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Modelling and control of 4WD parallel split hybrid electric vehicle converted from a conventional vehicle

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Abstract. This paper presents a HEV modelling and simulation that incorporates both energy management system (EMS) controller and vehicle dynamics controller (VDC) which was converted from a conventional vehicle. Prior to building the HEV model, a vehicle dynamics experiment was conducted purposely to validate to base model created in ADAMS/Car. The base and HEV vehicle model was built in ADAMS/Car whilst the controller which includes the EMS and VDC was built in MATLAB/Simulink by utilising the Fuzzy Logic Controller (FLC). The HEV model and its controllers were analyzed for its performance and characteristics using co-simulation environment between ADAMS/Car and MATLAB/Simulink. Initially, separate sets of simulations were performed to test the operations of the vehicle dynamic controller and energy management controller. The model was found to have improved in handling characteristics and the results from EMS controller was found to be in close agreement with the results of the model simulated using ADVISOR. Later, an integrated simulation set was conducted with two controllers functioning concurrently and an additional simulation concentrating on the fuel usage during cornering was conducted. The results revealed that the HEV model has shown some improvement in term of fuel consumption and handling in comparison to the base model. The results obtained from the simulations revealed that the HEV model converted from a conventional vehicle proposed in this research was a success.

Keywords: converted conventional vehicle, HEV, co-simulation, fuzzy logic control, vehicle dynamic control, energy management control, ADVISOR

1 Introduction

Converting a conventional car powered by internal combustion engine (ICE) into a Hybrid Electric Vehicle (HEV) is one of the methods employed in the development of a HEV. This type of HEVs are developed based on the modification from existing conventional car, where the modified conventional vehicle cum HEV has an additional propulsion system that can either assist or propel the vehicle. Some examples of this technology are the Poulsen Hybrid® Power Assist System[2], the REVOLO[3], and MIRA's H4V Plug-in Hybrid[4].

The approach of converting a conventional vehicle into a hybrid vehicle is an alternative solution to reduce the increasing numbers of vehicles in production nowadays because the aging cars can be upgraded with better version. The value of existing cars deteriorates every year, causing the owners to have less chance to own a new vehicle because the trade-in value is much less than the cost of a new car. Therefore, conversion of an existing vehicle into a hybrid vehicle could be one of the solutions to the problems.

By having a HEV model built from a conventional vehicle, it is expected that the HEV model would have the same driving characteristic as the base model. In addition, the HEV model would also improve the performance in term of fuel consumption and handling compared to original vehicle. The HEV must have the same characteristic as the original vehicle in order to avoid the driver from feeling any difference or irregularities when driving a conventional vehicle retrofitted with the IWM.

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In most common practice, prior to converting the conventional car into a HEV, modelling work using commercial software is required. The vehicle model must resemble the actual vehicle as close as possible. Previous works on modelling of a converted conventional car into a HEV is very common but very few literatures can be found because most automotive manufacturers tend to keep secrets from their competitors. Therefore, due to the lack of literatures, general work related to the HEV designs and modelling are essentials for the reference/guidance of converting a conventional car into HEV.

For the optimization of energy management, several commercial software had been utilized by researchers together with their proposed controllers. Brian et. al. had utilitized the co-simulation of MATLAB/Simulink and ADAMS/car to simulate the energy management system of his HEV. The vehicle model was built in ADAMS/Car while the rest of the systems inclusive of the controller were built in MATLAB/Simulink [7].

Due to the modifications imposed on the conventional car, the handling characteristics of the new modified cum HEV have changed owing to the additional masses such as batteries, controller, motors, etc. Therefore, the new HEV requires a vehicle dynamics controller in order to ensure that the handling characteristic such as under steer gradient matches the original car. Several forms of control system designs had been proposed or developed by previous researchers both for HEV and electric vehicles. Most of the researchers[10, 16, 19] made use of Direct Yaw control to stabilize their vehicles but using different approaches in the control design implementation. The common methods[10, 19] used to control vehicle models were the PID controller which equations were derived from 2-D Bicycle Model. The derived equation should suit the behaviour of the desired vehicle characteristics. Researchers[14, 16] had implemented fuzzy logic controllers to control their vehicle model and it was found that the controller was simpler and easier to develop as compared to the PID controllers. In general, it was discovered that all the objectives could be met regardless of the type of controller being used.

