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16. Abstract

Electrically Peaking Hybrid (ELPH) is a parallel hybrid electric vehicle propulsion concept that was invented at Texas A&M University, by the advanced vehicle systems research group. Over the past six years, design methodologies, component development, and system optimization work has been going on for this invention.

This project was a first attempt in integrating the above developments into an optimized design of an ELPH passenger car. Design specifications were chosen for a full size passenger car, performing as well as any conventional car, over the EPA-FTP-75 combined city/highway drive cycles.

The results of this design project were two propulsion systems. Both were appropriate for commercial production, from the points of view of cost, availability of the technologies, and components. One utilized regenerative braking and the other did not.

Substantial fuel savings and emissions reductions resulted from simulating these designs on the FTP-75 drive cycle. For example, our ELPH full size car, with regenerative braking, was capable of delivering over 50 miles per gallon in city driving, with corresponding reductions in its emissions.

This project established the viability of our ELPH concept and our design methodologies, in computer simulations. More work remains to be done on investigating more advanced power plants, such as fuel cells, and more advanced components, such as switched reluctance motor drives, for our designs. Furthermore, our design optimization can be carried out to more detailed levels, for prototyping and production.

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DESIGN OPTIMIZATION OF THE
ELECTRICALLY PEAKING HYBRID (ELPH) VEHICLE

by

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Executive Summary

This project was the first attempt at optimizing and designing Electrically Peaking Hybrid (ELPH) vehicle. The ELPH vehicle was invented in our research center, at Texas A&M University. Extensive work had previously been done in developing design methodologies, computer models and controls, toward the realization of the ELPH car. This project used these background works to develop the first viable ELPH car design, which is appropriate for commercial mass production.

The objectives of this project were to optimize and design the ELPH propulsion system for a typical 5-seat full size passenger car that possesses features such as

(1) Comparable performance to conventional vehicles that have similar space and loading capacity,

(2) Similar mass production cost to that for corresponding conventional vehicles,

(3) The same operation as driving conventional vehicles,

(4) Two to three times fuel economy over the conventional vehicles and,

(5) Self sustained battery state-of-charge (The batteries on board do not need to be charged from outside of the vehicle).

The ELPH propulsion system operates based on the Electrically Peaking Hybrid principle developed in our research center, which is described in detail at page 2 of the Technical Report attached

The key issues in the ELPH propulsion system optimization and design are (1) proper selection of the propulsion components, (2) control strategy designs, (3) regenerative braking consideration, (4) driving simulation, and (5) performance prediction.

The car that was designed is a 4-door, 5-seat full size passenger car with front - wheel drive, spark-ignition gasoline engine, induction AC motor and lead/acid batteries on board and

single gear transmission (Please see the design specifications at page 7 of the Technical Report attached).

The engineering data and driving performances obtained from the simulated test drives show that the ELPH vehicle design is very reasonable. This report show that ELPH propulsion system can meet the practical design specifications and is suitable for the mass production. The fuel consumption can be significantly reduced. Emissions of the toxic and green house gases are expected to also be greatly reduced (Please see the Design Results at pages 10 through 14).

Component improvements, design improvements and simulation model improvements are being aggressively continued. Our new discoveries of better electric motor drives, control methods, new power plants and system design methodologies are being individually perfected at the present time. We request continuation of funding of this design optimization effort. In the next phase of this project, we propose to deliver the second-generation ELPH design, incorporating the above developments. Thus, we can produce car propulsion system designs that far surpass the existing technologies, in performance, fuel efficiency emission and cost of manufacturing. Proposals for further study are also briefly mentioned in this report (Please see page 15 through 16 in the Technical report attached).

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INTRODUCTION

In vehicle development and design, the current major issues are marketability and impact on the environment. Conventional gasoline and diesel fueled vehicles possess the advantages of (1) good performance, (2) long driving range, (3) ease of refueling, (4) light-weight energy source, (5) well known manufacturing technology, and (6) safety. These advantages have enabled the conventional vehicles to dominate the market. However, the conventional vehicles have serious disadvantages in regard to fuel consumption and environment impact. The electric vehicles, which have been under development for many years, are considered to be important substitutes of the conventional vehicles. But the commercialization of the electric vehicles 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, 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 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 both engine and motor. Therefore, the control strategy of the power plants is a crucial aspect in the development of hybrid electric vehicles.

A hybrid electric propulsion system, with a parallel configuration, referred to as <u>EL</u>ectrically <u>P</u>eaking <u>H</u>ybrid (ELPH) propulsion system, was introduced by our group. 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[2,3,7,8,9]. 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.

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ELPH PRINCIPLE

For a full size vehicle, the required acceleration performance usually determines the power capacity of the power plants. For instance, for a vehicle with 1500 kg gross weight, the average power needed to accelerate the vehicle from zero speed to 100 km/h (62.5 mph) in 10 seconds is about 60 kW, and the peak power of the engine needed would reach about 90 to 100 kW. However, in normal driving, the average load power is only 15 to 20 kW. 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 mostly in its efficient region, resulting in much more 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. 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 and potential energy of the vehicle in down-hill driving. The second approach is to charge the batteries by the excess 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 be maintained at a reasonable level in the driving, and the battery size (energy capacity) can be small[2].

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. The choice of 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].

The ELPH propulsion can potentially realize 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. 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 is 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

In urban driving, the frequently accelerating–decelerating driving would discharge the batteries quickly. Therefore, Maintaining the battery SOC at high level is crucial for the operation of the vehicle. In this case, the control system should, a priori, charge the batteries to prevent them from complete depleting. Therefore, Maximum battery SOC control strategy would be the best control strategy while the vehicle drives in urban.

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 the engine being used as much as possible and the electric traction system should be used as little as possible. The details of this control strategy are illustrated in Fig.4, which is explained in detail below.

