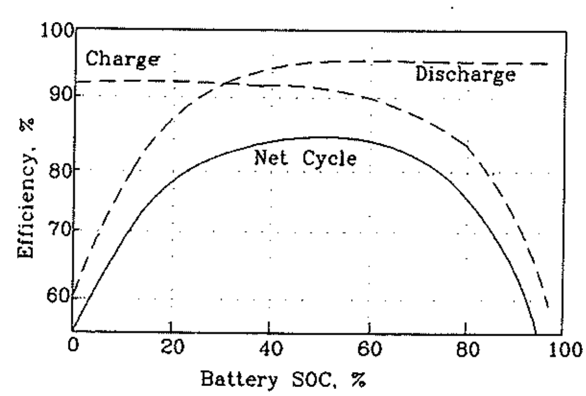


Fig.16 battery efficiency versus state-of-charge

Acknowledgment

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Analysis of Electric Vehicle Utilization on Global CO_2 Emission Levels

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ABSTRACT

The increase of CO_2 emissions in the last quarter of century has risen at an alarming rate. In the U.S.A. alone the CO_2 emissions have increased by 50%, from 1 billion tons of carbon to 1.55 billion tons. The transportation industry contributes currently (1991 figures) 24.7% of the total emissions from the United States. Transportation utilization has grown faster, however, but more efficient vehicles allow for more travel without increasing the CO_2 proportionally. The advancements made in the 1980s have reduced emissions by 21 million tons of CO_2 per year on average.

Electric Vehicles have been a proposed method of reducing the CO_2 emissions due to transportation. Electric vehicles produce no emissions while driving, making them ideal candidates for heavily polluted and concentrated areas such as urban locations. However, it is debatable if electric vehicles are feasible on the global scale of CO_2 reduction. This study compares the amount of emissions produced charging the electric vehicles with the amount of emissions produced by operating a conventional vehicle for equivalent usage. Conclusions are drawn about the advantages and the emissions reductions (if any) that are found by electric vehicle usage.

INTRODUCTION

This portion of the paper will focus of the ratio of the total energy usage (and thus CO_2 production) and transportation energy consumption in the United States. Because the U.S. is globally the foremost producer of emissions from transportation, such is a study is crucial to initial understanding of the problem. The transportation industry in the U.S. has now consumes over 27% of the total energy in 1991, and that number has most certainly increased since then, vs. less than 25% in 1970. With transportation consuming a larger share of the energy budget, any changes in CO_2 production due to technological advancements such as electric vehicles will have a greater impact.

With multiple other countries approaching the CO_2 emission levels of the United States such as Canada, France, Germany, Italy and UK the impact of electric and/or advanced vehicle technology can be extended from the U.S. study. Large developed countries such as the former Soviet Union republics, the People's Republic of China, and India represent a very large share of the next century's transportation energy budget as well.

TRENDS OF U.S. CO_2 EMISSIONS

The total CO_2 emissions from the United States alone have increased by half from 1 billion tons of carbon in 1970 to 1.55 billion tons in 1992. This increase represents multiple sources, including electric plants, transportation, and industrial sources. This increase reflects a total energy consumption increase of about 1% per year between 1970 to 1991. The transportation industry energy use increased at a rate of 1.6% per year in the time span, faster than the average total energy annual growth rate. This is reflected in that the transportation industry gained a greater share of the transportation energy budget from 24.5% in 1970 to 27.3% in 1991. In 1993, the U.S. transportation energy reached 22.8 quadrillion Btu.

A direct correlation can be drawn between energy production and CO_2 emissions. CO_2 is a unique greenhouse gas because it has a stable physical relationship to energy use. Emissions such as NOx and Sulfates can be reduced by combustion techniques and exhaust technologies such as catalytic converters. However, fossil fuels contain a fixed amount of carbon, thus releasing a fixed amount of CO_2 upon utilization. Thus, CO_2 emissions trends closely follow energy trends (this concept is covered in more detail with Table 3 later on). A note must be made that hydroelectric and nuclear power are exceptions.

Between 1970 and 1991 the U.S. emissions from energy use increased with an annual growth rate of 0.8%, from 5,554 million tons (mmt) to 6566 mmt in 1991. During the same period the CO_2 emissions from transportation rose at a growth rate of 1.67%, rising from 1146 mmt to 1624 mmt. Thus, the total amount of transportation emissions rose from 20.6% to 24.7% [1].

Table 1. Increase of Energy Use by the Transportation Industry

	1970	1991	Δ	% Change
Total CO_2 Emissions	5554 mmt	6566 mmt	+1012 mmt	+0.80%
Transportation CO_2	1146 mmt	1624 mmt	+478 mmt	+1.67%
% Share of Emissions	20.6%	24.7%	+4.1%	
% Share of Energy	24.5%	27.3%	+2.8%	

Inspecting Table 1, the most striking feature is that the transportation industry claimed 27.3% of the energy and only contributed 24.7% of the emissions. This is primarily due to the fact that the electric utility industry uses coal, which is significantly higher in carbon content than the fuels used in transportation. Note must be taken on this fact when considering electric vehicles because any emissions that are avoided by using an electric vehicle is deferred to the coal-burning electric utilities used to charge the vehicle's battery.

Even though overall energy production produced more CO_2 than the transportation energy production, non-CO_2 producing power generation such as hydroelectric or nuclear has increased in the United States from 16.9% to 28.5% [2]. Thus with the evaluation of more statistics, it can be proven that the CO_2 emissions per unit energy produced as a whole has declined. Diesel fuel has increased popularity as a transportation fuel from 18.8% in 1970 to 23.69% in 1991 [3]. Since diesel fuel contains more carbon per unit Btu, there was an increase of CO_2 production per unit of transportation energy use.

TRANSPORTATION GROWTH TRENDS

Personal and freight transportation has increased tremendously in the past two decades due to several factors. The United States has maintained an almost constant population growth rate of +1% per year over the last decades, from 205 million in 1970 to 252.2 million in 1991 (18.7% increase). During the same amount of time, personal transportation has increased from 2245 billion passenger-miles (pm) to 3998 billion at a growth rate of 2.8% per year, a 43.84% increase. An interesting fact is that light truck personal transportation has increased at a rate of 5.9% per year, indicating the popularity of the pickup truck for commuter applications [4]. Taking into account the population growth, the per capita increase of commuter miles has been from 10,950 miles per capita to 15,822 miles over the same period of time.

Table 2. Passenger Transportation Trends (U.S.)

	1970	1991	Δ	%
Population	$205x10^6$	$252.2x10^6$	$47.2x10^6$	+18.7%
U.S. GNP	$\$2702x10^9$	$\$4528x10^9$	$\$1826x10^9$	+40.3%
Miles per Capita	10950	15822	4872	+30.8%
Total pm	$2245x10^9$	$3998x10^9$	$1753x10^9$	+43.8%

It is obvious that from this table the increase in transportation is not because there are more people (18.7% population growth vs. 43.8% increase of miles driven). However, the increase of transportation seems to mirror the increase of GNP more closely (40.3% GNP growth correlates to a 43.8% increase of miles driven). Thus two contributing factors of increasing transportation energy usage can be attributed to population growth and economic growth.

Freight transportation increased at a more rapid rate than personal transportation, from 2467 billion ton miles (tm) to 3689 billion tm, a 49.5% increase at a rate of 1.9% per year. It should be noted that air freight now handles 8.86 billion tm, growing at a rate of 5.3% per year. In comparison, truck freight handles 1150 billion tm per year.

IMPROVEMENTS IN TRANSPORTATION EFFICIENCY

Technological advancements in the transportation industry have resulted in a variety of efficiency improvements. Many of these improvements are driven by availability of advanced technology that increases marketable performance while increasing efficiency. Other improvements are brought on by government, public opinion, or legislation. More details on these factors will be brought up in section 3. The Bureau of Transportation Statistics ranks several different types of vehicles based upon their average energy efficiency, expressed as Btu per passenger-mile. It must be pointed out that this statistic reflects how much energy is required to transport one person per mile. A crowded city bus scores high marks in this category compared to a pickup truck with one commuter driver, because the city bus carries more passengers per unit energy than the commuter vehicle (Figure 1):

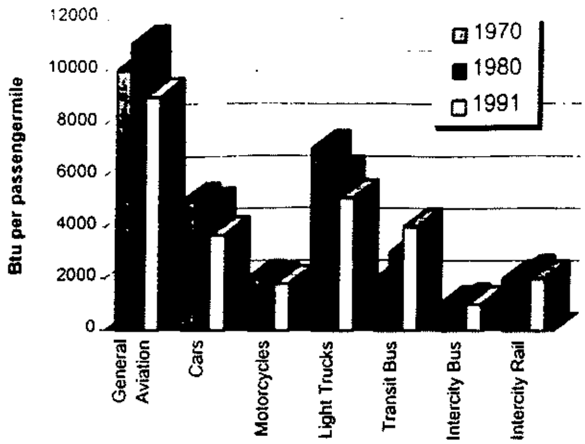

Figure 1. Btu per Passenger-Mile [5]

An interesting note is that the transit bus passenger-mile energy efficiency has decreased. This can be attributed to a general propensity to travel in personal commuter vehicles rather than in public transit busses.

CHANGES IN TRANSPORTATION ENERGY USAGE

The preceding sections detailed the increase of the transportation sector and its attributing causes, which are important to realize if this analysis is to be applied on a global scale in order to make observations about future trends. Next, a scientific and statistical analysis needs to be done to compute the weights and effects of the energy usage in the transportation sector. The beginning of this study is to examine the carbon content of various fossil fuels and rank them accordingly:

Table 3. Common fossil fuels and carbon content [6]

Fuel	Grams of CO_2/gJ	Tons of CO_2/billion Btu
Hard Coal	94.2	99.2
Ship Oil	78.1	82.4
Diesel	73.8	77.9
Aviation Gas	71.2	75.1
Gasoline	71.2	75.1
Jet Aviation Fuel	70.8	74.7
Rail Diesel	70.0	73.9
Natural Gas	56.1	59.2

Conversion was made based on 1 Btu = 1055 joules. All hydrocarbon bound carbon is assumed to be eventually converted to CO_2. True combustion does not result in 100% conversion because incomplete combustion can result in CO (which is rapidly converted to CO_2 in the atmosphere) and CH_4, an important greenhouse gas. It is assumed that the amount of CO_2 produced by incomplete combustion is not significant, even more so considering the advanced engine technologies available presently.