The robustness and flexibility of the fuzzy logic controller in optimizing its component has become the preferred control method for the energy management of the HEV[1, 6, 9, 15]. All the research works[8, 11, 13, 18, 20] which were conducted have the same objective namely to optimize the fuel economy as well as to reduce the emissions. In order to achieve these objectives, several control strategies had been implemented. The most common implemented strategies were the driver's input must be followed consistently, and the battery must be sufficiently charged all the time[8, 11, 13, 18, 20]. Additional control strategy proposed by researchers[11, 13] was to improve the overall system efficiency; therefore the extended driving range could be achieved. In addition to the common control strategies mentioned earlier, H. Hannoun et al. [8] specified the strategy to reduce the fuel consumption and also CO_2 emission. N. J Shouten et al. [20] on the other hands was aiming at maintaining or enhancing the vehicle performance measure such as grade ability, acceleration etc. The control was implemented so that the vehicle performances were not sacrificed during control strategy design. It was observed that some strategies have become common in the design of a control system because the results of the control were satisfactory.

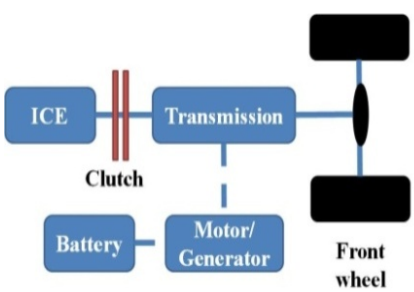

Fig. 1. Common parallel hybrid used by other researchers

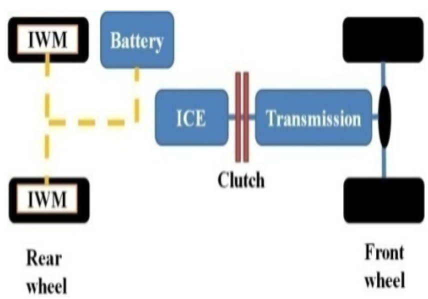

Fig. 2. Proposed parallel hybrid configuration

The common configuration of HEVs proposed by the previous researchers can summarized in Fig. 1. In general, the basic configuration of HEV consists of both the motors/generators and ICE which are attached together to the final common driveline with each possessing a clutch.

The purpose of this paper is to present the modelling, simulation and control involved in converting a conventional car into a HEV. The main scope of research includes vehicle modelling, vehicle dynamic control (VDC) and energy management system (EMS). The HEV software model was created by building a complete vehicle model with its subsystems in ADAMS/Car together with the ICE and in-wheel motor (IWM). The control was modelled separately in MATLAB/Simulink; and the two sets of software were then integrated in a co-simulation environment. The energy management controller allocates the torque to be provided by ICE and IWM in order to achieve the target which is to optimize the fuel consumption and at the same time to reduce the emission. On the other hands, the vehicle dynamic controller assists the movement of the vehicle during manoeuvres depending on driving conditions. The IWMs are independently controlled both during driving assistance and regenerative braking.

Some software was designed to perform discrete simulations only. In this research, the HEV model is required to be simulated with two different requirements but within the same time. Therefore, co-simulation method was chosen to suit this purpose. The method allows interaction between the software to compute the required tasks in a continuous manner.

In this research, a custom modified HEV was built from a conventional commercial vehicle (WAJA) produced by a Malaysian company, Proton. A parallel configuration was adapted as found in the previous research by researchers[12, 17] but their vehicle models were slightly different from the common parallel configurations because the motors were directly attached to the rear wheels. Each rear wheel was retrofitted with IWMs while the ICE is used to drive the front wheels. The configuration of the HEV is shown in Fig. 2.