(1) Hybrid Traction Mode: when the traction power required is greater than the power that the engine can supply (this may occur in acceleration and hill-climbing) as shown in Fig. 4 by point A, hybrid traction mode must be used. 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. So, output traction power of the electric motor and battery discharge power are expressed as

and

$$P_{mt} = \frac{P_L - P_{eopt}\eta_{T,e}}{\eta_{T.m}} \qquad (1)$$

$$P_{bd} = \frac{P_{mt}}{\eta_m \eta_{bd}} \qquad (2)$$

where, P_L is the load power of the vehicle,

P_{eopt} is the engine power corresponding to its optimal operating line, which is near the full-throttle operation,

$\eta_{T,e}$ is the transmission efficiency from the engine to the driven wheels,

η_m is the efficiency of the traction motor,

η_{bd} is the battery discharge efficiency.

(2) Engine Alone Traction Mode: When the traction power required is less than the power that the engine can produced with near full throttle as shown in Fig.4 by point B, the engine can be controlled depending on the battery SOC. If the battery SOC reaches its top level, the engine should be controlled to produce its power that is equal the load power. In this case, the engine output power is

$$P_e = \frac{P_L}{\eta_{T,e}} \qquad (3)$$

and the electric motor and battery power are zero. In ELPH power train design, this operation mode should be avoided as mush as possible, because the partial-load operation will result in low engine operation efficiency.

(3) Battery Charging Mode from Engine Excess Power: When the traction power requirement is the same as in (2) represented by point B and the battery SOC does 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. In this case, the electric motor will function as a generator and the batteries will absorb energy from the electric motor. The output power of the electric motor and the battery charging power are expressed as and

$$P_{mg} = (P_{eopt} - \frac{P_L}{\eta_{T,e}})\eta_{T,em}\eta_m \qquad (4)$$

$$P_{bc} = \frac{P_{mg}}{\eta_{bc}} \qquad (5)$$

Where, $\eta_{T,em}$ is the transmission efficiency from the engine to the electric motor,

η_{bc} is battery charging efficiency.

(4) Motor Alone Traction Mode: When the vehicle speed is less than the speed which corresponds to the minimum speed of the engine, the engine stands still and the electric motor alone propels the vehicle. In this case, the motor output power is expressed as

and

$$P_{mt} = \frac{P_L}{\eta_{T,m}} \qquad (6)$$

$$P_{dc} = \frac{P_{mt}}{\eta_m\eta_{bd}} \qquad (7)$$

(5) Hybrid Braking Mode: In braking operation, if the braking power is greater than the power that the electric system (electric motor and batteries) can absorb, as shown in Fig.4 by point C, and 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 supplied by the frictional brake system. The generating power of the electric motor and the battery charging power can be expressed as

$$P_{mg} = P_{mmax} \qquad (8)$$

and

$$P_{bc} = \frac{P_{mg}}{\eta_m\eta_{bc}} \qquad (9)$$

The braking power distribution between the electric braking and mechanical frictional braking will be described in following section.

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(6) Electrically Regenerative Braking Alone Mode: When the braking power needed is less than the power the electric system can handle, as shown in Fig.4 by point D, the electrically regenerative braking alone is used. The generating power of the electric motor and battery charging power can be expressed as

and
$$P_{mg} = P_b \eta_{T,m} \qquad (10)$$

$$P_{bc} = \frac{P_{mg}}{\eta_m \eta_{bc}} \qquad (11)$$

Using the equations above and the control strategy, the engine power, motor power and the battery charging and discharging power can be calculated at any time of a given driving cycle.

Engine Turn-on and Turn-off Control Strategy

When vehicle is driven on the highway, the power and energy supplied by the electric system are much smaller than driving in urban areas, 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

REGENERATIVE BRAKING AND FRICTIONAL BRAKING

For improving the economy of the vehicle, the power train should recover the kinetic and potential energy of the vehicle as much as possible. In the case that the electric traction system is only available for one drive axle (front or rear) and braking must be applied on two axles (front and rear) for safety season, completely recovering the braking energy is impossible. In this study, a parallel braking system is applied. Parallel braking means that an additional electric braking system is added to the traditional frictional brake system. While braking, both brake systems are

in effect. The braking forces supplied by the electric and frictional brake systems are shown in Fig.6, where front wheel drive is assumed.

Fig.6 shows the frictional brake force, summation of frictional and regenerative braking forces and the ideal braking force curves. The frictional braking forces on the front and rear axles are proportional to the hydraulic pressure in the master brake cylinder. The regenerative braking force developed by the electric motor on the front axle is a preset function of the hydraulic pressure of the master cylinder, and therefore the preset function of vehicle deceleration. The braking operation is divided into three regions according to braking deceleration. First is the region in which the deceleration of the vehicle is less than 0.1g. In this case, the brake force of the vehicle is only applied to the front axle by the electric braking. Second is the region in which the deceleration of the vehicle is greater than 0.1g and less than 0.7g. In this case, the braking force on the rear axle is only supplied by the frictional barking system, and the braking force of the front axle is the summation of the frictional and electric braking forces, as shown in Fig.6. Third is the region in which the deceleration of the vehicle is greater than 0.7g. In this case, the braking forces on the front and rear axles are applied only by the frictional braking system.

PROPULSION DESIGN FOR FULL SIZE PASSENGER CAR

The design targets of the ELPH propulsion are that the full size passenger cars have:
(1) comparable performance to the conventional cars that have similar space and loading capacity,
(2) similar mass production cost to that of the conventional cars,
(3) the same operation as driving conventional cars,
(4) two to three times fuel economy over the conventional cars, and
(5) self sustained battery SOC.

Design Specification

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

Overall dimensions:
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% @ 100 km/h

Maximum speed;

Engine only: 120 km/h (75 mph)

Hybrid traction   160 km/h (100 mph)

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

Estimate of the Propulsion Parameters

In vehicle design, the first step is to estimate the size of the power plant(s) and the transmission parameters according to the design specification. In the ELPH propulsion design, The choices of the engine size, electric motor size and transmission have crucial influence on the vehicle performance, fuel economy, battery size, and driving range.

Engine Size—According to the ELPH operation principle, the engine is used to supply the average load power (the load power in steady driving). Thus, the engine power capacity can be initially determined by the load power demand in steady driving, which can be expressed as

$$P_e = \frac{V}{1000\eta_{T,e}}\left(mgf_r + \frac{1}{2}\rho_a C_D A_f V^2\right) \qquad (kW), \qquad (12)$$

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 are as follows.