The amount of CO_2 produced by combustion of each fuel is governed a fixed physical relationship based on the carbon content per Btu yield. When undergoing incomplete combustion, utilization of fossil fuels can result in emission of long-chain hydrocarbons, which break down into methane and CO_2. Thus the actual 'greenhouse' emission is not only based on the carbon content but combustion method. The combustion technology combined with the exhaust technology also can result in a wide range of NOx and sulfate emissions.

Next, a table was constructed using the values of Table 3 to compute the actual CO_2 production resulting from each factor (Table 4):

Table 4. Breakdown of driving forces in terms of CO_2 emissions [1]

Increase of CO_2 production for each decade	1970-1980	1980-1991
	mmts CO_2	Mmts CO_2
Efficiency	-54.33	-177.80
Transportation Mode	37.96	1.89
Economic Growth (GDP)	79.80	191.13
Population Growth	87.01	100.21
Other Interactions	-20.73	-37.41
Changes from Passenger Transportation	**129.70**	**78.02**

Increases of Btu use for each decade	1970-1980	1980-1991
	Trillion Btu	Trillion Btu
Efficiency	-725.98	-2369.35
Transportation Mode	508.20	27.91
Economic Growth (GDP)	1062.76	2545.30
Population Growth	1158.78	1334.55
Other Interactions	-277.06	-498.01
Changes from Passenger Transportation	**2333.37**	**1040.41**

During the period of 1970-1980 the transportation sector increased CO_2 production by 315.75 million metric tons (mmt) per year. Because of primarily efficiency gains in personal automotive technology, CO_2 production was reduced to average 162.223 mmt per year. This is key in the study of electric vehicles because for an electric vehicle to compete with standard combustion types there must be a clear advantage. With vehicle technology increasing efficiency and reducing emissions at the current pace, it will remain to be seen if EVs will hold a clear advantage.

Notice again, it is indicated that the economic growth as seen with the GDP contributes largely to the increased use of passenger transportation. Population growth (thus more individuals owning vehicles or using public transportation systems) was the second largest contributing cause.

CONCLUSIONS ABOUT CO_2 PRODUCTION IN THE TRANSPORTATION SECTOR

The most significant observations obtained in this section are listed below:

- Passenger transportation has increased at a rate of 2.8% per year whereas the population increase is only 1.0% per year.
- Per capita miles traveled per year has increased 30.9% between 1970 and 1991.
- Transportation CO_2 emissions only accounted for 20.6% of the total emissions in 1970. In 1991 that number increased by 4.1% to 24.7%.
- Transportation consumed 24.5% of the total energy consumed in the United States in 1970 and 27.3% of the total energy in 1991, a difference of 2.8%.

Passenger transportation technological advancements have saved 227 trillion Btu of energy and 21 million tons of CO_2 per year on average from 1980 to 1991.

TRENDS OF GLOBAL CO_2 PRODUCTION

As automotive technology continues to advance and transportation becomes more available, the economy and society is dictating people to travel more now than ever before. This is not only true for the United States but also in almost every country in the world. Considering that transportation accounted for 24.7% of total CO_2 emissions in the U.S., other countries are facing similar statistics. Table 5 lists several major transportation-related CO_2 contributing countries. Notice that some omissions include China, India, and the former Soviet Union republics due to lack of available data.

Table 5. Some major transportation-related CO_2 contributing countries [7]

	Emissions (mmt/year)		
	CO_2	HC	NOx
Canada	9928	2100	1942
USA	76000	22800	20300
Japan	*5013*	*1503*	1339
Austria	1126	251	211
Belgium	839	*356*	317
Denmark	602	106	241
Finland	660	112	284
France	5200	2185	2567
Germany	8960	1860	3090
Greece	695	82	196
Ireland	497	62	71
Italy	4036	496	1550
Netherlands	1368	452	500
Norway	632	158	125
Portugal	533	91	248
Spain	3780	739	778
Sweden	1250	410	328
Switzerland	711	311	196
Turkey	3707	201	380
UK	5127	1954	1932

GOVERNMENT AND PUBLIC INITIATIVES

Government policy toward CO_2 regulation, especially in the transportation sector, has oscillated dramatically in the last decade. Early optimism about the technology associated with electric vehicles resulted in numerous 'mandates' that a certain percent of the automobile fleet in particular countries be electric. As electric vehicles became a reality and their poor performance, range and cost became obvious these mandates were delayed, decreased, or in some cases, removed altogether.

The low oil prices in the 1980s have also contributed to the loss of interest in electric vehicles. The economy in the 1970s drove technology to search for alternative and possibly cheaper transportation that was not dependent on an imported fuel that looked like was in a shortage. A slight resurgence of research is now underway to develop vehicle technology to reduce urban pollution.

Governments in USA, Japan and some European countries have developed ways to encourage further research [8]. Some particular government regulations regarding CO_2 vehicle emissions include (1993 data).

Some notable U.S. trends include:

- Some U.S. state governments (most notably California due to severe urban pollution) have required a sales percentage of ultra low emission vehicles (ULEVs) or electric vehicles. Many local governments have developed incentives (e.g., tax) for fleets and individuals to operate ULEVs or EVs.
- The U.S. federal government aggressively funds hybrid electric (HEV) and electric vehicle research at both national laboratories and independent research facilities.

Japan has integrated a very aggressive plan called the 'Electric Vehicle Market Expansion Program' that specifically targets government and private fleets:

- Government fleet vehicles of Tokyo and Osaka have been targeted to migrate to electric vehicle use, and private enterprises offered financial incentives to switch to EVs.

- Financial incentives and government subsidies are offered to private utility companies and delivery firms to migrate to EVs.
- Future incentives are planned for individual automobile owners. In 1993, these incentives were only 4% of the cost of an electric vehicle, which is not a significant amount compared to how much more expensive an EV is in comparison to a standard automobile.

All major automotive industries in Europe now have electric vehicle programs, many of them offering electric versions of existing models. In 1993, there were in excess of 25,000 EVs operating in Europe, primarily in UK.

- UK, Germany and Denmark impose a vehicle tax based on vehicle weight, which discourages the use of EVs. Temporary tax measures have been put in place to avoid this problem.
- Many European countries tax vehicles on engine size, which is EV operators avoid.
- The European Community has determined that based upon current EV development, EVs will have the capability of reducing urban pollution by 20-30% [9].
- The German government aggressively funds EV development and offers tax exemption for EV operators.
- In France 90% of electricity is produced by nuclear power or hydroelectric thus any use of electric vehicles will yield a major reduction of CO_2 emissions. Local governments are offered substantial subsidies to migrate to EV use.

An optimistic forecast [10] from the European Community has deterimined that the combined markets for electric vehicles will reach 2.1 million vehicles by 2010:

Table 6. Forecast of electric vehicle sales

		2000	2005	2010
USA	Total	16,860,000	17,290,000	17,360,000
	Evs	163,500	721,500	1,007,300
	ICE	16,696,500	16,568,500	16,352,700
Japan	Total	7,560,000	7,590,000	7,630,000
	Evs	73,500	266,500	485,500
	ICE	7,486,500	7,323,500	7,144,500
Europe	Total	17,410,000	18,110,000	18,640,000
	Evs	37,800	222,800	612,200
	ICE	17,372,200	17,887,200	18,027,800

This table is surprising in that it predicts electric vehicle production in the U.S. will increase from 1,000 vehicles (approximately current rate) to 163,500 in the year 2000. The developers of this table probably were considering the California air restrictions board legislation, which required a certain percentage of vehicles sold in California to be electric. This legislation has been reduced and some measures have even been removed. Thus the year 2000 estimate for electric vehicles sales is not probable. However, the Japanese market has indicated that it is moving toward electric vehicles at a rapid pace.

IMPACT OF ELECTRIC VEHICLES ON CURRENT CO_2 EMISSION LEVELS

The bulk of the data contained in this section is derived from a joint effort study done by the U.S. Department of Energy (DoE) and the Electric Power Research Institute (EPRI) [11]. This study concentrated on *four basic scenarios of EV market penetration compared to two basic scenarios of gasoline vehicle development.* The study forecasts automotive emissions for each of the scenarios and generates emissions savings potentials. The goal of the analysis is to discover the benefit of displacing fossil fuel consumption from individual automobiles to centralized electric generation facilities.

It should be noted emissions from EV battery recycling could be a potential concern. About 85% of used automotive batteries are collected and of those 95% are recycled. The process used to recycle batteries generally produces about 1g of NOx and 3.7g of CO_2 per ordinary automobile battery [12]. Assuming an EV battery on average is 120 times the size of the ordinary automobile battery (420 W-hr vs. 50 KW-hr capacity), an EV battery would require 120g of NOx and 450g of CO_2 per battery recycled. Considering the battery would have a usable lifetime of 400 charging cycles at 80 miles per charge (30,000+ mile battery lifetime, optimistic), the recharging emissions of 0.0001 g/mile of NOx and 0.014 g/mile of CO_2 would have to be entered into the total emissions computations. These numbers correspond to about 1% of that an ordinary automobile produces per mile.