In this research, the HEV is designed to have two modes of driving conditions. At low vehicle forward speed (0 - 30km/h), the HEV is only driven by the ICE. At specified vehicle forward medium speed (40 - 60 km/h), the HEV will be powered by both ICE and the IWM. During this mode, the controller will ensure that the ICE will run at its most efficient performance by controlling the IWM to assist the movement of the vehicle or performed a regenerative braking. If the energy from the battery reduces to a certain state of charge (SoC), the engine will run at full capacity and at this time IWMs will act as generators to charge the batteries. On the other hands, at high vehicle speed, the ICE provides all the propulsion power.

The strategy utilized for the EMS control is the efficiency strategy. The idea is to enable the ICE to operate about it's peak efficiency region. The operating points in this strategy are set near the torque region in which the efficiency is at maximum for that particular engine speed. Electric motor is used as a load leveller, where the motor will force the engine to operate in a region that consumes less fuel and at the same time maintaining the SoC of the battery pack.

2 Hev modelling

The model of the actual vehicle (base model) was built in ADAMS/Car prior to creating the HEV model. Unlike the base model, the HEV model has additional drive and masses at the rear wheel which represent the batteries as well as the controller for the IWM. Other subsystems in the HEV model are the same as the base model subsystem. In order to ensure that the model behaves like an actual vehicle, all the subsystems were modeled in accordance to the actual vehicle as much as possible. All templates in the subsystems used in ADAMS/Car were modified to match the characteristics of the actual vehicle.

The chassis of the vehicle was built as a rigid body subjected to drag force, Fd and pitching moment, T. The equation of drag force and pitching moment is shown in Eq. (1) and (2) respectively.

$$F_d = 0.5\rho C_d A V_x^2, \tag{1}$$

$$T = Fx \quad ride \quad height. \tag{2}$$

The body chassis is mounted on fronts and rear suspensions namely MacPherson and multilink; hence it is also subjected to the roll moment. The configuration of the rear multi-link suspension is different from the available multi-link suspension template found in ADAMS/Car. Therefore, the existing template available in ADAMS/car was modified to represent the actual vehicle suspension as shown in Fig 3.

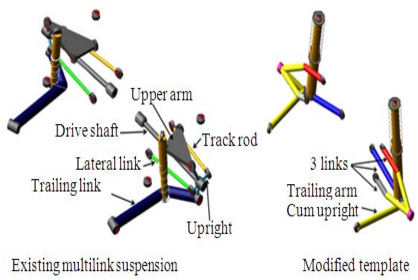

Fig. 3. Modification of existing multi-link suspension template

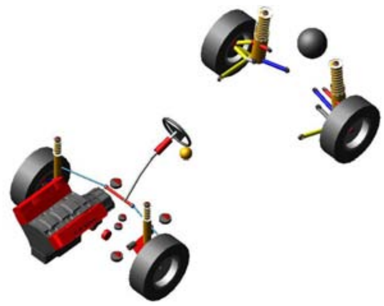

Fig. 4. Full HEV assembly in ADAMS/Car

For simplicity of modelling, several assumptions were made such as all the links were assumed to be consisted of rods. The complexity of the upright was simplified to represent a single construction combining with the trailing arm. In order to ensure the accuracy of the simulation results, the centre of gravity and the moment of inertia of each of the actual suspension links was determined using CAD software (CATIA). The data was then entered into the ADAMS/car modified templates to represent the actual suspension properties. Several modifications were made to the base model in order to build the HEV model. One of the modifications was to attach additional drive at each of the rear wheel to represent electric motors using torque function in ADAMS/Car. The function was defined as a single component torque acting along y-axis at each of the rear wheel. In order for the torque to activate according to the driving condition, it receives the input from MATLAB/Simulink. Another modification includes the attachment of the batteries and controller centre of mass. Both the batteries and the controller which give an extra 100kg to the existing vehicle weight were represented as a lump mass attached to the rear vehicle body. Fig. 4 shows a complete HEV model assembled with all the subsystems.