Vehicle mass	1700 kg
Rolling resistance	0.01
Transmission efficiency	0.92
Aerodynamic drag coefficient	0.3

| Front area | 2.25m^2 |

The power demand along the vehicle speed is shown in Fig.7. This figure indicates that about 21 to 33 kW of engine power can meet the power requirement for the speed between 120 to 140 km/h (75 to 87.5 mph) with steady driving. This power demand is 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 28 to 40 kW engine would be needed. The speed – power and speed torque characteristics of a typical gasoline engine are shown in Fig.8.

Electric Motor Size – Based on the ELPH principle, 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 requirements. In practice, the acceleration is the first consideration in design of passenger cars.

As initial estimate, an assumption would be made that the steady-state load is handled by 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]

$$P_{m\,max} = \frac{30m\delta}{9546\pi t_f}\left(\frac{V_b^2 + V_f^2}{2}\right) \quad (kW), \qquad (13)$$

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 estimate of the maximum power of the electric motor.

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

The maximum motor power of about 65 kW is calculated using equation (13) and the parameters above. It should be noted that engine has, actually, some excess power to help electric motor to accelerate the vehicle as shown in Fig 9. 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 55 kW. 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 10 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.7 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.

It should be noted that all the parameters mentioned above are the initial estimated values. They should be verified and confirmed by further performance calculation and driving simulation. If necessary, they should be modified for achieving optimum operation results and meeting the requirements of the design specification.

DESIGN RESULTS

Design of the ELPH propulsion has been performed with the aid of the V-ELPH simulation package developed in ELPH Research Group, Department of Electrical Engineering, Texas A&M University. By running the computer program, and iteratively refining the propulsion parameters, the optimum design can be found, which optimize the fuel economy of the vehicle under the condition of meeting the design specification.

In order to find the influence of the regenerative braking on the vehicle performance and fuel economy. Two designs have been made, one is regenerative breaking available and the other unavailable.

Design Results (Regenerative Braking Unavailable)

In calculation of the vehicle economy in the EPA FTP75 driving cycles (urban and highway) and performance for the propulsion without regenerative braking, the propulsion parameters below are used.

Maximum power of engine	42(kW) (35 kW available for traction)
Maximum power of electric motor	55 kW
Gear ratio from the engine to the driven wheels	3.9
Gear ratio from the traction motor driven wheels	6.58
Transmission efficiency	0.92

Fuel Economy in EPA FTP75 Driving Cycles

Driving in FTP75 Urban cycle – Fig.11 shows the simulation results, which includes vehicle speed, engine power output, electric motor power output and the changes in battery storage energy, in which, the **Maximum battery SOC control strategy** is used. This figure indicates that, with the selected propulsion parameters, the battery storage energy can be balanced at the beginning and end of the driving cycle. This results means that the vehicle can be free from its battery recharging from outside of the vehicle. The fuel economy of the vehicle, in this case, reaches 34.32 mpg (6.89 L/100 km). Fig.12 shows the engine operating points on the characteristic map of

the engine fuel economy. This figure indicates that actual engine operating points coincide to the optimal operating line and the potential of the engine fuel economy can be mostly used.

Driving In FTP75 Highway Driving – Fig.13 shows vehicle speed, engine power output, motor power output and the changes in the battery storage energy versus the driving time with Engine Turn-on and Turn-off control strategy. Fig. 14 shows the actual engine operating points on the characteristic map of the engine fuel economy. In this case, the fuel economy of the vehicle is 42.34 mpg(5.58 L/100 km), and the vehicle can also be free from the outside charging.

Performance

The acceleration performance is shown in Fig.15. This figure show that the time needed for the vehicle to accelerate from zero speed to 96 km/h (60 mph) needs 11.7 seconds and the covered distance is about 174m.

The gradeability and the maximum cruising speed of the vehicle can be found in Fig.16, which is a diagram maximum traction force on the driven wheel versus vehicle speed. The maximum gradeability, represented by point A, is about 18 degrees (32.5%) and the gradeability at the speed of 96 km/h (60 mph) is about 8.5 degrees (15%). The maximum speeds reach 160 and 140 km/h (87.5 and 100 mph) for hybrid traction and engine only traction modes respectively.

Design Results (Regenerative Braking Available)

The regenerative braking can recover the vehicle kinetic and potential energy, therefore reduce the battery charging energy from the engine. Thus the size of the engine can be reduced further. The regenerative braking principle in the design is referred to as parallel braking as shown in Fig.6. The maximum power of the engine is reduced from 35 kW (without regenerative braking to 23 kW (traction available, the maximum power may reaches 30 kW for additionally powering the accessories). The other parameters are the same as above.

Fuel Economy in EPA FTP75 Driving Cycles

Driving in FTP75 Urban cycle – Fig.17 shows the simulation results, which includes vehicle speed, engine power output, electric motor power output and the changes in battery storage energy, in which, the **Maximum battery SOC control strategy** is used. This figure indicates the, even reducing the engine size, the battery storage energy can be balanced at the beginning and end of the driving cycle. The fuel economy of the vehicle, in this case, reaches 50.7 mpg (4.66L/100 km). Fig.18 shows the engine operating points on the characteristic map of the engine fuel economy. This figure indicates that actual engine operating points can coincide to the optimal operating line and the potential of the engine fuel economy can be mostly used.

Driving In FTP75 Highway Driving – Fig.19 shows vehicle speed, engine power output, motor power output and the changes in the battery storage energy versus the driving time with

Engine Turn-on and Turn-off control strategy. Fig. 20 shows the actual engine operating points on the characteristic map of the engine fuel economy. In this case, the fuel economy of the vehicle is 49.8 mpg(4.74L/100 km), and the vehicle can also be free from the outside charging.

Performance

The acceleration performance is shown in Fig.21. This figure show that the time needed for the vehicle to accelerate from zero speed to 96 km/h (60 mph) needs 12.7 seconds and the covered distance is about 205m.

