

DEVELOPMENT AND PERFORMANCE EVALUATION OF A PROTOTYPE ELECTRIC HYBRID POWERTRAIN SYSTEM FOR AUTOMOTIVE APPLICATIONS

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ABSTRAK

Researchers at Universiti Teknologi Malaysia (UTM) have developed a dedicated hybrid power plant based on the parallel configuration using a gasoline engine coupled to a high performance electric motor, specifically targeted for automotive application. The aims are to achieve even lower exhaust emissions, better fuel economy and better performance than the conventional arrangement, demonstrating an alternative solution to the conventional power plant. The engine used is a 1.3 litre spark-ignition, coupled with a 27.5 kW Nexus electric motor. The control strategy developed in conjunction with the program is to use the electric drive motor for initial acceleration and for regeneration braking energy recovery, and for reducing the peak load and transients seen by the engine. A relatively small pack of advanced lead acid batteries is use for energy storage. The design, development and evaluation exercises are fully described giving a comprehensive insight of the prototype and its capabilities.

Keywords : Automotive, parallel, electric motor, batteries, hybrid

NOMENCLATURE

P_{road}	Road power demand, kW
P_{roll}	Power to overcome rolling resistance, kW
P_{hill}	Power required for hill climbing, kW
P_{aero}	Power to overcome aerodynamic drag, kW
P_{accel}	Power for acceleration, kW
m	Mass, kg
g	Gravitational constant, 9.81 m/s^2
V	Velocity, m/s
C_{-r}	Rolling resistance coefficient
C_d	Aerodynamic drag coefficient
ρ	Density of air, kg/m^3
A	Frontal area of vehicle, m^2
ICE	Internal Combustion Engine
SOC	State of Charge
HEV	Hybrid Electric Vehicle

INTRODUCTION

Today's motorised vehicles can be improved from the perspective of fuel economy and emission. While the major auto manufacturers invest huge sums to perfect the fuel cell technology, electric hybrid system – a conventional internal combustion engine boosted by an electric motor – looks the more likely to be the interim technology, before fuel cell can be the ideal replacement of the low efficiency internal combustion engines.

Hybrid systems are essentially tandem energy sources. Hybrids offer major advantages - they can provide the best of both performance and fuel economy in the same package and able to capture energy usually lost in braking and recover it as electric energy. All these looks promising provided the systems be reasonably priced. Hybrid configurations are generally more complex in design compared to vehicles with conventional

powertrains. They contain various extra components and the interaction and energy flows between components, as well as their management is more complex. Despite this, it offers certain design flexibility as powertrain components can be placed in different parts of the vehicle where practical.

In a hybrid system, the internal combustion engine (ICE) can operate at a constant speed to charge the engine alternator and generate power for the electric traction motors - a series approach. Likewise, it is can be linked directly to the drive train and propel the vehicle in parallel using electric motors – a parallel system. A group of researchers from UTM has undertaken to develop a prototype electric hybrid power plant in the first of the many phases of the development program, from design to prototyping, dedicated for automotive application.

DESIGN OBJECTIVES

The aims of building the electric hybrid power plant are:

1. Component integration and design
2. Control algorithm
3. System architecture development

The unforeseeable objective is the establishment of the learning curve in developing such technology on a low cost research budget.

PARALLEL VERSUS SERIES

In initiating such a broad base R&D project, the choice of either series or parallel configuration must be seriously given due consideration.

Series Hybrids: Most beneficial in city driving conditions, since electric motors, which operate efficiently through a wide range of conditions, propel the vehicle. The IC engine can run at a constant speed to operate the

alternator, while regenerative braking captures braking efficiency energy normally lost to help charge the batteries. The engine of series hybrid is uncoupled from the road load and runs in either a fixed or a restricted range of operating points. The engine-generator set generally supplies the average demanded power, while an energy storage device (mostly batteries) supplies peak power.

Parallel Hybrids: Most efficient at highway speeds, since the IC engine is directly connected to the drive wheels and an electric motor can augment the IC engine during launches and acceleration. Regenerative braking and surplus power from the engine keep the batteries charged. The two power sources may contribute torque separately or in combination with each other. This offer design flexibility of the components placement.

The parallel hybrid electric configuration is the choice for two main reasons. First, a hybrid vehicle yields the most acceptable combination of the low emissions and high-energy economy achieved by electric vehicles with the superior range and performance of an IC engine vehicle [1]. Second, an extremely high efficiency IC engine was available to the team with a peak power of 54 kW (86 hp). These traits allow parallel hybrid to perform well in high load, high average power conditions. This is the choice of many interested parties and is well demonstrated by a group of engineering students (univ. of Wisconsin, US) who is an active participant in the annual Future Truck competition [2].