In addition to ADAMS/Car model, the modelling for control system and electrical parts such as battery and IWM was done in MATLAB/Simulink. The model built in MATLAB/Simulink comprises of several blocks which are the ADAMS/Car model and also the control block. ADAMS/Car block consists of input and output parameters which were defined in ADAMS/Car software itself. On the other hands, the control block consists of a few other sub-blocks such as the driver model, tractive force, vehicle dynamics reference, etc. (Fig. 5).

The driver model used the PID controller to control the input either to provide thorttle or braking demand for the vehicle model. The input is obtained from comparison between actual velocity and velocity input from ADAMS/Car. The comparison produced a velocity error in which this error was used as an input for the PID controller. The output from the PID controller was the percentage throttle and percentage braking. Any value above zero which is positive value was treated as throttling value whereas negative value was set to be the braking percentage. The PID controller was used to represent the driver model because of its ability to be tuned based on the simulation requirement.

The tractive force required to move the HEV is computed using vehicle dynamics equation of motions. The equation is:

$$M\frac{\mathrm{d}V}{\mathrm{d}t} = (F_{tf}) - (F_{rf} + F_{rr} + F_w + F_g), \tag{3}$$

where M is the vehicle mass, F_{tf} is the vehicle tractive force (front), F_{rf} is the front rolling resistance, F_{rr} is the rear rolling resistance, F_w is the drag resistance and F_g is the grading resistance. For control purposes, a 2-degree of freedom bicycle model which provides the side slip angle and yaw rate as used as inputs to the controller. The equation shown below is in a state space form is shown as follows:

$$\dot{x} = Ax + B\delta_f, \tag{4}$$

$$x = [B, \gamma]^t, \tag{5}$$

$$A = \left[\begin{array}{cc} -2\frac{C_f - C_r}{mV} & -1 - 2\frac{l_f C_f - l_r C_r}{mV^2} \\ -2\frac{l_f C_f - l_r C_r}{IV} & -2\frac{l_f^2 C_f - l_r^2 C_r}{IV} \end{array} \right], \tag{6}$$

$$B = \left[\begin{array}{cc} \frac{2C_f}{mV} & \frac{2l_f C_f}{I} \end{array} \right], \tag{7}$$

Where C_f is the front cornering stiffness, C_r is the rear cornering stiffness, l_f is the centre of mass distance to the front, l_r is the centre of mass distance to the rear, m is the vehicle mass, V is the vehicle velocity and I is the vehicle mass moment of inertia.

The propulsion for the rear wheels come from two IWM installed independently at the wheel. In order for the IWM to move the vehicle, it requires a torque which can be calculated using the following equation:

$$T = K_t I_{\text{demand}}, \tag{8}$$

K_t is the motor toque constant. The value was obtained from a look up table and it was built as a function of the vehicle speed. I_{demand} is the current demand and the value is obtained from the controller which provides the right amount of current corresponding to the driver's driving condition.

As for the energy storage system, it was modeled as a circuit with open circuit voltage source (V_{oc}) in series with the effective internal resistance (R_{int}) as a function of SoC. This block contains another subsystems that limit the power output of the battery, calculate the current output and compute the SoC of the battery. The power limiter restricts the current demand from exceeding its limit by considering three limitations such as the SoC, circuit parameters and minimum allowable voltage. Once the limitation is satisfied, the output current is calculated using the following equation:

$$I_{\text{out}} = \frac{V_{oc} - \sqrt{V_{oc}^2 - 4RP_{\text{out}}}}{2R}, \tag{9}$$

Where, V_{oc} is the open circuit voltage, P_{out} is the power output and is the battery internal resistance. Finally, the corresponding SoC of the battery is calculated using the following equation:

$$\text{SoC} = \frac{\text{Max} \quad \text{capacity} - Ah \quad \text{used}}{\text{Max} \quad \text{capacity}}, \tag{10}$$