The gradeability and the maximum cruising speed of the vehicle can be found in figure 22. The maximum gradeability, represented by point A, is about 17.5 degrees (31.5%) and the gradeability at the speed of 96 km/h (60 mph) is about 7.8 degrees (13.5%). The maximum speeds reach 160 and 120 km/h (100 and 75 mph) for hybrid traction and engine only traction modes respectively.

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 (*55 kW*). The modern lead/acid traction batteries show the average specific power of *280W/kg* and power volume density of *470W/dm³*[9], Thus, the total battery weight needed is about *200 kg (55×10³/280)* and the total battery volume is about *120 d^{m3} (55×10³/470)*.

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 *0.3 kW.h*. The battery storage energy capacity of the batteries can be obtained by

$$C_b = \frac{\Delta E_b}{SOC_{top} - SOC_{bottom}}$$

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.23. 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 *68 W.h/dm³*. Thus the total weight and total volume of the batteries required by the storage energy are about *37.5 kg (1.5×10³/40)* and *22 dᵐ³ (1.5×10³/68)* 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.

Summary of the ELPH propulsion Design

Based on the ELPH principle and the simulation package developed in ELPH Research Group, Department of Electrical Engineering, Texas A&M University, The design results for a full size passenger car are summarized as below

The car without regenerative braking:

Components:

Maximum engine power	
(Including powering the accessories)	42 kW (57 hp)
Maximum motor power (1 minute)	55 kW
Transmission	Single gear
Gear ratio from engine to driven wheels	3.9 (37 rpm/(km/h)) or (59 rpm/mph)
Gear ratio from traction motor to driven wheels	6.58 (62.5 rpm/(km/h)) or 100 rpm/mph)
Battery type	Lead/acid
Energy capacity	8 kW.h
Peak power	57 kW

Performance:

Acceleration time (0 to 96 km/h(60 mph))	11.7 Seconds
Acceleration distance	175m (574 ft.)
Maximum speed	160 km/h (100 mph) with hybrid mode
	140 km/h (87.5 mph) with engine-only mode
Gradeability	18 degrees (32.5%) maximum
	8.5 degrees(15%) at 96 km/h (100 mph)

Fuel economy

EPA FTP75 Urban driving	34.3 mpg (6.89L/100 km)
EPA FTP75 Highway driving	42.32 mpg (4.74L/100 km)
Range	Free from battery charging outside of the vehicle

The car with regenerative braking:

Components:
Maximum engine power
       (Including powering the accessories)   30 kW (57 hp)

Maximum motor power (1 minute)   55 kW

Transmission   Single gear
Gear ratio from engine to driven wheels   3.9 (37 rpm/(km/h)) or (59 rpm/mph)
Gear ratio from traction motor to driven wheels   6.58 (62.5 rpm/(km/h)) or 100 rpm/mph)

Battery type   Lead/acid
Energy capacity   8 kW.h
Peak power   57 kW

Performance:
Acceleration time (0 to 96 km/h(60 mph))   12.7 Seconds
Acceleration distance   205 (673 ft.)
Maximum speed   160 km/h (100 mph) with hybrid mode
        120 km/h (75 mph) with engine-only mode
Gradeability   17.5 degrees (31.5%) maximum
        7.8 degrees(13.7%) at 96 km/h (100 mph)

Fuel economy
EPA FTP75 Urban driving   50.7 mpg (4.76L/100 km)
EPA FTP75 Highway driving   49.8 mpg (4.74L/100 km)

Range   Free from battery charging outside of
        the vehicle

Manufacturing Analysis

All the main components of the ELPH vehicles are available in mass production with well known technologies. The engine is a small spark-ignition engine popularly used in modern motor cars and motorcycles. The electric traction motor is a power electronics controlled AC induction motor. Batteries are commonly used lead/acid batteries. And the transmission is a single-gear mechanical speed reducer. The components do not need much R&D effort for application to the ELPH vehicles. These advantages are of vital importance for reduction of manufacturing cost and marketability.

Conclusion

The ELPH propulsion of hybrid electric vehicle, which has parallel configuration and operates with electrically peaking manner, can optimize the overall efficiency and satisfy the performance requirements of the vehicle. When driving inside cities, the Maximum Battery SOC control strategy is used, which can prevent the batteries from being completely depleted. When driving on highway, the Engine Turn-on and Turn-off control strategy is used, which can optimize the overall efficiency of the vehicle.

Simulation results, obtained by running the V-ELPH simulation package, developed by the ELPH Research Group, Department of Electrical Engineering, Texas A&M University, shows that, comparing with conventional gasoline fueled passenger cars, the full size passenger car with ELPH propulsion has comparable performance, similar space and loading capacity, the same driving operation, self sustained battery SOC and two to three times the fuel economy.

Functioning as power source more than as energy source, modern lead/acid batteries, which have good power density and bad energy density, would be the best choice. The ELPH propulsion does not have specific requirement from the electric traction system (traction motor and controller). Therefore, AC induction motor with power electronics controller would be a good selection. The single gear transmission can greatly simplify the construction and control system. Therefore, the cost of mass production is expected not to be higher than that for conventional cars.

Further Study

(1) **Further Study in Regenerative Braking**: As seen in the design results of the ELPH propulsion, availability of the regenerative braking can greatly improve the fuel economy of the vehicle, even though part of the kinetic energy of the vehicle is recovered (for example, in this design, only part of the braking power of the front axle is to be recovered). If the kinetic energy can be completely recovered, it is expected that the overall efficiency would be greatly improved. This may be implemented by adding energy storage devices (electric or mechanical) at the rear axle. Usually, peak value of the braking power is much greater than that the electric system can directly handled. This difficulty may be solved by adding some power leveling devices to reduce the peak value of the braking power (springs, magnetic coils and capacitors, for example). The braking power is stored in the energy storage elements temporarily, and then used to propel the vehicle or send to the batteries. The regenerative braking system may also function as anti-lock brake system (ABS).