DESIGN OF HYBRID ELECTRIC VEHICLE

A hybrid electric vehicle (HEV) has two sources of on-board power. The integration of these power-producing components with the electrical energy storage components allows for many different types of HEV designs. The flexibility in the design comes from the ability of the control strategy to manage how much power is flowing to or from each component. This way, the components are match with the control strategy to achieve the optimal design for a given set of design constraints. There are many, often conflicting objectives desirable for HEVs. The primary ones being:

- maximise fuel economy
- minimise emissions
- minimise propulsion system to keep cost affordable
- do all the above while maintaining or improving upon acceptable performance (acceleration, range, noise etc.)

To achieve these objectives, both the hardware configuration and the power control strategy are integrated as a package. The hardware configuration dictates to some extent what control strategies make sense, although there is a wide spectrum of control strategies for each hardware configuration. As described earlier, a parallel hybrid configuration was selected based on the project requirements and literature studies. The series layout was not given consideration because of its low overall power conversion efficiency [2]. It is required to convert the mechanical energy of engine to electrical energy at the generator, and finally to mechanical energy at the motor.

In the parallel configuration, the engine and electric motor are parallel to one another, with their shafts coupled by a torque coupler so that the combined torque can be

absorb by the dynamometer (Figure 1). The torque coupler consists of, one-way clutch, electro-magnetic clutch and belt drive. With a one-way clutch on the engine shaft output, the electric motor can directed motive power to the dynamometer without driving the engine. Further, by decoupling the electro-magnetic clutch on the motor shaft, the engine can run independently as prime mover. The one-way clutch and electro-magnetic clutch transition the parallel hybrid powertrain from one mode of operation to another.

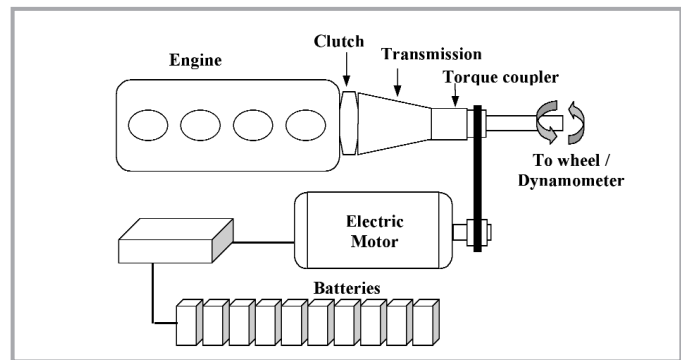


Figure 1: The parallel power plant configuration

VEHICLE ENERGY ANALYSIS

The Road power demand equation represents the energy consumption of a vehicle over a period. This equation defines how power is use in a vehicle as it travels down the road. It is the principle behind the vehicle simulation and all the components and modifications integrated into the vehicle. Equation 1 describes the road power demand in details.

$$P_{\text{road}} = P_{\text{roll}} + P_{\text{hill}} + P_{\text{aero}} + P_{\text{accel}} + P_{\text{aux}} \quad (1)$$

It encompasses all of the vehicle design aspects that UTM-HEV team could vary to improve the overall economy. The relative importance of reducing the different parameters of the equation is shown in Figure 2.

In order to increase the fuel economy of the vehicle the road power demand must be decreased, which is accomplish by reducing the power demands that make up the road power.

The power to overcome rolling resistance is equal to the product of the vehicle mass, gravity, velocity, coefficient of rolling resistance, and the cosine angle that the road makes with

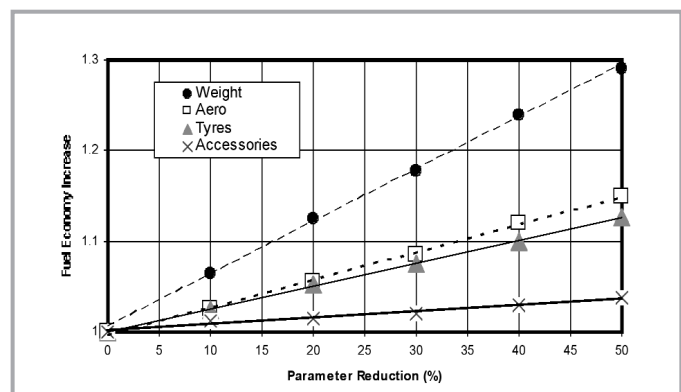


Figure 2: Parameter reduction to increase fuel economy [3]

level ground. Equation 2 describes this fact in details.

$$P_{\text{roll}} = mg V C_r \cos\theta \quad (2)$$

This power loss is reduced by aggressively pursuing weight reduction in the vehicle through numerous means. Selecting tyres with a very low rolling resistance will also prove the system performance.

The second portion of road power demand is the power required to climb hills. The value for the hill power loss is determined using Equation 3.

$$P_{\text{hill}} = mgV\sin\theta \quad (3)$$

Mass is the only portion of this equation that can be changed in the design.