3 Experimental works

In this research, the experiments were conducted mainly for the validation of vehicle models in ADAMS/car. The experiments were vital in order to ensure the accuracy of results when designing the HEV model. A unit of data logger called DL2 manufactured by Race Technology[5] was used to acquire the vehicle dynamics parameters such as forward speed, yaw velocity, lateral acceleration, etc. The equipment was capable of storing data over 30 channels (e.g. speed, acceleration, engine speed, and etc.) in over 100 times every second. The unit utilised a very high accuracy global positioning system (GPS) data logger operating at 20Hz (no interpolation) and also equipped with three axis 6g built-in accelerometer. The steering angle data was measured using a potentiometer attached to the steering column on the actual vehicle. The magnetic based antenna was mounted on the top of the vehicle to receive satellite signal and the data logger was placed approximately at the centre of gravity of the vehicle (Fig. 6). The types of experiments conducted on the real vehicle were step steer and single lane change manoeuvres. For the step steer test, the vehicle was driven to an approximate speed of 40km/h and then the steering wheel was steered from straight ahead position to an angle of 90^o within approximately 0.5 seconds. Meanwhile, for the single lane change test, the vehicle was driven at a constant speed of 40km/h and after a certain period, the steering wheel was steered from a straight ahead position to 90^o steering wheel angle in a few seconds (either to the left or right) and after some period, the steering was steered back to its original position (zero degree).

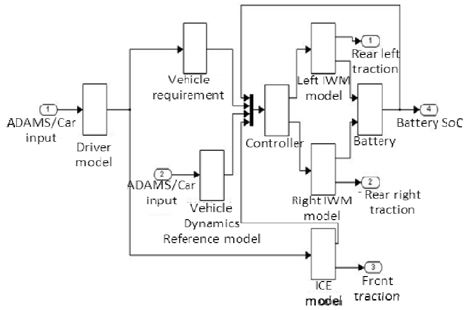

Fig. 5. Overall structure of control block

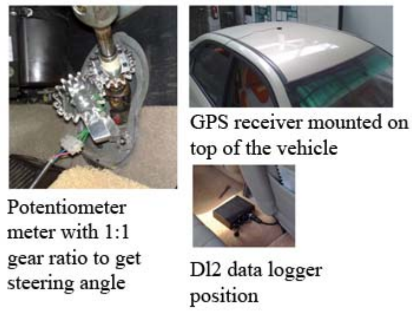

Fig. 6. Experiment setup on actual vehicle

The main expected results from the experiments are the steering wheel angle and lateral accelerations as functions of time. In order to compare the simulation results such as lateral acceleration with the experimental data, the same steering wheel input obtained from the experiments were used in the simulation.

4 Vehicle control

The ultimate goal for such HEV design is to enable the ICE to operate at its most efficient condition thus reduces the fuel consumption of the vehicle. Therefore, the proposal may improve the overall powertrain's efficiency. In order to ensure smooth operation of the ICE and IWM in vehicle dynamics handling, the HEV model in ADAMS/Car was equipped with a control method that can control the distribution of the required torque which ensures that the power train will deliver an efficient output torque. The proportion of the torque provided between the ICE and the IWM was controlled in MATLAB/Simulink with a fuzzy logic controller.

Commonly, there are two strategies that can be implemented in order to determine the torque proportion between the ICE and the IWM namely the fuel use strategy and the efficiency strategy. The first strategy makes use of the fuel control where the controller limits the amount of spent fuel not to exceed beyond a particular value regardless of the efficiency of the ICE. The second strategy imposed the efficiency control where the controller ensures that the engine is always running at its best efficiency. The latter strategy suits the objective of the installed IWM because it assists the vehicle during medium forward speed driving, and therefore this control strategy has been adopted for this research. The existence of the IWM helps the ICE operate with less fuel consumption and at the same time maintaining the State of Charge (SoC) of the battery pack over the drive cycle. This could be achieved because the IWM could compensate the lack of engine torque required to meet the driving condition.

Several rules and conditions stated in Tabs. 1 and 2 were set for the implementation of the HEV control. These rules are the inputs for the controller in deciding the amount of torque that the ICE and IWM need to produce in order to meet the objective. The fuzzy logic controller utilized in this research is an integrated controller which combines the energy management system and vehicle dynamics control. The first stage is the energy management controller while the second stage is the vehicle dynamics controller. The capability of fuzzy logic controller in receiving several inputs and producing several outputs has been an added advantage[8, 11, 13, 18].