(2) **Alternative Power Source:** Based on the ELPH operation principle, one power plant supplies its power to meet the steady load and the other to meet the dynamic load as mentioned in this report. The chemical battery-electric motor may be the most suitable system for dynamic load. But, internal combustion engines used as the power plants in modern vehicles may not be the best power plants to supply the steady load power, due to their very inefficient operation and toxic emissions. Other potential power plants including fuel cell, diesel engine, gas turbine engine, Sterling engine, two stroke engine with fuel ejection system, and so on would be more attractive than common 4-stroke spark-ignition engine

gasoline engine in the application on the ELPH vehicles. Among the potential power plants, the fuel cell may be the most viable one, due to its high efficiency, non-toxic emission advantages and favoring operation in steady state. Combining a better power plant with the ELPH principle, may result in a better propulsion system.

(3) **Driving Pattern Automatic Identification**: For different driving patterns (speed-time profiles, such as urban and highway drivings), the control strategies should be different. For instance, Maximum Battery SOC control strategy for urban driving and Engine Turn-on and turn-off for highway driving as mentioned in this report. The control strategies should be shifted automatically, rather than left to the driver. This may be done by averaging the speed experienced and finding the derivative of the speed, from its average value. The values of the average speed and speed derivative may be taken as the basis for the identification of the driving pattern. Microcomputer based vehicle controller may easily make the decision of which control strategy should be used in the current driving condition.

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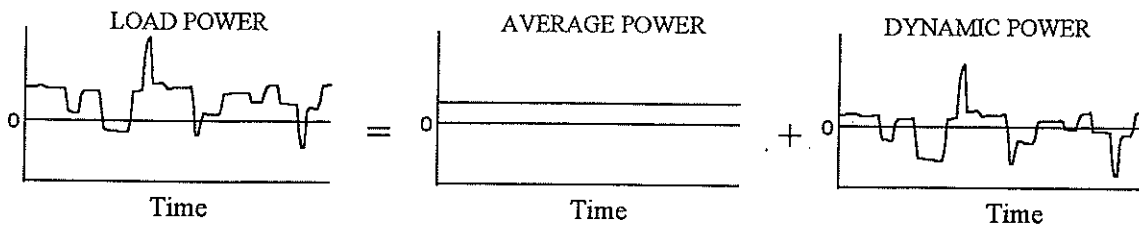
Fig.1 The load power demand and its steady and dynamic components
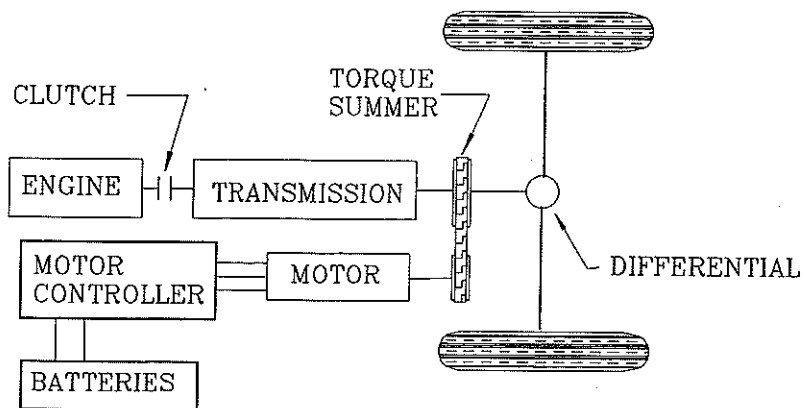
Fig.2 Two-shaft configuration of ELPH propulsion