The third power loss is due to aerodynamic drag. Shown as Equation 4, aerodynamic drag power loss is dependent on the air density, front area profile, velocity, and the coefficient of aerodynamic drag.

$$P_{\text{aero}} = 0.5 \rho A V^3 C_d \quad (4)$$

In the above equation, the front area profile and drag coefficient are the only changeable parameters.

Equation 5 is the power consumption caused by acceleration.

$$P_{\text{accel}} = d/dt E_{\text{kinetic}} = m V dV/dt \quad (5)$$

Again, mass reduction appears as a key to energy economy, but neither the velocity nor the change in velocity (with respect to time) are altered in the design.

The final portion of the road power demanded is the energy drawn by the auxiliary functions. This power consumption is reduced in the Perodua Rusa van by employing a smaller localised air conditioning system. Equations to quantify auxiliary power are more complex than this discussion warrants and have been omitted.

COMPUTER MODEL

A parallel hybrid drive train was conceptualised, simulated, fabricated, and assembled at the Automotive Development Centre (ADC), in UTM. All parts used were off-the-shelf, except for the control system, which was custom designed and fabricated.

Prior to developing the hardware, a rigorous computer model of the drive train was developed using the ADVISOR, a hybrid modeling and simulation software produced by NREL (National Renewable Energy Laboratory). For reasons of brevity, the mathematical model derivation of the drive train is omitted. ADVISOR is a Matlab/Simulink[®] based simulation analysis tool.

The developed computer model is of the forward-looking type, with a driver sending commands to the drive train controller based on vehicle speed deviation from the desired driving schedule.

DRIVETRAIN SIMULATION

The parallel electric hybrid power plant combines an IC engine and an electric motor, drawing energy from gasoline fuel and batteries. Prediction of how the changing one aspect of the drive train will interact and affect the performance of

the other systems becomes very difficult, especially under varying driving conditions. An effective control strategy must balance several design tradeoffs that each plays a role in the overall efficiency of the vehicle. The team needed an inexpensive but a fast method to make sound engineering decisions regarding what components to use and how to tune them once installed in the vehicle. For this reason, the research team developed the system using the computer simulation approach, i.e. the dynamic simulation program, i.e. the dynamic simulation program SIMULINK.

CONTROL STRATEGY

The team has also developed a hybrid control strategy capable of regulating state of charge (SOC) and load leveling. A SOC regulating strategy will monitor the battery voltage level and maintain the voltage within a prescribed range, neither full nor empty. Transient emissions caused by the changes in the engine load, was over come by the use of the electric motor. The gradual increase in engine power output is up set by the motor output. Buffering the engine from the road in this manner also increases the vehicle fuel economy. Keeping the average engine load within the permissible limits controls steady state emission concentrations.

The control system (refer Figure 3) was developed as a machine with four conditional states. Upon assigning the control strategy as a finite state machine, the software is restricted to run in a sequence of one state at a time. Since the current vehicle state can always be determined, each state can be tested, debugged, and tuned separately. Each of the states is reviewed in the following sections.

STATE 1: ENGINE ONLY

The first state is engine only mode. In this state, the vehicle operates as if the electrical system were not present. All pedal commands go directly to the engine and the motor provides no load leveling assistance. This state is use during vehicle forward driving, high speed coasting, and battery recharging operation. When conditions dictate for high voltage requirements, the state ceases to operate. The state is not for reverse driving.

STATE 2: ELECTRIC ONLY

The second state is electric only mode. In this state, the vehicle operates as pure electric vehicle. All pedal commands go to the electric motor through motor speed controller. This state is use during low speed operation or city driving and reverses driving within the sufficient SOC of the battery. When the battery SOC drops to low level, the state will automatically change to Hybrid state.

STATE 3: REGENERATIVE BRAKING

The third state is the regenerative braking system state. Regenerative braking is the act of using the mechanical energy from the wheels to drive the motor, generating electricity for storage in the battery. This process recharges the battery while decreasing the vehicle speed.

The vehicle goes into the regenerative braking state only if the brake pedal is depressed and the high voltage system has room to store energy. All regenerative braking commands are passed through a set of filters. The first filter reduces the regenerative motor commands at low velocities to avoid "chatter" present at

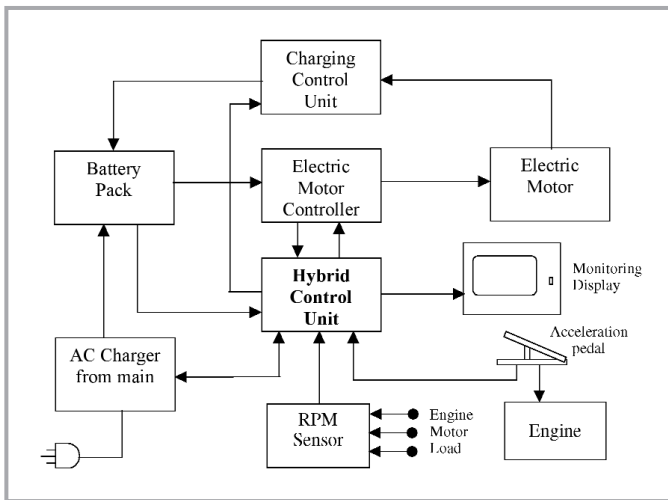


Figure 3: Schematic diagram of the control system

low motor speeds. The second filter reduces regenerative commands as the SOC approaches dangerously high levels.