MODEL SCENERIOS

Emission levels from six scenarios were computed for comparison purposes [11]:

a. Electric and Hybrid Vehicle (EHV) are assumed to be high efficiency and electric utilities are assumed to have average emission rates. This is the best case scenario.
b. EVH are assumed to have marginal efficiency and electric utilities to have average emission rates.
c. EVH are assumed to have high efficiency and electric utilities to have marginal emissions rates.
d. EVH are assumed to have marginal efficiency and electric utilities to have marginal emission rates. This is the worst case scenario for EVHs.
e. Conventional Vehicles (CV) are assumed to be low efficiency. This is the worst case control scenario with (no EVHs and low efficiency CVs).
f. Conventional Vehicles are assumed to have high efficiency. Good case control scenario.

The first four scenarios apply to EVHs and the last two are control runs with only ordinary automobiles. Thus conclusions can be drawn when comparing an EVH scenario with a control run. Emissions considered in each case are six pollutants: CO_2, SO_2, CO, VOC (incomplete combustion hydrocarbons), and NOx. It should be noted that SO_2 and NOx are precursors to acid rain, SO_2 creates an localized aerosol that combats greenhouse warming and CO_2 and NOx are greenhouse gasses. The VOCs will decompose eventually into CO_2 or CH_4, which both contributes to greenhouse warming.

Conventional vehicles were modeled assuming that existing vehicles operated at the fuel efficiencies specified on Table 7.1-7.3 for the two control scenarios. The reason behind the decreasing mpg trend in light trucks is due to the increasing popularity of larger and more powerful engine options available. The Moblie4 computer model [13] was used to compute the gasoline vehicle emissions and *the CO_2 production was based on the physical equations of carbon content of fuel, fuel efficiency, CO_2 produced during fuel extraction, refinery operation and distribution.*

Table 7.1. Average vehicle fuel economy (mpg) 'worst case scenario

Year	Automobiles	Light Trucks
1995	22.2	17.0
2000	22.3	16.8
2005	22.6	16.8
2010	22.9	16.9

Table 7.2. Average vehicle fuel economy (mpg) 'good scenario'

Year	Automobiles	Light Trucks
1995	27.8	17.0
2000	27.8	16.8
2005	27.8	16.8
2010	27.8	16.9

Table 4.3. Gasoline/Diesel percent market share for Light Trucks

Year	Gasoline	Diesel
1995	90%	10%
2000	76%	24%
2005	63%	37%
2010	58%	42%

Referring back to Table 3 and assuming that 98% of the carbon content of gasoline is burned in each combustion cycle and 99% conversion of Diesel fuel, the mass of CO_2 produced per gallon of fuel can be computed:

(mass of carbon per gallon) x conversion percent x 44/12 = mass CO_2

Grams per gallon are then converted into grams per mile using the fuel efficiency Tables 7.1-7.3.

The electric vehicle scenarios are divided into two subcategories, the high and low efficiency EVs. Low efficiency EVs require more frequent changing for equivalent miles traveled, thus the demands from the electric utilities are increased. Examining the loads on electric utilities,

Table 8. High and low EV efficiency cases and total annual charging electricity use (GWhw)

	2000	2005	2010
Low Case	3,137	25,332	80,096
High Case	1,511	10,169	26,843

Electric utility plants are modeled by two factors: fuel types and emissions standards. The average and marginal emission calculations were performed using the fuel types (and thus average emissions content) and 1990 CAAA regulations on SO_2 and Nox. Table 9 indicates the breakdown of the different fuel usages.

Table 9. Percent use of different fuel types

Coal	Oil	Gas	Nuclear	Alternative
57.4%	4.43%	6.8%	21.4%	1%

The alternative power utilities include hydroelectric and wind power most (>50%) of this type of power generation is found in the western U.S. Notice that nuclear holds a large portion of power generation in the U.S., but it is not nearly as comparable to France's nuclear efforts of reaching well above 75% of all power is non-fossil fuel. In cases where nuclear power is available, CO_2 production for the use of electric vehicles is significantly reduced.

SCENERIO RESULTS

Because the primary purpose of this review to study the impact of specifically greenhouse gasses, only the CO_2 emission results will be presented. Table 10 shows the model results for CO_2 for each of the six scenarios.

Table 10. CO_2 Emissions in mmt/year for each scenario of EV utilization in the U.S.

	Scenario a	Scenario b	Scenario c
1995	5,197	6,822	6,896
2000	948,572	1,967,166	1,260,386
2005	5,735,672	14,265,967	8,477,902
2010	13,406,344	39,950,717	22,351,069

	Scenario d	Scenario e	Scenario f
1995	9,052	9,757	9,757
2000	2,615,800	2,356,751	2,228,850
2005	21,108,398	19,581,189	17,842,184
2010	66,665,956	64,452,227	54,187,308

There are several pieces of important *general* information to obtain from this table:

- Highly efficient EHVs combined with strict electric utility regulation (Scenario a) can reduce the CO_2 emissions due to transportation over 20%. Because transportation currently is responsible for 24.7% of total CO_2 emissions, it would be a reduction of 5.5% of total U.S. CO_2 emissions.
- Even the worst case scenario (case e) is better than poorly efficient EVHs and marginal utility plants (case d)!
- Conventional vehicles can compete within 25% with poorly efficient EVHs with good efficiency power utilities.

The result of this study indicates that if EVHs are to become (1) a reality and (2) a solution to CO_2 emissions then they must be highly efficient with efficient power generation utility infrastructure. Nuclear energy has a great advantage in this type of study, as does wind energy and hydroelectric systems. However, these types of production are either politically difficult, economically unfeasible, or produce emissions or effluents of their own.

CONCLUSION

There are several important realizations to be made about this study:

- Transportation in the U.S. is increasing at a rapid pace. Population has only increased at a rate of 1.0% per year but total miles traveled has increased by 2.8% per year. Per capita miles traveled has increased by 30.9% since 1970.
- Transportation related CO_2 emissions are responsible for 24.7% of the total CO_2 emissions in the U.S., yet transportation is responsible for 27.3% of the energy usage.
- Conventional gasoline vehicles will continue to compete in CO_2 emissions unless electric or hybrid vehicles and electric power utilities increase efficiency.
- Conventional gasoline vehicles compete favorably to marginally efficient electric vehicles when the electric utility emissions are factored in.
- Conventional vehicles will favorably compete economically unless a technological breakthroughs occurs to lower cost or governments employ financial subsidies initiatives.
- Several governments are funding and/or sponsoring major research efforts for efficient electric or hybrid vehicle technologies.
- Several governments are offering financial incentives or federal subsidies for automobile users to migrate to electric vehicles.

Comparing scenario a to scenario e it can seen that total U.S. CO_2 emissions can be reduced by 5.5% with the use of electric vehicles and efficient power utilities. This is a significant beginning but several things must be considered:

- Advanced electric utilities need to be developed before electric vehicles will become truly useful. At today's present technologies, there is not enough emissions advantage to use electric vehicles because they still need to be charged from emissions-generating power plants.
- Electric vehicle technology today is expensive and battery lifetime is short (~30,000 miles). Electric vehicle technology needs to expand beyond the limitations of electrochemical energy storage before high enough efficiency is to be realized.
- Developing countries and countries such as China, India, and the former Soviet Union republics have to be considered because their share of CO_2 emissions are going to increase considerably. If the U.S. switches to optimal EV usage, the global effect will be small in comparison to the emissions created from other countries. The technology must be universally applied for significant reductions.

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An Open Architecture System for Simulation of Electric and Hybrid Electric Vehicles

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ABSTRACT - There has been increased interest by the automobile industry to design zero and near-zero emission automobiles due to the regulations that have been adopted by several states in the U.S. In recent years, computer simulation has provided lower cost and less-time intensive analysis of new design options as compared to the past practice of hardware prototypes. This paper discusses a computer simulation tool, V-Elph, which has been developed to facilitate the design and analysis of electric and hybrid vehicles. V-Elph is composed of detailed models of four major types of components: electric motors, internal combustion engines, batteries, and support components which can be integrated to simulate drive trains having all electric, series hybrid, and parallel hybrid configurations.

The system and component models in V-Elph were developed in a modular manner with standardized interfaces for easy integration of components. A hierarchical, layered design philosophy was adopted for programming V-Elph so that users with different levels of expertise and interests could utilize the tool. It was written in the Matlab/Simulink graphical simulation language and is portable to most computer platforms.

This paper discusses the design methodology, features, and component and system-level functions of V-Elph. The design steps for a series hybrid vehicle are illustrated and simulation results for a sedan vehicle are discussed.

INTRODUCTION

Presently, only electric and low-emissions hybrid vehicles can meet the criteria outlined in the California Air Regulatory Board (CARB) regulations which require a progressively increasing percentage of automobiles to be ultra-low or zero emissions beginning in the year 1998 [1]. Though purely electric vehicles are a promising technology for the long range goal of energy efficiency and reduced atmospheric pollution, their limited range and lack of supporting infrastructure may hinder their public acceptance [2]. Hybrid vehicles offer the promise of higher energy efficiency and reduced emissions when compared with conventional automobiles, but they can also be designed to overcome the range limitations inherent in a purely electric automobile by utilizing two distinct energy sources to provide energy for propulsion. With hybrid vehicles, energy is stored as a petroleum fuel and in an electrical storage device such as a battery pack and is then converted to mechanical energy by an internal combustion engine (ICE) and electric motor, respectively. The electric motor is used for peaking power demands while the ICE provides base power demand. Though many different arrangements of power sources and converters are possible in a hybrid power plant, the two generally accepted classifications are series and parallel [3].

Computer modeling and simulation can be used to reduce the expense and length of the design cycle of hybrid vehicles by testing configurations and energy management strategies before prototype construction begins. Interest in hybrid vehicle simulation began to pick up in the 1970's along side the development of several prototypes which were used to collect a considerable amount of test data on the performance of hybrid drive trains [4]. Also studies have been conducted to study the hybrid electric vehicle concepts [5-7]. Several computer programs have since been developed to describe the operation of hybrid electric power trains, including: Simple Electric Vehicle Simulation (SIMPLEV) from the DOE's Idaho National Laboratory [8], MARVEL from Argonne National Laboratory [9], CarSim from AeroVironment Inc., JANUS from Durham University [10], and ADVISOR from the DOE's National Renewable Energy Laboratory [11]. A previous simulation model, ELPH, developed at Texas A&M University was used to study the viability of an electrically-peaking control scheme and to determine the applicability of computer modeling to hybrid vehicle design [12] but was essentially limited to a single vehicle architecture. Other work conducted by the hybrid vehicle design team at Texas A&M University is reported in [13-17].