Fig3 Single-shaft configuration of ELPH propulsion

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
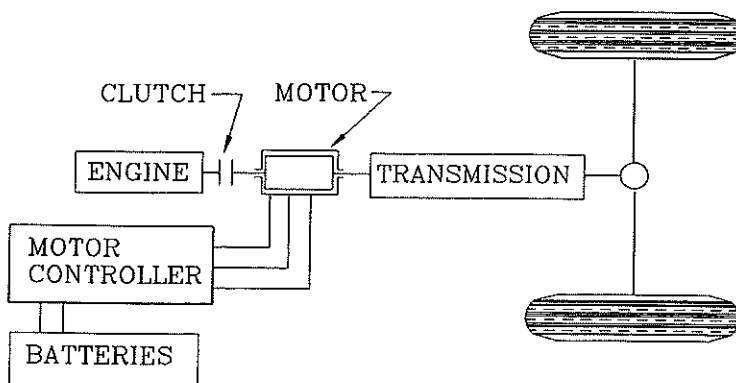
Fig.4 Illustration of the Maximum Battery SOC control strategy
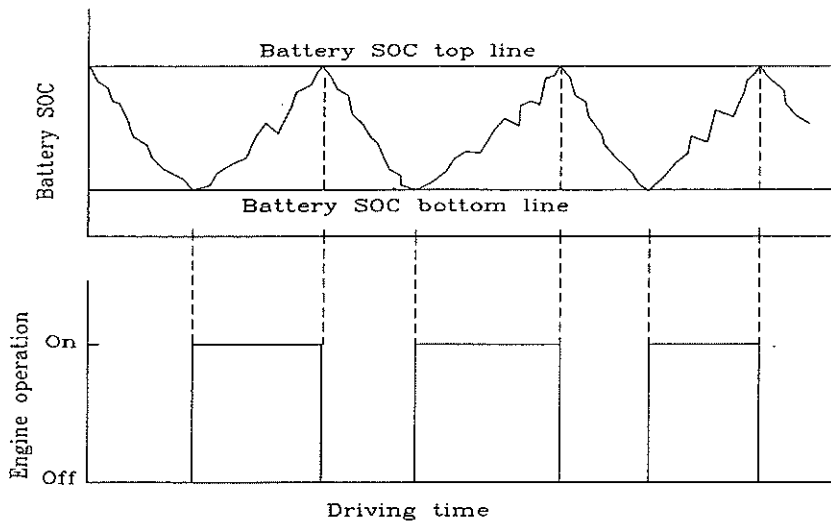
Fig.5 Illustration of the Engine Turn-on and Turn-off operation
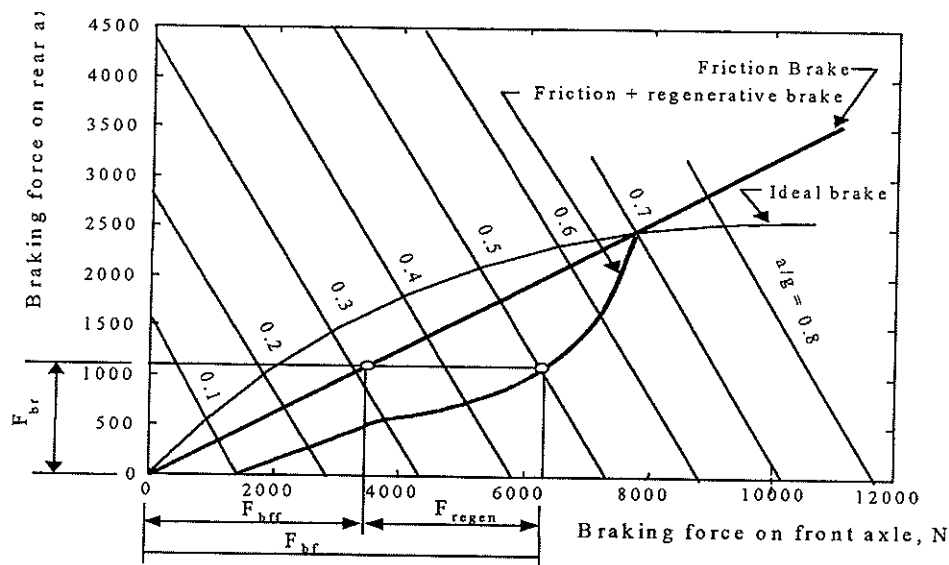
Fig.6 Demonstration of parallel braking principle
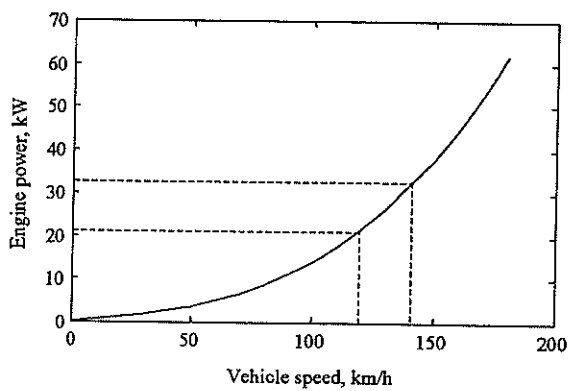
Fig.7 Engine power demand versus vehicle speed in steady driving
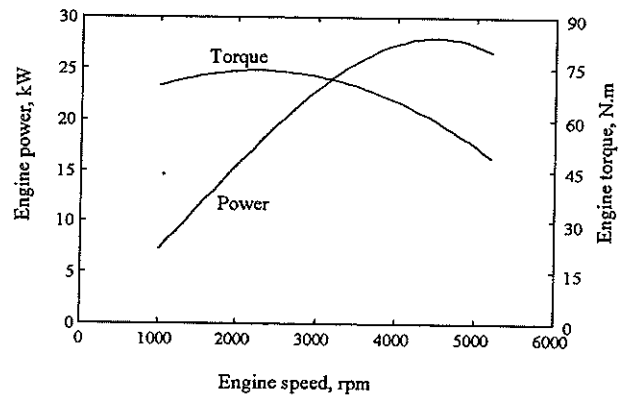
Fig.8 Speed-power and speed torque Characteristics if typical gasine engine
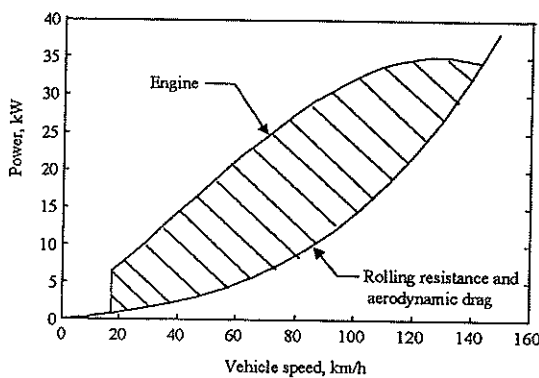
Fig.9 Illustration of the excess power of engine in acceleration
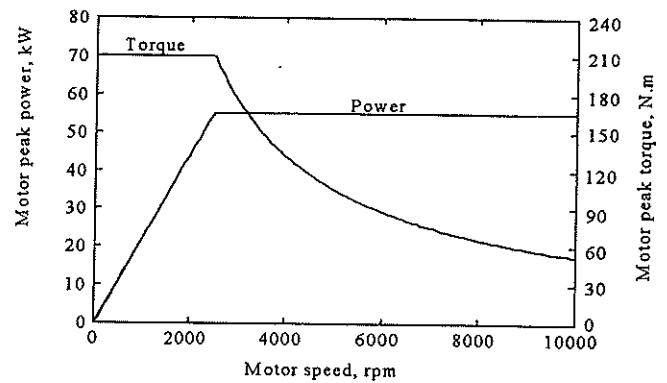
Fig.10 Electric motor characteristics
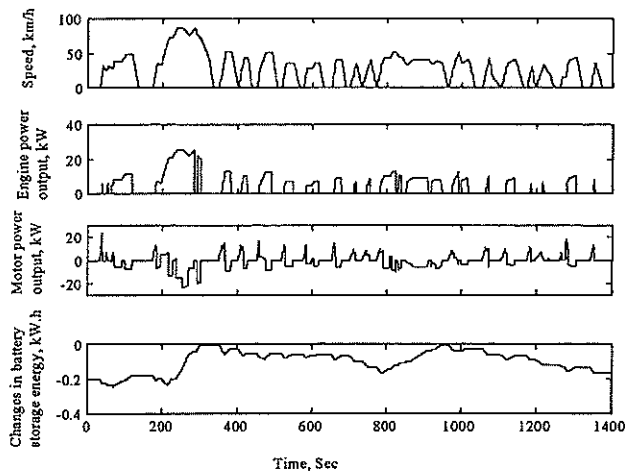
Fig.11 The time history of vehicle speed, engine power output, motor power output, and changes in battery storage energy in EPA FTP75 Urban Driving (regenerative braking unavailable)
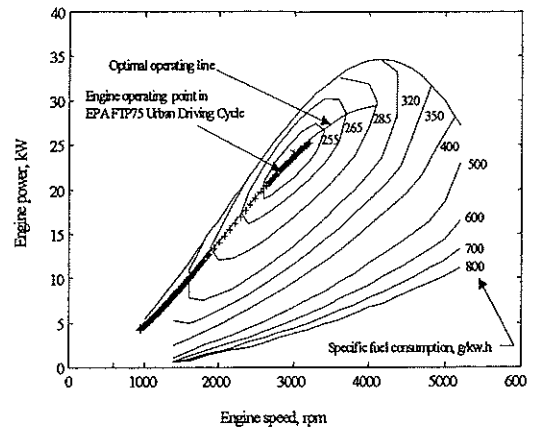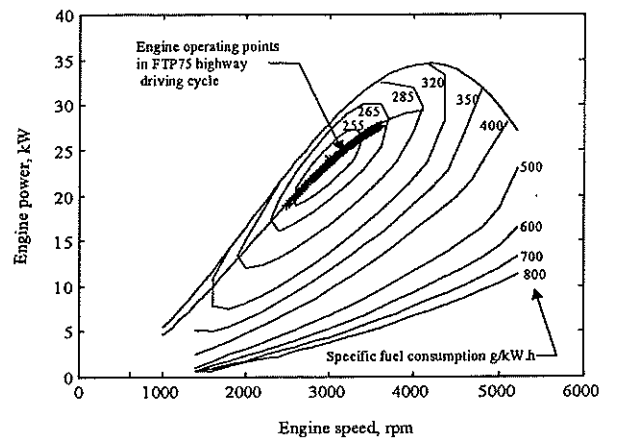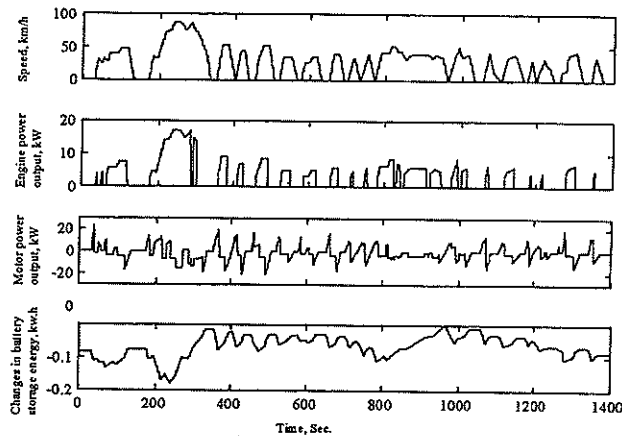