STATE 4: HYBRID

HYBRID state is the forth and most common state of the control strategy. It contains the SOC regulator control code, that manages the battery voltage as previously described. The range within the high and low bounds of the SOC regulator is called the SOC dead-zone. The dead-zone, set approximately between 50 to 60% SOC, adjusts for the best efficiency during battery charging and discharging. While in the HEV state, the control system will make use of both the engine and the motor conditions to meet the driver's demands.

COMPONENTS IDENTIFICATION AND SELECTION

With the overall parallel powertrain chosen and the road load energy analysed, it was time to select the major components so that the complete drivetrain could be developed. Firstly, the two power sources must be determined. The team had selected the gasoline engine as the prime mover, while the electric motor as mover to augment the engine.

ENGINE

The engine is to provide the average power needed for all operating conditions. A Daihatsu gasoline 1.3 litre engine is use for the hybrid system design. The engine has sufficient power to maintain a highway cruising mode of 110 km/hr.

ELECTRIC MOTOR

One of the most critical components of a HEV is the electric motor. The selection was due to its efficiency, performance, functionality and size. DC motors are typically easier to

control, thus their controllers tend to be less expansive [4]. The Nexus brushed DC motor was the choice. It was originally develop as part of the hybrid electric-diesel bus drive system in the UK. The motor has a rated power of 27.5 kW (at 160 VDC, 60 minutes rating) and a peak torque of 180 Nm (at 55 kW). The speed range of the motor is up to 7000 rpm having a bulk mass of 80 kg and input voltage ranging from 24 to 160 V respectively.

With the power sources selected, the remaining components selection can now be made and the overall layout finalised. The parallel electric hybrid powertrain layout is shown in Figure 4. The components shown in this figure are described in the following paragraph.

A. ENGINE

The engine selected was a four cylinder, in-line, 53 kW, gasoline type. The engine and its accessories are supported by a custom-made frame.

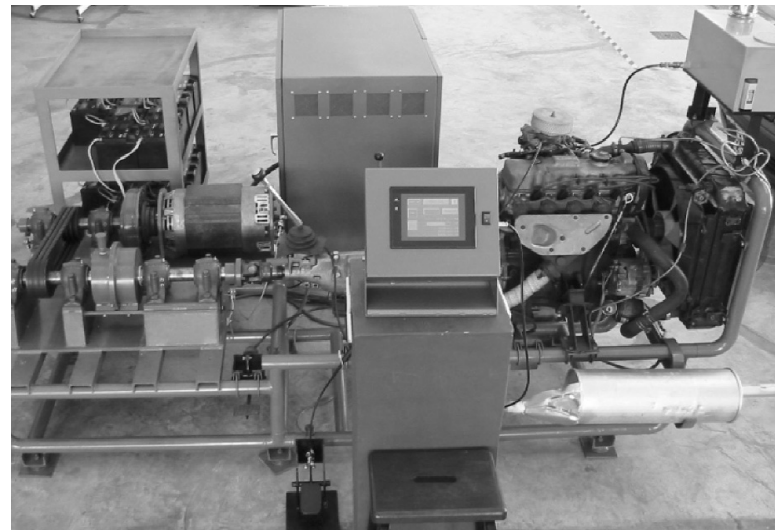


Figure 4: Photograph of the parallel hybrid power plant

B. ELECTRIC MOTOR

Nexus brushed DC motor with rated power of 27.5 kW and maximum torque of 180 Nm.

C. BATTERY PACK

Electrochemical batteries are the most commonly used devices in hybrid vehicles. Due to cost constraint and availability, Hawker Genesis advanced lead-acid battery was selected, with specification of 12 Volt and 42 Ah respectively. The batteries are arranged in series to supply power to the electric motor.

D. TRANSMISSION

A 5-speed manual transmission was used in the laboratory evaluation of the parallel hybrid arrangement.

E. CONTROL UNIT

The control unit built up of motor controller, speed encoder, switches, safety devices, and power electronic components. The heart of the hybrid control is the Siemen programmable logic controller (PLC), which integrates all components involved.