Table 1. EMS control strategy

Motor assist mode	Motor regen mode
$Throttle\% > 50\%$	$Throttle\% < 0\%$
Target velocity > achieve velocity	Target velocity < achieve velocity
$Engineefficiency < 0.2$	$SoC < 60\%$
Vehicle is accelerating	Vehicle is decelerating

Table 2. VDC strategy(Vehicle Dynamic controller strategies)

Input	Left IWM	Right IWM
Steer angle steer to left, yaw rate error > 0	Regen	Assist
Steer angle steer to right, yaw rate error < 0	Assist	Regen

The inputs to the first stage controller are the steering wheel angle, percentage of throttle and braking, and vehicle speed which are obtained from HEV model built in ADAMS/Car. The second stage controller controls the proportion of torque between the left IWM and right IWM. This controller is activated when a driving condition requires suitable amount of torque to be proportioned between left and right wheels, upon receiving the inputs such as steering wheel angle and yaw rate error.

During the energy management mode control, the drive cycle provides a velocity reference to the driver model which provides the driver's command to the fuzzy logic controller. This driver command is actually represented by the velocity error between the drive cycle and HEV model in ADAMS/Car. The percentages of the throttle (positive value) or braking/regeneration (negative value) determine the amount of torque proportion between ICE and IWM.

When the controller detected a signal representing the yaw rate and lateral acceleration differences, it will automatically shift the mode from energy management control to vehicle dynamic control. A reference model representing a 2-DOF bicycle model was used in the control. The equation was described in section 2 page 6 of this paper. It computes the side slip angle and yaw rate for the reference model.

When a vehicle endures several manoeuvres such as changing lane, making a U turn or sudden steer angle change, it will experience understeer or oversteer effects. This occurrence will yield slight difference in term of yaw rate, and lateral acceleration in comparison to the reference model. The difference was used as an input for the fuzzy logic controller to control the torque to be supplied to the right and left IWM so that smooth cornering characteristics can be realized.

5 Results and discussion

In this section, the results which will be discussed are the experimental results to validate the base model and the simulations results for vehicle dynamics, energy management and the combinations of both.

5.1 Experimental results for validation of base model

Experimental works were conducted on the actual vehicle in order to obtain some data which could be used to validate the ADAMs/car models. For comparison purposes, two types of manoeuvres namely single lane change and step steer were selected. In order to ensure that identical manoeuvres were conducted in the experiment and in the simulation, identical steering wheel inputs were used for the two cases. The experimental data, namely the lateral acceleration values, were then compared with the simulation data and the results are shown in Fig. 7 and 8 for steep steer test and single lane change test respectively.

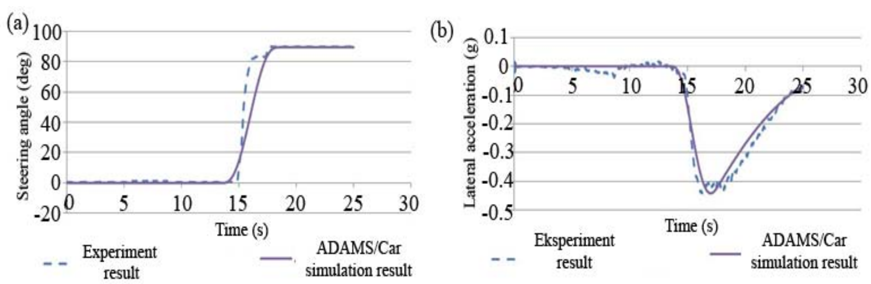

Fig. 7. Results for step steer test (a) Steering wheel input (b) Lateral acceleration