Fig. 12 Engine operating points on the fuel economy characteristics of the engine (regenerative braking unavailable)
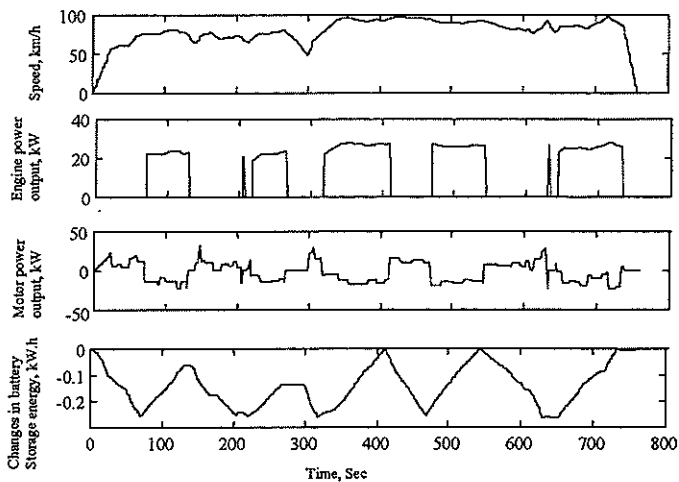
Fig. 13 The time history of vehicle speed, engine power output, motor power output, and changes in battery storage energy in EPA FTP75 Highway Driving (regenerative braking unavailable)

Fig. 14 Engine operating points on the fuel economy characteristics of the engine in EPA FTP75 highway driving (regenerative braking unavailable)
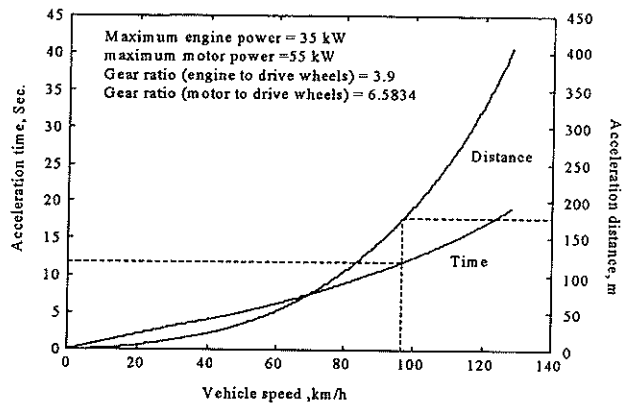
Fig. 15 Acceleration time and distance versus vehicle speed. (regenerative braking unavailable)
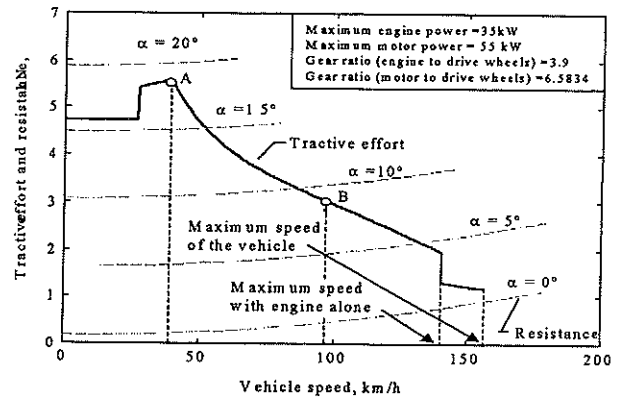
Fig. 16 Tractive effort and resistance on various grade of road versus vehicle speed (regenerative braking unavailable)