Table 1: Engine specifications

Type	Petrol engine, in-line, 4-cylinder, 4-cycle, 16 valve, SOHC
Displacement	1296 cc
Compression ratio	9.5:1
Max. output	54 kW/6000 rpm
Max. torque	101 Nm/3200 rpm

F. BELT DRIVE

The two parallel shafts were coupled by belt drive assembly and were supported by bearings. The structure of the platform enables drivetrain offset and adjustment to the tensioning of the drive belt be made.

G. ONE-WAY CLUTCH

In order to allow electric motor to operate without driving the engine, a one-way clutch or overrunning clutch is needed. This enables the engine to be isolated when it is not required, and to start and rotate up to the motor speed when its torque is needed to execute certain portion of the drive cycle. The Means One-way clutch which suitable for high rotational speed and torque for automotive transmission purpose is selected (refer to Figure 5.a).

H. ELECTRO-MAGNETIC CLUTCH

In engine mode operation, electric motor is disconnected from the main drive shaft. A high speed and high torque electro-magnetic clutch is needed for this application. Warner Electric clutch with static torque of 350 Nm and maximum running speed of 3600 rpm was selected (refer to Figure 5.b).

(a) One-way Clutch



(b) Electro-magnetic Clutch

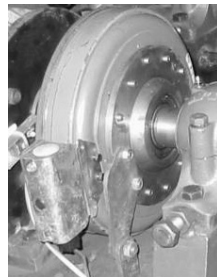


Figure 5: Photographs of the clutches

I. FLEXIBLE COUPLING

Flexible coupling protect against misalignment that may damage the components.

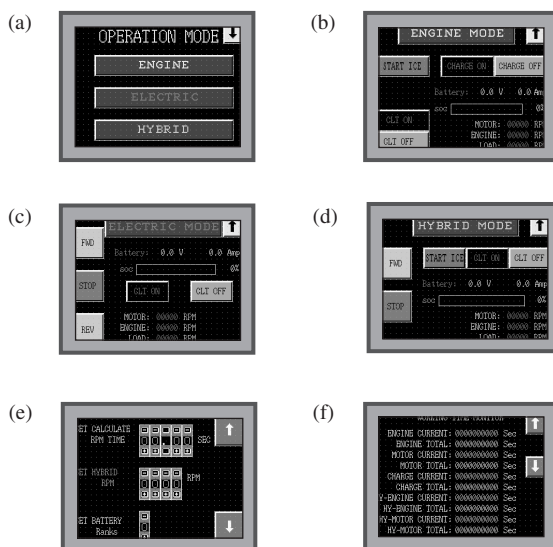


Figure 6: The displays of touch screen

J. ACCELERATION PEDAL

The acceleration pedal was a combination design specially to throttle the engine and control the electric motor speed.

K. TOUCH SCREEN

The touch screen facilitate display, monitor and control. It serves as a user-friendly way for control parameter input. Omron touch pad was selected. Figure 6 shows several views of touch screen display windows. When the system is switch on, the screen display three operation modes for selection (Figure 6.a). By touching the desire box on the screen will select the mode for driving. Each operation modes (Figure 6.b, c and d) display driving command (forward, reverse, and stop), electro-magnetic clutch status ("CLT ON" for clutch engage, "CLT OFF" for clutch disengage), button to start engine (ICE), battery SOC and rotational speed displays. Operator can also set parameter input (Figure 6.e) and monitor the working time of various components (Figure 6.f).

SEQUENCE OF OPERATION

The operation of hybrid electric vehicle is meant for maximising fuel economy and reducing emission that makes use the advantages of both power sources. Therefore, three modes of operation are specified. They are (i) Engine mode, (ii) Electric mode and (iii) Hybrid mode. The selection of mode depend on the driving requirement and available of battery charge. The battery level is measure in state of charge (SOC). When the battery is full, SOC indicates 100% and when the battery is empty, SOC indicates zero. The control system will monitor the SOC within the range of 40% to 100%. The three-operational mode control strategy is shown in Figure 7 and 8.

For high SOC, the vehicle operates as electric vehicle at low speed. When power requirement is above electric motor capability, engine will take over the driving task in hybrid mode. During high speed, the vehicle operates as conventional vehicle. Battery charging is possible. If hard acceleration or high power is needed exceeding engine capability, electric motor will assist in hybrid mode.

For low SOC, certainly the vehicle operates in engine mode and charges the battery whenever have excessive power.