V-Elph [18-19] is a system level modeling, simulation and analysis package developed at Texas A&M University using Matlab/Simulink [20] to study issues related to electric vehicle (EV) and hybrid electric vehicle (HEV) design such as component sizing, energy efficiency, fuel economy, and vehicle emissions. The package uses an open architecture so that any type of hybrid electric, electric, or conventional internal combustion engine vehicle configuration can be designed and studied. The framework of the package is general enough that additional features, such as estimates of lifetime vehicle cost or other items of interest can be added without changing the core computer code. It extends the capabilities of previous modeling and simulation efforts by facilitating in-depth studies of power plant configurations, component sizing, energy management strategies, and the optimization of important component parameters for any type of hybrid or electric configuration. Visual programming techniques are used which allow the user to quickly change architectures, parameters, and to view output data graphically. It also includes detailed models of electric motors, internal combustion engines, batteries, and vehicle dynamics developed at Texas A&M University.

In this paper the design methodology, various features, and functions of the V-Elph simulation package are discussed. A series hybrid vehicle is designed to illustrate how the V-Elph package is used to design and study component and control technologies for a vehicle drive train. However, any other propulsion system architecture such as parallel hybrid, electric vehicle, and conventional ICE can be configured and simulated with similar ease.

DESIGN METHODOLOGY

A. Abstraction Levels

The V-Elph software package is organized in a hierarchical and modular manner. Five conceptual levels of abstraction are used in V-Elph to organize a system model and to represent the specific functional levels of a vehicle drive train [18]. The levels are: (1) vehicle control level, (2) power plant control level, (3) configuration level, (4) component level, and (5) coupling level. Defining these levels introduces a hierarchical structure where each level of abstraction encapsulates the functionality of its subsystems while maintaining a common interface to higher levels. Each level of abstraction also isolates a different part of the vehicle design process, allowing systematic analysis.

The highest level of abstraction in the model, the vehicle control level, describes the driver interactions with the vehicle and the environment in which the vehicle operates. It is at this level that the expectations of the driver such as acceleration performance, range, and grade are defined by altering the drive-cycle and/or the driver model. The vehicle control layer separates the actions of the driver from the modeling of the hybrid vehicle plant so that the driver model can be changed without affecting the implementation of the power plant. The vehicle control level receives speed information in km/h and produces a desired torque command which is sent to a power plant controller. A driver can be modeled by matching a reference speed, modeling a driver's behavior through a predetermined course, or by using human input to control vehicle speed.

The power plant control level defines how the components are controlled to meet the torque command produced by the vehicle control level. The implementation of this level is contained within a power plant controller block. By altering the algorithms in the power plant controller block, the vehicle's energy management strategy can be changed for a particular power plant configuration. The power plant controller produces the appropriate signals to be sent to the drive train components to implement the desired control scheme such as ICE throttle command, electric machine torque command, clutch signals, and gear selection signals. The inputs and outputs from the power plant controller vary depending on the information needed to implement a particular control scheme.

The configuration level is not an actual block, but refers to how the components in a drive train interact because of their sizing and how they are arranged. Altering the configuration allows the construction of both series and parallel hybrids and changes the fundamental attributes of a hybrid power plant by changing the components' functional roles; the ICE in a series hybrid plays no direct role in providing torque to the wheels while the ICE in a parallel design is an integral part of propulsion. Sizing components differently within the same arrangement can also drastically change the components' functional roles since the amount of power that they can contribute changes. In a parallel configuration if the electric motor is large and the size of the ICE is small, an ICE based design where the electric motor assists during acceleration results.

The component level describes the local dynamics and control of individual components. The implementation of this level is contained within each of the component blocks in the power plant.

The coupling level defines the interface used to connect components of a certain type. A lumped parameter coupling scheme was chosen to implement V-Elph. All of the components are assumed to be rigidly connected and the component torque and inertia are referred to a single point to calculate the system dynamics. The system acceleration is calculated by summing all of the torques and dividing by the total inertia at a single reference point. The speed of the system is then determined by numerically integrating the acceleration, and this value is passed back to the component models to determine the torque at the next time-step. This scheme was selected because it does not require a small integration time step to capture coupling dynamics and it eliminates the algebraic loops inherently created by the looping of non-integrated signals in the distributed parameter scheme.

B. Buses

The interfaces for electrical and mechanical components are a direct result of implementing the coupling methods described above. Data bussing, a concept borrowed from the computer industry, was used to implement the two-way lumped parameter passing scheme in the model. The concept of a data bus revolves around developing common interfacing specifications which allow different devices to be connected to a common bus regardless of their internal function or implementation. As long as a component's inputs and outputs comply with the interface definition and care is taken to ensure that the model operates within its intended boundaries, it can be attached to the data bus.

The electrical bus concept for the V-Elph is defined as shown in Fig. 1. The electrical bus supplies a voltage to all of the electrical components and then the components determine their current flow based on that voltage. The amount of current drawn or supplied by each electrical energy converter is then passed back to the bus to calculate the voltage at the next time step. The electrical bus usually consists of a storage device such as a battery pack or an ultra-capacitor, which stores electrical energy until it is needed by the electrical components in the systems.

The mechanical bus concept for the V-Elph is defined as shown in fig. 2. The component torque and inertia are combined into a vector to be passed to the rest of the system using a single output line. The friction term is incorporated inside each individual component block since the speed information is available to the component.

C. Control Paradigm

To separate the control of the overall system from the control of each individual component, the master/local control paradigm, shown in Fig. 3, was adopted. The master controller (the power-plant control level) determines how to distribute the driver torque request among the various energy converters in the hybrid power-plant and creates the control signals to implement the desired energy management strategy. The local controller adjusts the component model parameters to meet the demands of the master controller within the component's bounds of operation and then sends information on the status of the component back to the master controller.

The master/local control paradigm helps to encapsulate the inner workings of a component model, limiting outside access through the common interface specification. For example, it separates the functional role of a component as a torque producer from a model's actual implementation and control, allowing a variety of different engines and electric machines to be used without changing the common interface to the rest of the system. The inputs which drive a dc motor and an induction motor are quite different, but by using the master/local control paradigm, which depends on the functional role of the components and not their implementation, a common interface for an electric machine is used for both the dc motor and the induction motor.

D. User Levels

Several levels of depth are available in V-Elph to allow users to take advantage of the features that interest them. At the most basic level, a user can run simulation studies by selecting one the electric vehicles, series or parallel hybrid vehicles, or conventional vehicles provided and display the results using the graphical plotting tools. In addition to being able to change the drive cycle and the environmental conditions under which the vehicle operates, the user can switch components in and out of a model to try different types of engines, motors, and batteries models. The user can also change vehicle characteristics such as size and weight, gear ratios, and the size of the components that make up the drive train.

An intermediate user can create his/her own vehicle configurations using a blank vehicle template and the V-Elph component library. Components can be isolated to run parameter sweeps to create performance maps to assist in component sizing and selection. Given a set of system performance criteria, the performance maps of the components can be used to develop a suitable vehicle design. Finally, advanced users can pursue sophisticated design objectives such as the creation of entirely new component models and the optimization of a power plant by creating add-on features that are compatible with the modeling system interface.

PACKAGE FEATURES

A. Main Menu

The main menu as shown in Fig. 4 provides several options for the user.

- V-Elph – provides information about the V-Elph software and commands to exit the software
- Models – provides facilities for building and sizing electric and hybrid vehicle drivetrains
- Simulation – provides facilities for creating and managing simulation data
- Analysis – provides data analysis tools to organize and plot the information generated during V-Elph simulation
- Help – provides a description of V-Elph.
-

The pull-down entries under each option are stated below.

Models

- Load Vehicle
- Load Component
- Parameter Sweep

Analysis

- Plotter
- Quick Plots
- Data Summary

Simulation

- Setup
- Load Simulation Data
- Save Simulation Data
- Clear Current Data

B. Analysis Tools

There are three major types of analysis tools: ***Plotter***, ***Quick Plots***, and ***Data Summary***. The selection of the ***Plotting Tool*** icon in the *Analysis* menu brings up the graphical plotter as shown in fig. 5. The user selects the x-axis variable from a menu list of variables generated from the current Matlab workspace. Further the user selects the y-axis from a button list of variables generated from the current Matlab workspace. The user can also type labels for the x-axis, y-axis and title. Then the user presses the *Plot* button to generate plots of the y-axis variables versus the x-axis variable.

The selection of the *Quick Plots* icon in the *Analysis* menu allows the user to quickly generate several plots. *Quick plot* allows the user to view vital simulation information instantly. When selected, it produces a drop down menu which has the following fields representing parameters related to the major components: *Battery SoC, Battery Voltage, Battery Current, EM Current, EM Torque, Torque* (EM Torque, ICE Torque*), ICE Fuel Consumption , ICE Torque, ICE Emissions* (CO, HC, NOX). The user can plot any of the above variables provided they have been generated during the simulation. The selected variable is then plotted versus time and is labeled accordingly. This tool is useful when running many studies to observe how changes in a parameter effects various outputs.

Another analysis feature of the V-Elph package is the ability to compile the information from a simulation run into a summary of results. To view the simulation results in a summary form, the *Data Summary* icon is selected in the *Analysis* menu, cumulative variables such as total emissions, fuel consumption are calculated and displayed in the data summary output as shown in fig. 6.