Fig.17 Time history of vehicle speed, engine power, motor power and changes in battery storage energy in EPA FTP75 urban driving cycle (regenerative braking available)
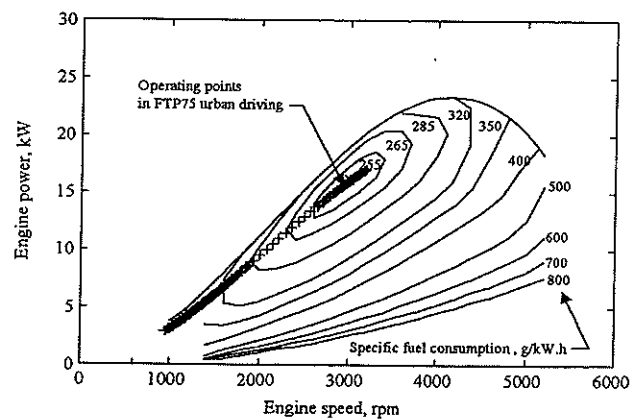

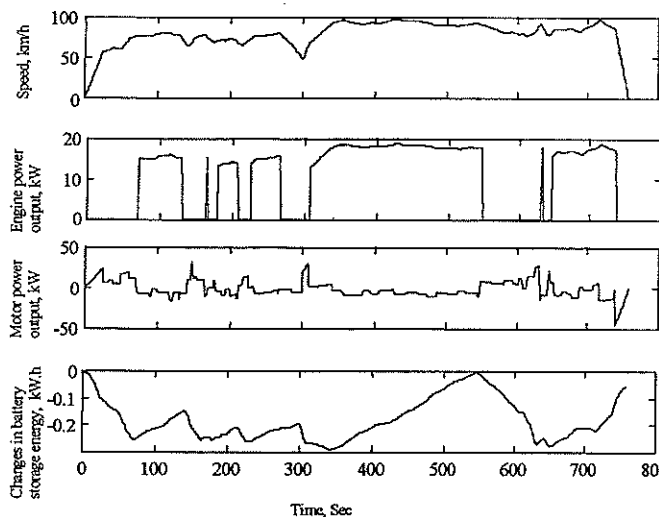Fig.18 Engine operating points on the fuel economy map (regenerative braking available)

Fig.19 Time history of vehicle speed, engine power, motor power and changes in battery storage energy in EPA FTP75 highway driving cycle (regenerative braking available)
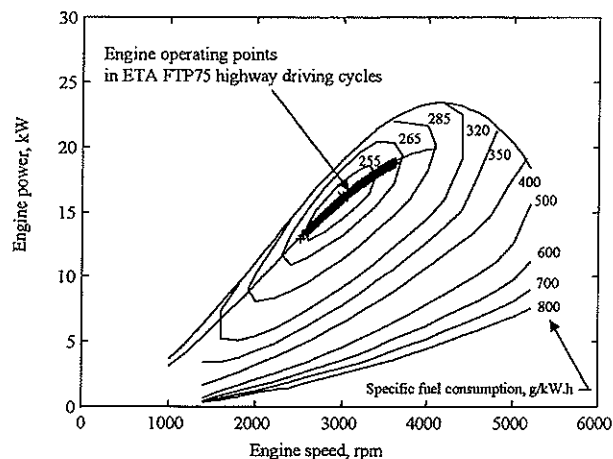

Fig.20 Engine operating points on the engine fuel consumption map. (regenerative braking available)
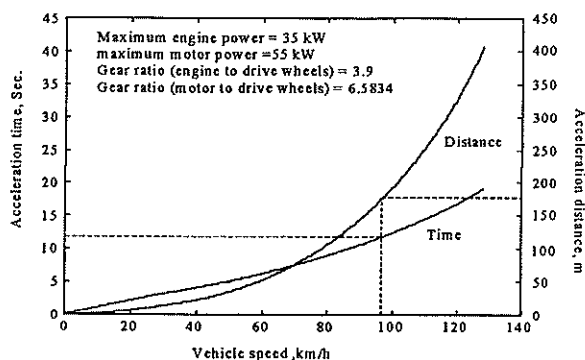

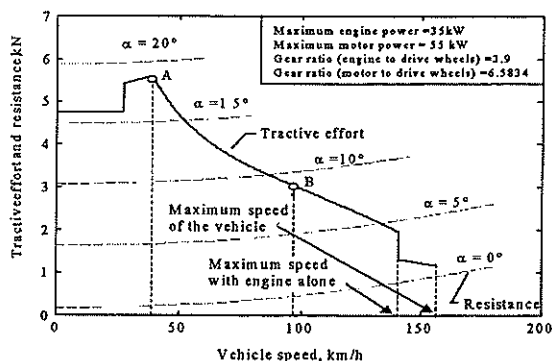Fig.21 Acceleration time and distance versus vehicle speed (regenerative braking avaialble)

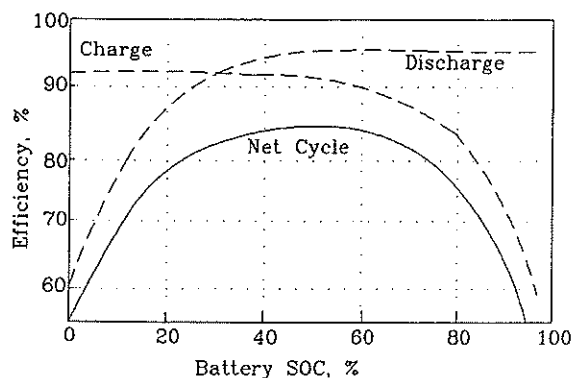Fig.22 Diagram of vehicle traction effort and resistance versus vehicle speed and road angles (regenerative braking available)

Fig.23 Battery efficiency versus state-of-charge

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