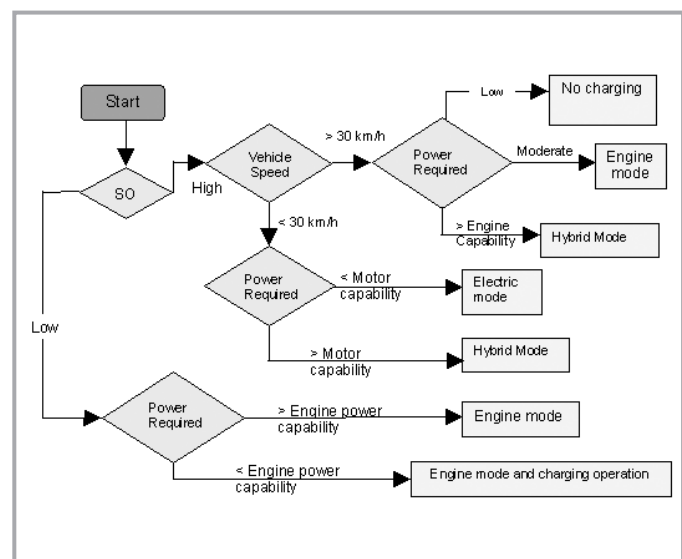


Figure 7: Flow chart of control strategy

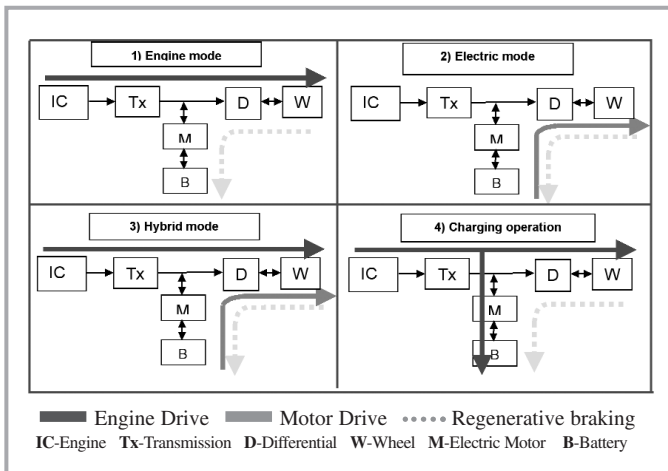


Figure 8: Power flow of multi-mode control strategy

ENGINE MODE

This mode is for highway driving and when the battery SOC is low. ICE provides power for forward driving requirement. The vehicle will function as conventional vehicle except for reversing, where the electric power is opt. Extra power of the engine is used to charge the battery until reaching high SOC. While charging, the electro-magnetic clutch will be engaged.

ELECTRIC MODE

This mode is for urban driving and when the battery SOC is high. The vehicle will be completely driven by the electric powered motor. The electro-magnetic clutch will be engaged. It is only intended for short driving range, which is restricted by the battery capacity.

HYBRID MODE

Hybrid mode is the most common mode during driving. In this mode, the electric motor is to accelerate the vehicle from rest to a speed of 30 km/h. Once reaching the speed, the engine is activated to provide motive power. The engine can adequately provide power up to 100 km/h and climbing at 5% gradient. During high acceleration and load, the motor will assist the engine in meeting the power demand. The vehicle drives in reverse when it is in the electric mode.

Regenerative braking will be present in all the modes to salvage the recovered energy and stored in the battery.

PERFORMANCE EVALUATION

Two driving cycles were used to predict the power plant performance and emission results, as shown in Figure 9. The Urban Dynamometer Driving Schedule (UDDS) was used for city test and represents city driving condition [5]. The Highway Fuel Economy Test (HWFET) on the other hand, is to simulate for highway driving. Currently it is used by the US EPA for Corporate Average Fuel Economy (CAFE) certification of passenger vehicles in the United States.

RESULTS AND DISCUSSION

The performances of the batteries, motor and engine (in conjunction with the UDDS driving cycle, in hybrid mode) are shown in Figure 10. The type of control strategy used is "parallel electric assist" [6]. Here the motor is to provide additional power when needed by the vehicle and to maintain the state of charge (SOC). By observing the battery

performance, the SOC is opted, and maintained above 60%. The initial battery SOC is 70%. Throughout the driving cycle, the engine is the sole source of power. It provides the average driving power to the vehicle while the motor is to augment the engine. As seen in the chart of motor power, the electric motor provides motive power during starting. Negative torque is noticeable in the motor during deceleration. At this stage, the motor acts as a generator to recover kinetic energy, which is used to charge the battery. As a whole, the simulated Parallel HEV is strictly in the path of the driving cycle.