COMPONENT LEVEL

A. Interfaces

Data flow within a general component model is shown in fig. 7, where signal connections are used to send information to and from the power plant controller and the power connections represent the physical coupling between components which provide a path for the transfer of energy. The ports for the signal connections are separated from the power connections since the control of each component might be different while the electrical and mechanical coupling mechanisms are the same for all components.

Strict interface definitions are defined for each type of component so that various types of models, e.g. empirical and detailed models, for the same type of component can be included in the V-Elph library of components. The general interface for components utilized in V-Elph is shown in fig. 8. More specifically, the interface for a battery model is shown in fig. 9. All battery models in V-Elph have the same component inputs and outputs and any new model developed by a user must conform to that standard.

B. Library

The component library, as shown in fig. 10, is composed of models of three major components: electric motors, internal combustion engines (ICE), and batteries. Also the library contains models of support components such as vehicle dynamics, controllers, transmissions, ambient conditions, and drive cycles. The speed at which the simulation executes is highly dependent on the complexity of the component models selected. The various detailed component models currently utilized in the V-Elph package were developed by members of the ELPH research team at Texas A&M University.

C. Design

A user can design new components or utilize existing components to build a hybrid, electric, or conventional drive train system. The component designer should have a detailed understanding of the component technology and can develop a model using empirical data or mathematical equations. The models can be written in Matlab, 'C' programming language, or imported into the package as an executable file.

D. Analysis

A powerful feature of the V-Elph system is the ability to create performance maps of components to help visualize their response characteristics. This feature, a parameter sweep workbench as shown in fig. 11, allows the analysis of the performance of a component over its operating range. Typically one parameter is varied and all other parameters are held constant. The *Constant Parameter* block is connected to the input that will be held constant through a particular sweep and the *Sweep Parameter* block is connected to the input that will be varied during a particular sweep. When the *Setup Sweep* button is selected, the user defines a sweep range of the constant parameter and a sweep time. The plotting tools can be used to observe the behavior of the parameters.

SYSTEM LEVEL

A. Design

The design of a vehicle drive train occurs at each of the five levels of abstraction described earlier. The design process usually begins at the vehicle control level by defining the vehicle mission and the performance that the driver expects from a vehicle of a certain size and a given set of aerodynamic characteristics. The next step is to select a vehicle configuration that meets mission and performance objectives. For example a commuter vehicle which will be driven less than 100 miles a day with access to a land-based charger would require a different configuration than a power-assisted hybrid where the electric motor aids in acceleration to improve fuel economy and emissions while maintaining the battery state of charge. The former defines an electric vehicle while the latter would best be implemented as a parallel hybrid with an electric motor and a downsized ICE. Once a basic configuration is chosen, the components and gearing is selected to meet the energy requirements of the vehicle. Then a control scheme is selected to meet the performance objectives and the design is iteratively modified until satisfactory performance is achieved.

A system-level model of a drive train can be constructed graphically by connecting the main and support component blocks such as the drive cycle, controller, power plant, and vehicle dynamics from the library of components. The Simulink visual programming methodology is used to connect the appropriate input and output ports. On the other hand, a system-level model can be created from the model section of the main menu which produces the model shown in figure 12 with a blank power plant. The appropriate component models are taken from the library of components to fill in the component blocks.

B. Analysis

Systems can be analyzed by applying a drive cycle to a particular drive train system. Studies may focus on varying component sizes, control strategies, system configurations, etc. The plotting tools and data summary can be used to observe the behavior of the system and component parameters.

CREATING A SERIES HYBRID VEHICLE DRIVE TRAIN

In this section, the design and analysis of a series hybrid electric vehicle drive train using the V-Elph package is discussed. For series hybrid electric vehicles, only one energy converter provides torque to the wheels while the others are used to recharge an energy accumulator, usually a battery pack.

A. Design

The series hybrid vehicle was designed as shown in fig. 13 consisting of a vector controlled induction motor driving the vehicle and an ICE/generator pair connected to the battery to maintain its charge.

A vector controlled induction motor powered by a D.C. battery pack of 156 volts supplies the power at the drive wheels. In addition, there is an A.P.U. (auxiliary power unit) comprising of an ICE driving an induction generator. The A.P.U. supplies power to the battery when the demanded current by the induction motor exceeds a threshold value of 75 amperes. The functionality of the components is based on Hochgraf's work [21]. The local controller is responsible for the following tasks

- demanding a torque (positive or negative) from the induction motor depending on drive cycle requirements.

- for switching on/off the APU.

The torque demanded from the induction motor is positive during acceleration and cruise phases of the drive cycle (motoring mode) and is negative during the deceleration phase of the drive cycle (generator mode). During the motoring mode, current is drawn from the battery (discharging) and during generation mode current is supplied to the battery (charging).

When the APU is on, the ICE is running at its optimum speed and the induction generator supplies charges the battery; in the 'off' mode, the ICE idles. Thus the APU is responsible for decreasing the drain on the battery pack, especially during the acceleration phases of the drive cycle. The ICE control is based on a "constant throttle strategy" which was found to be optimum [21].

The system control strategy for a series hybrid is not required to be as complex as the controller for a parallel hybrid since there is only one torque provider. For the series design discussed in the paper, the classic proportional, integral, and derivative (PID) controller [22] is utilized.

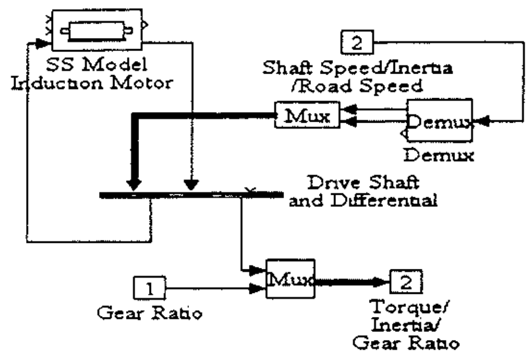
A typical mid-sized family sedan was used as the basis for the vehicle. The vehicle's' components were sized to provide enough power to maintain a cruising speed of 120 km/h on a level road and acceptable acceleration performance of 0 to 100 km/h in 16 seconds for short time intervals. The vehicle was also designed to maintain highway speeds for an extended period of time and provide adequate performance on hills. The sizes of the components for the series hybrid drive train are stated below in Table 1.

TABLE I
COMPONENTS OF SERIES HYBRID DRIVE TRAIN

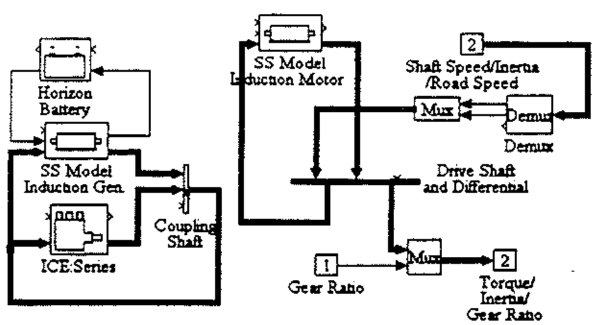
ICE	1.2 liter, 40 kW
Motor	Vector controlled, 40 kW
Generator	Vector controlled, 40 kW
Battery	13, 12-volt, lead acid

Recalling fig. 12, the major components such as controller, power plant, and vehicle design must be designed. The propulsion motor must be sized to provide the desired performance and the generator, an ICE/generator pair in this study, to provide the required range for the drive cycle. The steps performed to design the series hybrid vehicle are stated below.

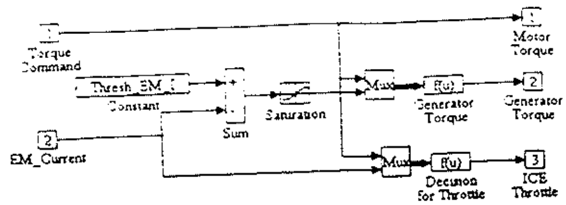
Step 1: Design the Power Plant. The induction motor is connected to the drive shaft of the vehicle. *The SS Model Induction Motor* and *Drive Shaft and Differential* models are dragged from the Library of Components. The *shaft speed, inertia* and *road* *speed* are passed from the vehicle dynamics to plant and are connected to the *drive shaft and differential* model as shown below. The *drive shaft torque, inertia* and gear ratio are multiplexed to the vehicle dynamics model as shown below.



Step 2: Create the ICE/Generator pair connected to the battery. Drag a copy of the *ICE*, the *Horizon Battery, SS Induction Generator*, and *Coupling Shaft* from the library of components. The *ICE* and *induction generator* are connected to the *coupling shaft* and arranged as shown below. The *battery pack* and the *induction generator* are connected to the DC bus as shown below. The appropriate sizes for the *ICE, induction generator,* and *induction motor* are entered in the dialog box which appears by double-clicking on each model.



Step 3: Design the controller. The controller determines how the demanded torque of the vehicle is to be met by various devices in the power plant as discussed below. The torque which will be demanded from the Induction Motor and Induction Generator and the throttle angle of the ICE are calculated as stated below.



- Motor Torque

The controller passes the entire torque command to the induction motor that is connected to the drive shaft. Since the induction motor drives the main shaft, it will always try to meet the torque demand of the vehicle.