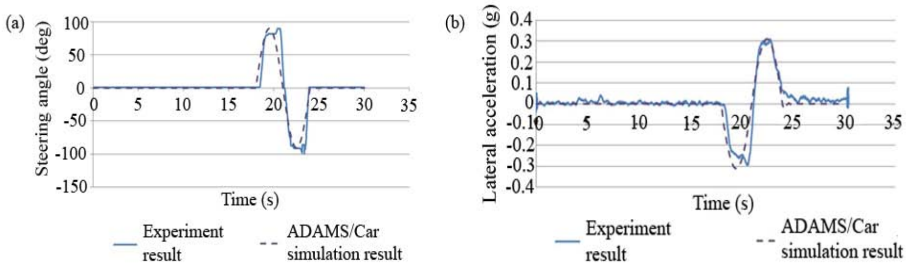

Fig. 8. Results for single lane change test (a) Steering wheel input (b) Lateral acceleration

The results show that the base model built in ADAMS/Car is in close agreement with the actual vehicle with maximum errors of only about 2%. The existence of errors was mostly attributed to the simplification in modelling vehicle system components, measurement device error, and assumptions on some of vehicle properties. It is therefore concluded that the software model is valid to be used for the modelling of the future HEV including its control.

5.2 Vehicle dynamic simulation of hev

The performance and characteristics of the HEV model as compared to the base model were then assessed by performing the single lane change manoeuvres. In this manoeuvre, both models were initially set to cruise at a speed of 90km/h for 4 seconds and the vehicle were then steered to 90^o for a complete single lane change manoeuvre within two seconds. Finally, the cars were brought back to a straight ahead position. The overlay plots of yaw rate, vehicle path and lateral accelerations from the simulations are shown in Fig. 9.

Fig. 9(a) shows the plot of yaw rate versus time for both base and HEV models. The result shows that the HEV model has able to improve the manoeuvring of the vehicle. The yaw rate plot of the HEV model was found to be more symmetric in comparison to the base model. On the other hands, the base model has produced a slight overshoot in yawing during the manoeuvre. In addition, the vehicle path plot in Fig. 9(b) also demonstrates that the base model deviates from the expected path during for the manoeuvre. In brief, the HEV model has able to maintain a straight ahead position after the single lane change manoeuvres, while the base model has failed to perform the same manoeuvre effectively. From Fig. 9(c), the lateral acceleration of the base model is found to have a slight offset from the HEV model. The situation suggests that the base model has experienced an understeer phenomena during the manoeuvre. To conclude, the HEV model not only capable of performing almost similar driving characteristics as the original/base model, but has also improved in vehicle handling performance of the base model.

5.3 Energy management simulation

The results from the simulation of energy management system of HEV is very crucial in the design of HEV because they determine the performance of the vehicle in term of fuel saving. In order to validate the results for the Energy management simulation using co-simulation between ADAMS/car and MATLAB SIMULINK, a software called Advance Vehicle Simulator (ADVISOR) was utilized. For comparison purposes, a simple drive cycle with 5 peaks velocity profile was selected because it had a simple profile that enabled it to trace the difference between the results from ADVISOR and co-simulation. The duration for the simulation is 850 seconds which covers the distance of 9.34 km. The profile has a maximum speed of 64.4km/h and an average speed of 39.5km/h. Fig. 10 shows the results of the velocity profile, the torque produced by the ICE, the torque produced by the IWM and the SoC of the battery.

The results obtained from the co-simulation indicated that it had similar characteristics as the ADVISOR's. Although the two simulations are different due to the difference in modelling, the vehicle speed for both simulations showed a close match (Fig. 10(a)). Meanwhile, the results of the engine torque and the IWM torque has shown some slight different as observed in Fig. 10(b) and 10(c). The torque patterns yield by both of the simulations is about the same but at certain time e.g. 450s and 600s there are spikes produced by the