Figure 11 shows comparison of the simulation results of conventional vehicle and parallel Hybrid Electric Vehicle

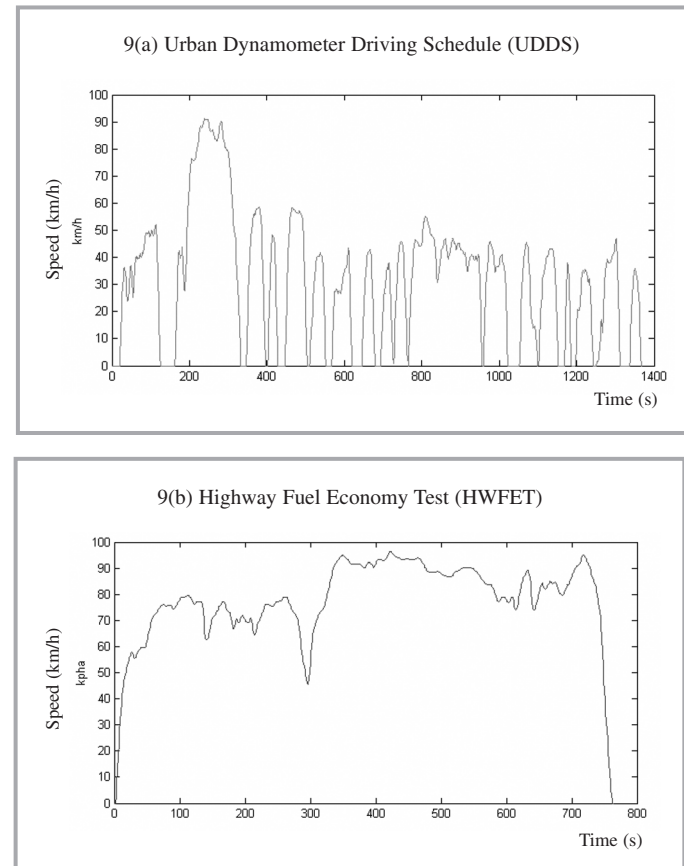


Figure 9: Driving cycle for power plant evaluation

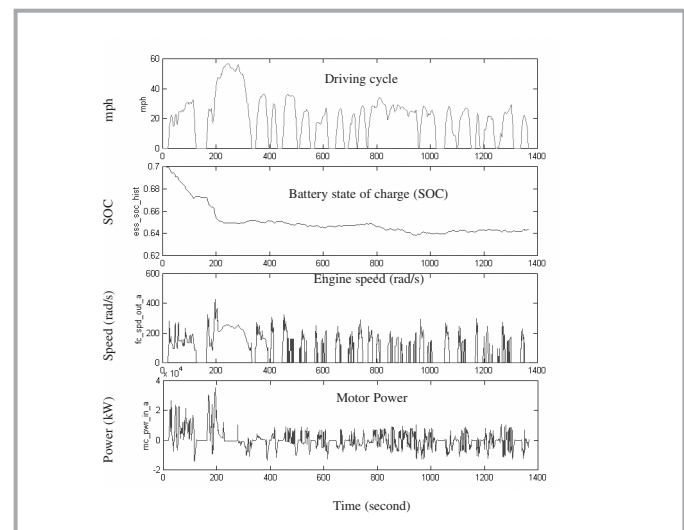


Figure 10: Simulation result of UDDS cycle

(HEV). Results indicate parallel HEV obtained fuel economy of 28.6 mpg as compared to 24.6 mpg of conventional power plant on the same platform running on the driving cycle of UDDS. HEV also achieved better acceleration performance. However, the gradeability at 55 mph is lower than conventional vehicle because hybrid vehicle carries extra weight of batteries and electric motor. Gradeability refers to the maximum grade the vehicle is able to maintain at 55 mph for 10 seconds. It is based on the requirement of PNGV (Partnership for a New Generation of Vehicle) associate with fuel economy and emission.

Table 2 summarises the emission concentration produced in UDDS cycle. Here the total emission concentration was

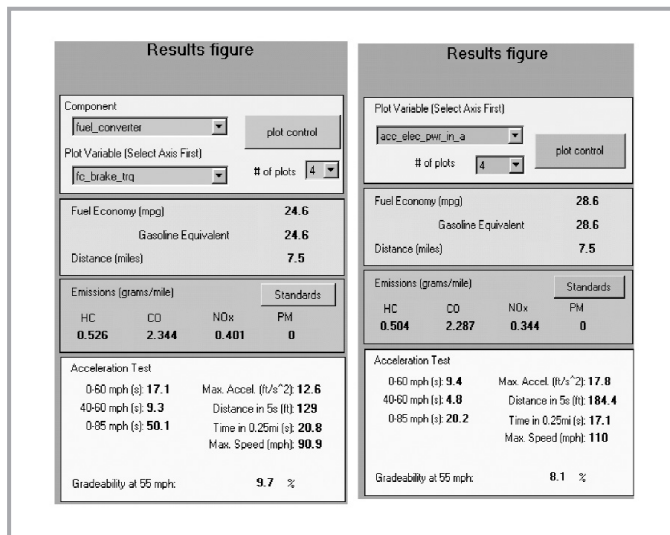


Figure 11: Results of conventional vehicle and hybrid electric vehicle

reduced drastically. Both the UDDS and HWFET test cycles depict promising results from the emission perspective. Same vehicle parameters were used which is the Perodua Rusa van with coefficient of drag 0.5, coefficient of rolling resistant 0.015 and frontal area of 2.221 m². Both used the 54 kW engine. Figure 12 illustrates the results. High emission can only be seen in the beginning of the cycle. Hybrid operation in electric mode assists in keeping the emission level to the minimum.