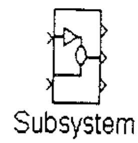
- Generator Torque

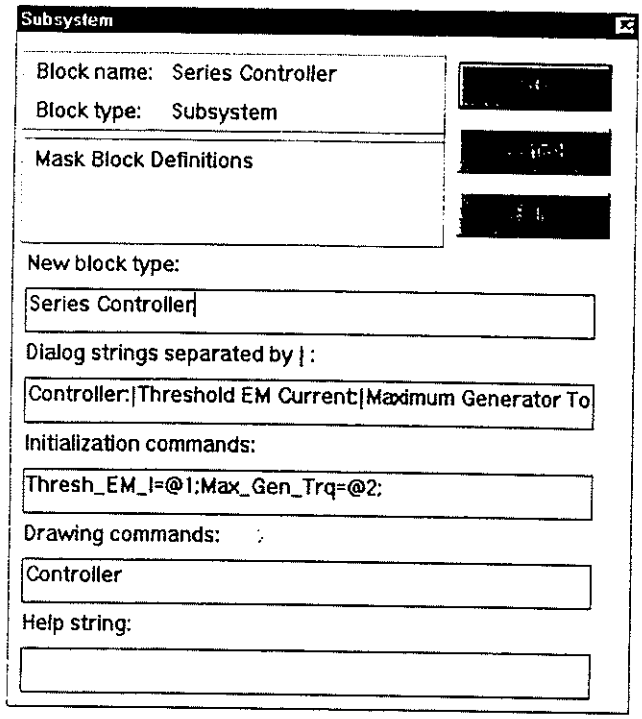
The torque demanded by the generator depends on the current demanded by the induction motor from the battery pack and the torque demanded by the vehicle. If the torque demanded by the vehicle is positive and the current demanded by the IM exceeds a threshold value, *Thresh_EM_I*, then the induction generator starts demanding a torque from the ICE to which it is coupled. If the demanded torque is negative then the generator cannot demand a torque from the ICE (this logic is embedded in the function block "Generator Torque"). However the torque demanded by the generator cannot exceed a threshold value, *Max_Gen_Trq*, otherwise it may stall the ICE to which it is coupled; this action is the function of the saturation block.

- ICE throttle

The ICE is operated at a constant throttle strategy. Whenever the *IM_current* is greater than the threshold current, *Thresh_EM_I*, (which indirectly implies that the drain on battery is increasing) and the demanded torque is positive, the *ICE throttle* is set to 80 degrees otherwise it is set to 10 degrees. This logic is written in the function block called *Decision for Throttle.*

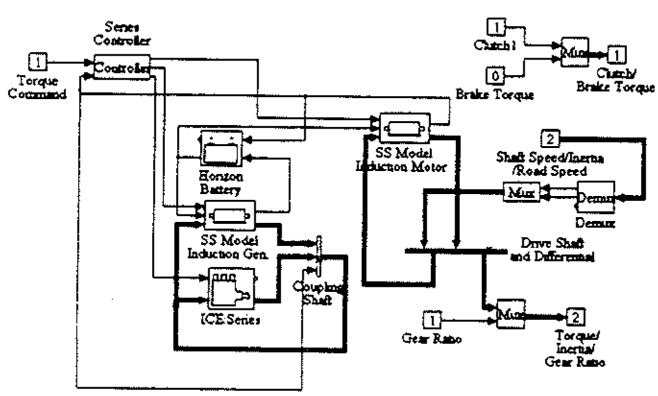
Step 4: The blocks are grouped into a single subsystem as shown above. The subsystem block is renamed to controller. A mask of the subsystem is built by entering the information as shown in the dialog box below. In the future, when one clicks on the controller subsystem, a dialog box pops up where the values of *Maximum Generator Torque* and *Threshold EM Current* can be entered.





Step 5: The *ICE, induction generator, battery, induction motor* and *controller* are connected in the power plant as shown below.

The *Clutch* and *Brake Torque* are multiplexed from the plant as shown.



B. Analysis

The results of applying the federal highway and federal urban [23] drive cycles are illustrated and discussed below. Figs. 14 shows the federal highway drive cycle. Figs. 15-17 illustrate a few of the outputs generated during the simulation of the federal highway drive cycle applied to the series hybrid vehicle. Plots of the EM, ICE, and Generator torques are shown in Figs. 15 and 16. As can be seen in Fig. 15, the EM torque is relatively constant in the sections where there is a cruising speed demand in the highway drive cycle. Fig. 17 shows a summary of the components' performance. In particular, it gives the fuel consumption and emissions of the ICE engine and the change in the battery SoC resulting from the simulation.

Fig. 18 shows the urban drive cycle. Figs. 19-22 illustrate the application of the urban drive cycle to the series hybrid drive train. In fig. 19, the EM torque has many transients between 200 Nm and -200 Nm due to the many quick acceleration and deceleration demands of the urban drive cycle. In comparing fig. 16 and fig. 20, the generator is used more on the urban drive cycle than the highway drive cycle. This point is also illustrated by comparing the fuel consumption generated during the application of the highway drive cycle in fig. 21 of 21.89 km/l to the fuel consumption of 19.68 km/l generated during the application of the urban drive cycle.

Figs. 21 and 22 show that when the EM current goes above 75 amperes, the generator is used. One such case is seen at 250 seconds which occurs as a result of the steep acceleration in speed demanded in the urban drive cycle.

CONCLUSION

This paper discussed a new system-level modeling, simulation and analysis package developed at Texas A&M University using Matlab/Simulink to study issues related to electric vehicle (EV) and hybrid electric vehicle (HEV) design such as energy efficiency, fuel economy, and vehicle emissions. The package uses visual programming techniques, allowing the user to quickly change architectures, parameters, and to view output data graphically. It also includes detailed models of electric motors, internal combustion engines, and batteries.

The V-Elph package design and user features are discussed. Further the design process for a series hybrid drive train is stated. Simulation results from the application of federal highway and urban drive cycles to the series hybrid drive train are discussed. These results illustrate the flexibility of the package for studying various issues related to electric and hybrid electric vehicle design. The simulation package developed at Texas A&M University runs on PC and Unix-based workstations platforms.

ACKNOWLEDGMENTS

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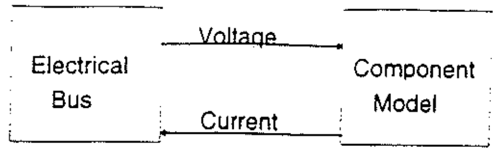

Fig. 1 Electrical Bus

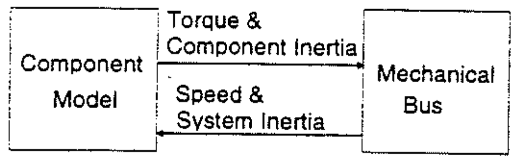

Fig. 2 Mechanical Bus

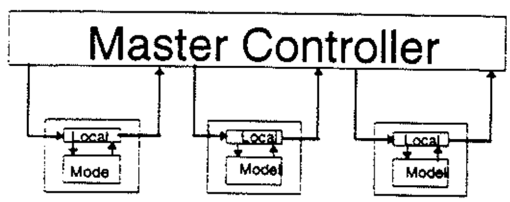

Fig. 3 Master/Control Paradigm

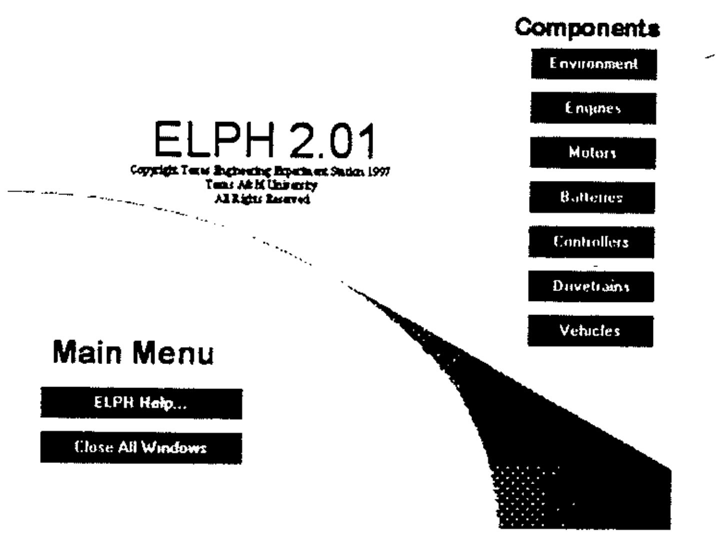

Fig. 4 Main Menu

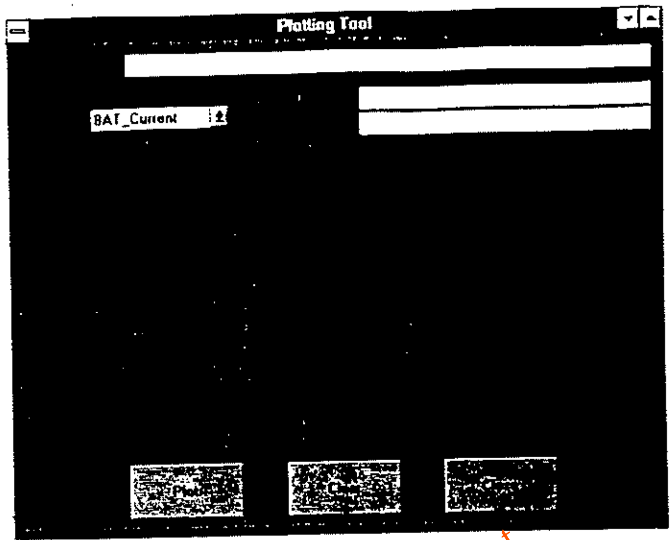

Fig. 5 Plotting Tool

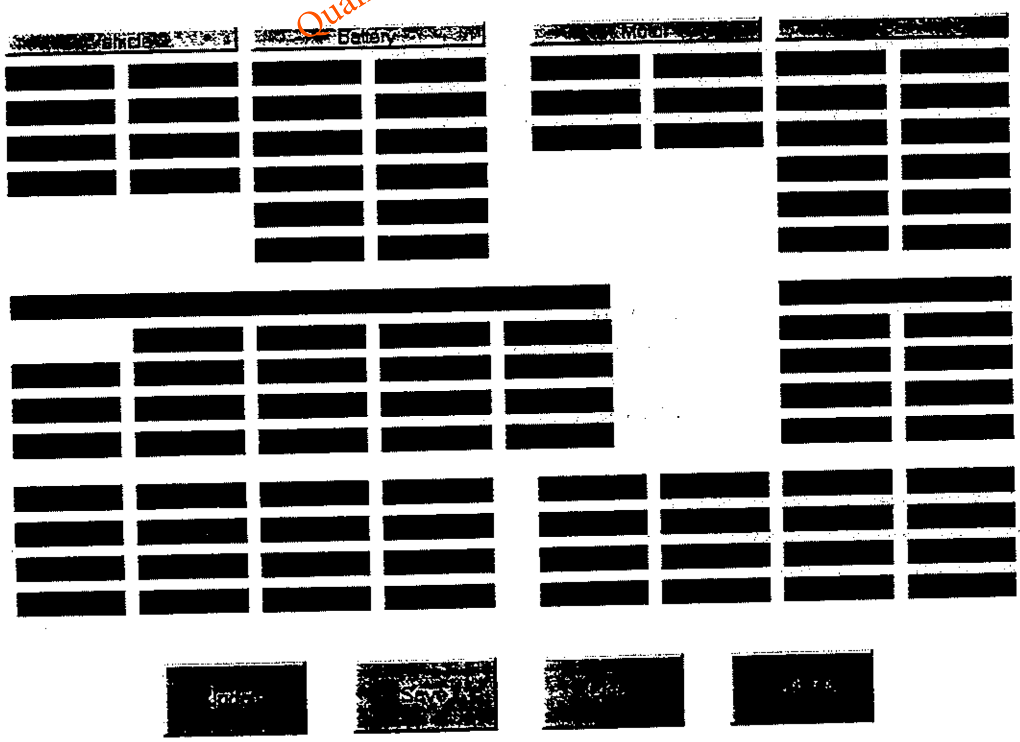

Fig. 6 Data Summary Tool

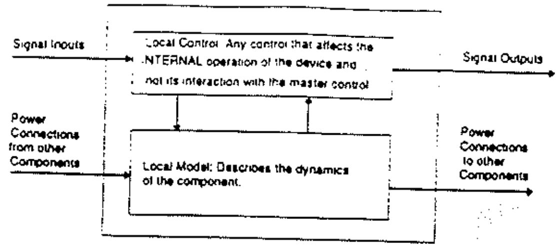

Fig. 7 Data flow through a component model

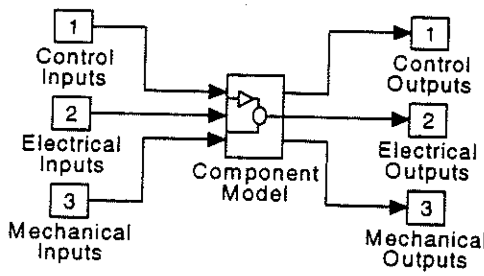

Fig. 8 General Input / Output Interface for a Component Model

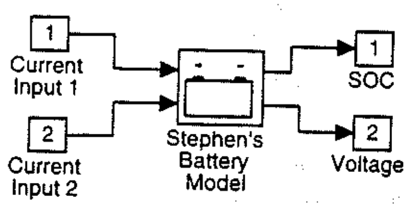

Fig. 9 Interface for a Battery Model

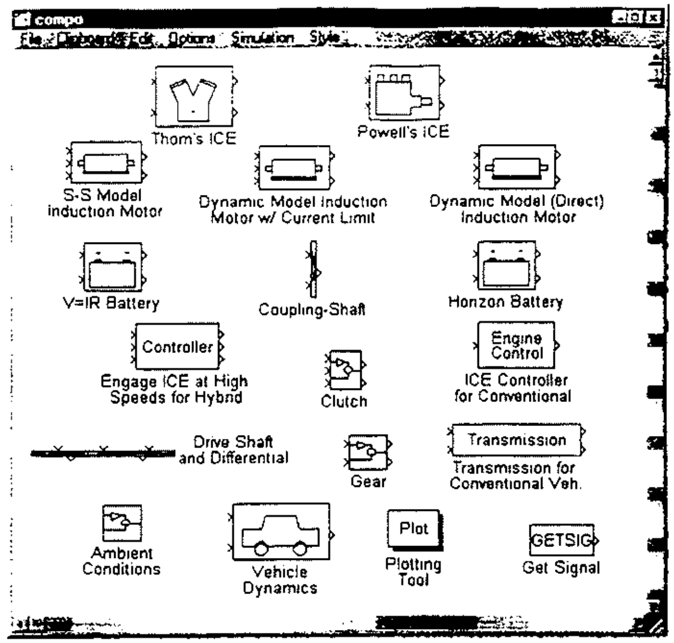

Fig 10. Library of Components

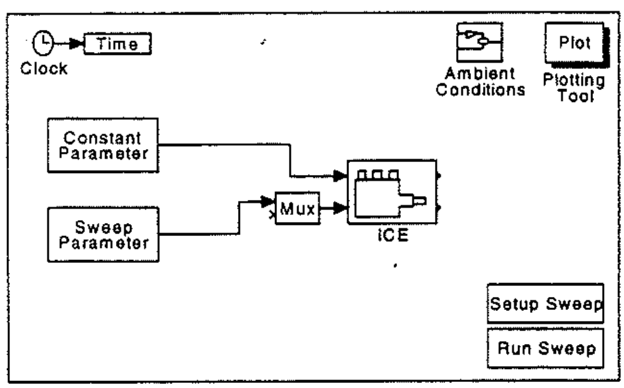

Fig. 11 Parameter sweep workbench

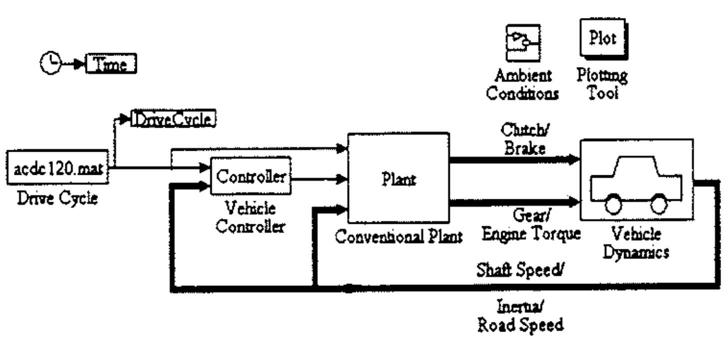

Fig. 12. System level representation of a general vehicle drive train in V-Elph

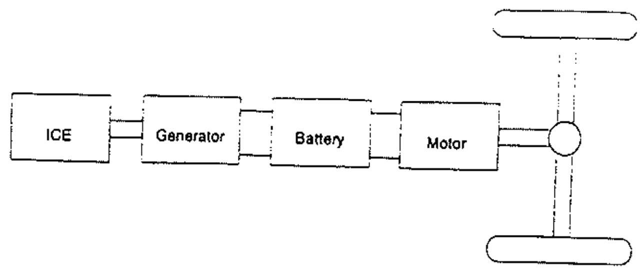