Table 2: Emission levels

Regulated Emission	Emission Levels (gram/mile)
Hydrocarbon (HC)	0.504
Carbon Monoxide (CO)	2.207
NOx	0.344
Particle Material (PM)	0

CONCLUSIONS

A parallel hybrid power train system based on the combination of an internal combustion engine and a dedicated electric motor was successfully developed and evaluated. The hybrid control strategy is to use the electric motor for initial acceleration, for battery charging and regenerative braking energy recovery, and to assist the engine when it's not operate effectively. This has been well developed and demonstrated to be feasible. From the

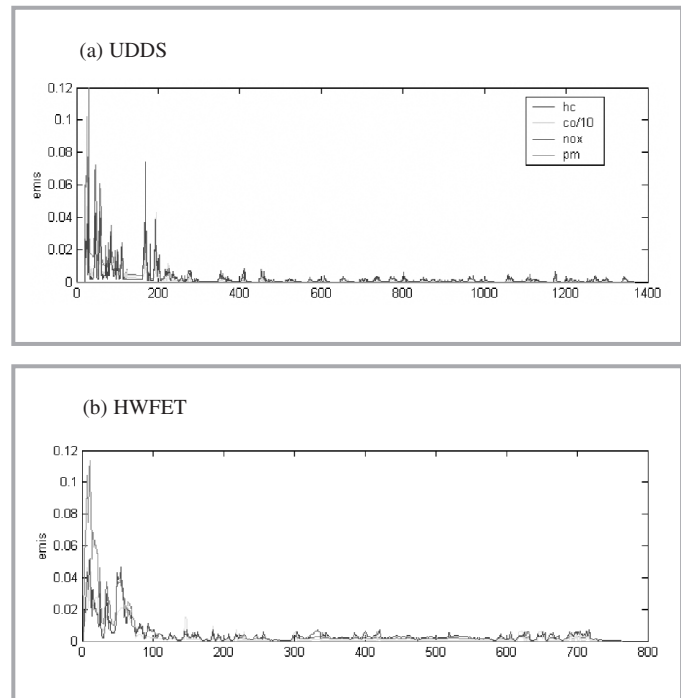


Figure 12: Emission charts

aspects of performance, the system has demonstrated its potential to minimise emission and fuel economy.

The completion of parallel electric hybrid prototype has brought many challenges and new ideas for improvement. In the second phase of the project, it will focus on the refinement of the complete system to render it having higher power-to-weight, smooth switching modes and power-to-volume ratios, suitable for fitting onto a platform (reference vehicle) for field trial evaluations.

ACKNOWLEDGEMENTS

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INFORMATION

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The main object of the refereeing procedure is to protect the reputation of the journal by excluding any material which is not original or significant or which is not sufficiently concise or well presented. A referee need not concern himself if with minor editorial matters.

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Experimental result can often be displayed more effectively by means of graphs than by tabulation, but, when a graph shows merely a simple mathematical law, it should be omitted and the author should be asked to

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CONTENT

- 1 Kesan Kuantiti Agen Penyerak Dalam Pencirian Saiz Zarah Oksida Seramik Menggunakan Kaedah Pembelajaran Laser by A. Muchtar
- 6 Analysis of Design Parameter Effects on Vibration Modes of a Motorcycle Drum Brake and Brake Shoe Using the Finite Element Method by Zahrul Fuadi
- 13 Elasto-Plastic Deformation of Hostun Sand During Cyclic Loading in Triaxial Test by Eqramul Hoque
- 19 A Generalised Price-Scoring Model for Tender Evaluation by Thum Peng Chew
- 28 Numerical Modelling of Reverse Pulse Cleaning on Rigid Ceramic Filters by T. G. Chuah
- 34 A Method to Evaluate Design Efficiency Based on Assembly Criteria in Support of Design for Modularity by A. B. Abdullah
- 41 Bedload Transport Model for Field Conditions - Using Characteristic Diameter Approach by Mohammad Ashiq
- 53 Highly Reactive Electrogenerated Zinc: Perparation and its Use in Cross-Coupling Reactions by Aishah Abdul Jalil
- 61 Determination of Probability Distribution for Data on Rainfall and Flood Levels in Bangladesh by M. Ferdows
- 73 Development and Performance Evaluation of a Prototype Electric Hybrid Powertrain System for Automotive Applications by Azhar Abdul Aziz

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