Fig. 13 Series Hybrid Drive Train

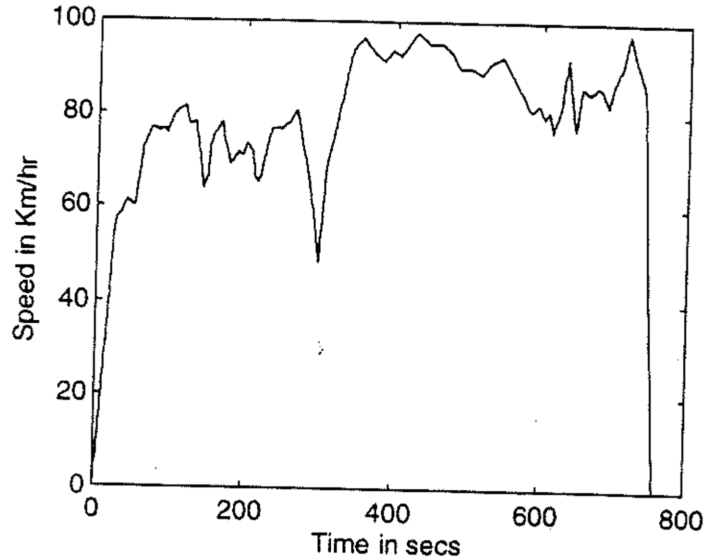

Fig. 14 Federal highway drive cycle

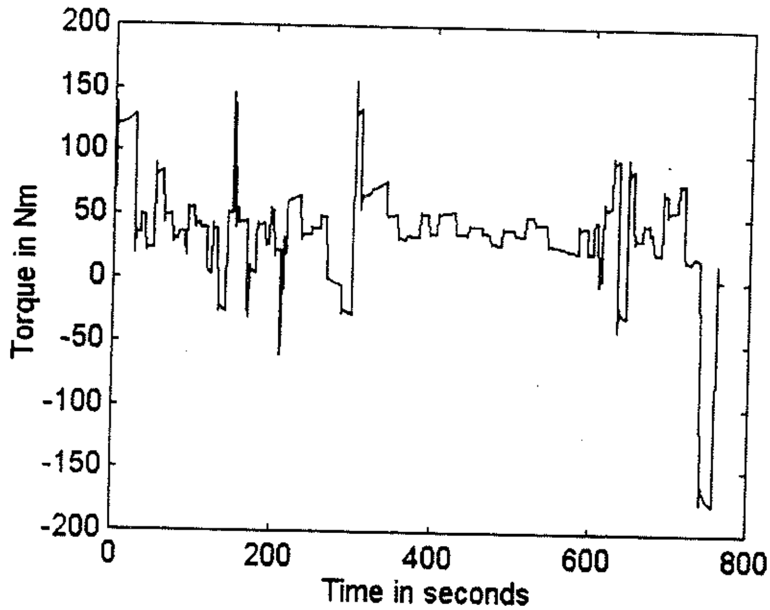

Fig. 15. EM torque for FTP highway applied to series HEV

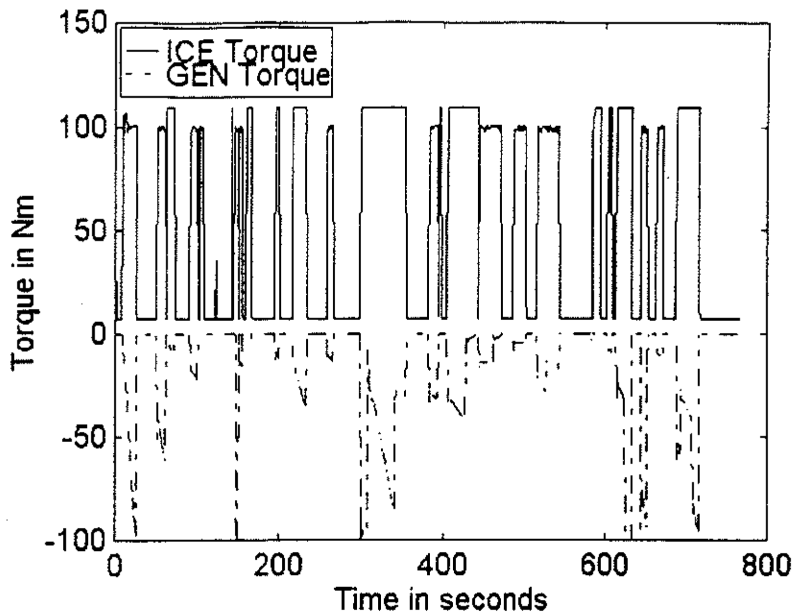

Fig. 16. ICE and generator torques for FTP highway applied to series HEV

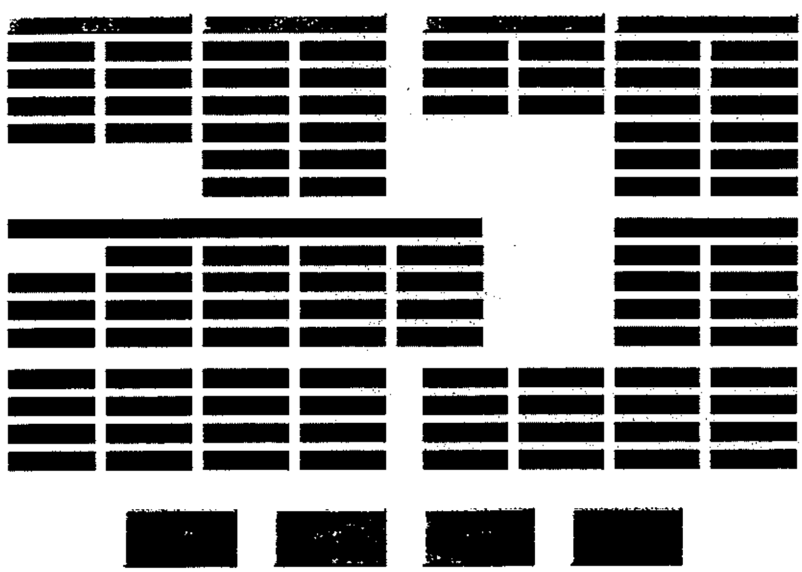

Fig. 17. Data summary for FTP highway applied to series HEV

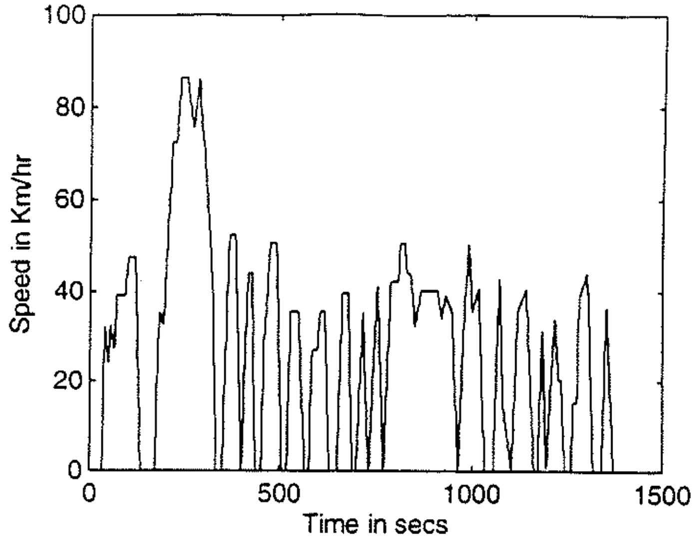

Fig. 18 FTP-75 Urban drive cycle

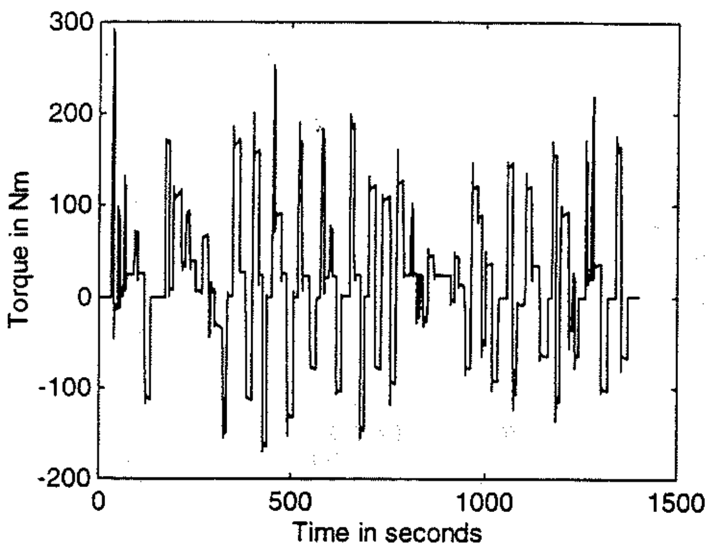

Fig. 19. EM torque for urban drive cycle applied to series HEV

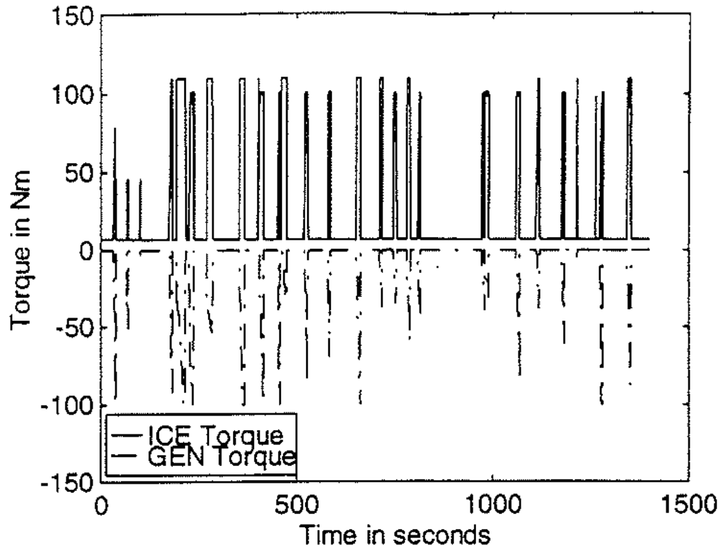

Fig. 20. ICE and generator torque for urban drive cycle applied to series HEV

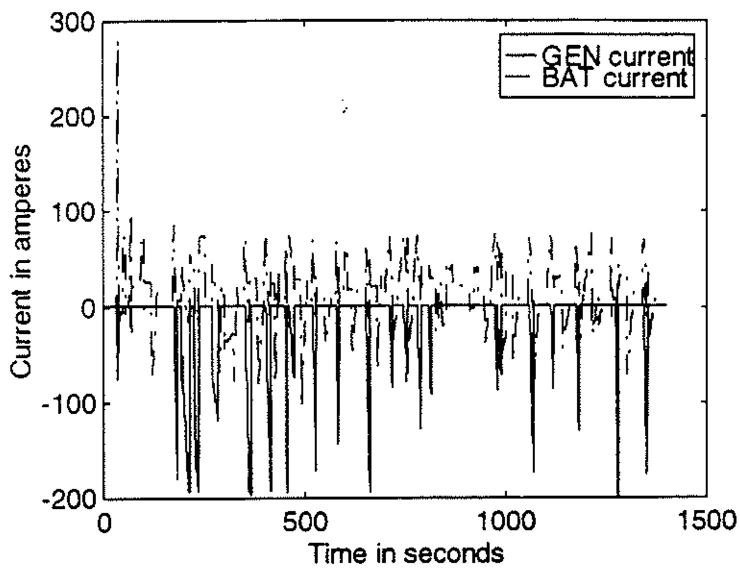

Fig. 21 Generator and battery current for urban drivecycle applied to series HEV

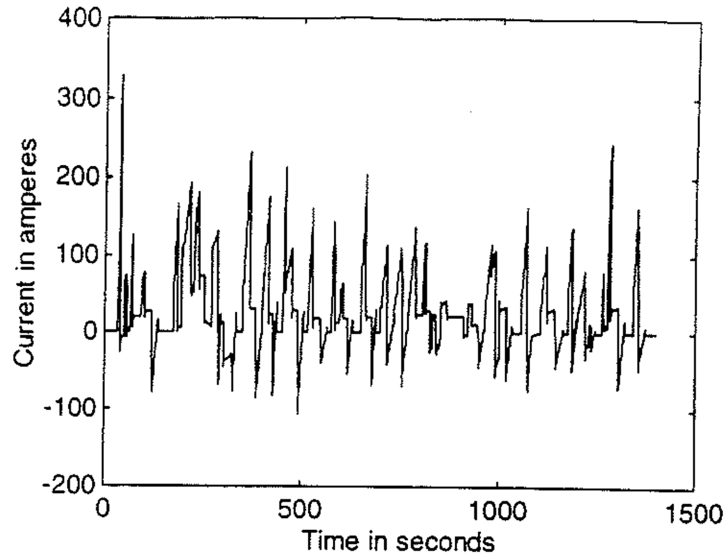

Fig. 22 EM current for urban drivecycle applied to series HEV