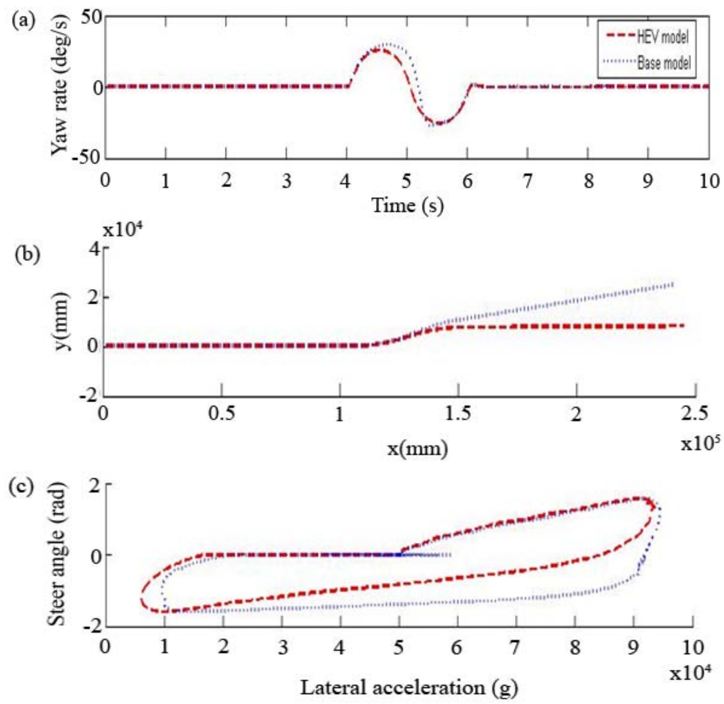

Fig. 9. Vehicle dynamics simulation results (a) Vehicle yaw rate (b) Vehicle path (c) Understeer gradient

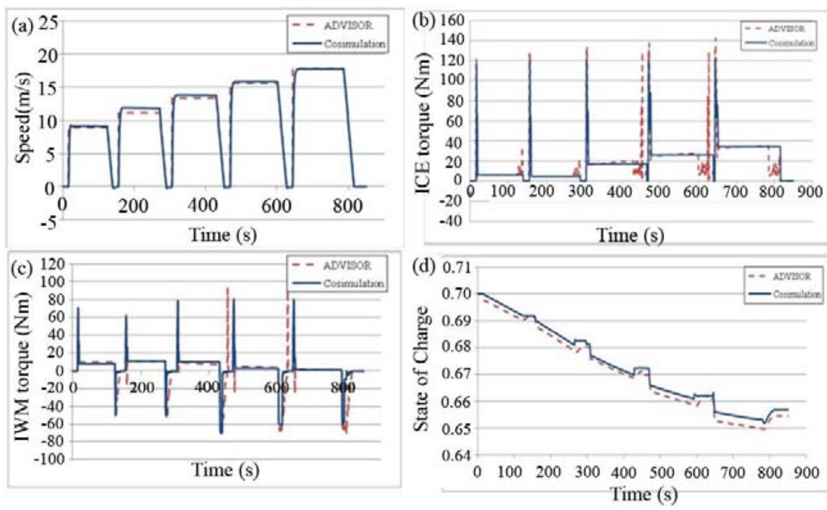

Fig. 10. Energy management simulation results (a) Velocity profile comparison (b) ICE torque comparison (c) IWM torque comparison (d) SoC comparison

results obtained from ADVISOR. These spikes could be caused by the detailed modelling of both ICE and IWM in ADVISOR which considers all the parameters and conditions that can provide the requested results. For instance, the gear box for the ADVISOR model is consisted of a controller that can control the gear change which considers the ICE torque and motor/generator capability whilst the model for the co-simulation was just based on the vehicle current speed.

For the results of the SoC of the battery, the co-simulation result manages to maintain the pattern of the ADVISOR result as what can be seen in Fig. 10(d). Due to the simple battery modelling in co-simulation model, the SoC obtained was not as accurate as the ADVISOR result which was the result from complex modelling. Even though the co-simulation results did not match the ADVISOR result closely, but it still can maintain the pattern. It can be concluded that the results obtained from co-simulation was validated with the ADVISOR results.

5.4 Combined simulation

Both EMS and VDC controller were assessed during this simulation. The simulation was conducted in order to ensure that both controllers could perform simultaneously within the same simulation and to evaluate their contributions in vehicle handling and fuel consumption.

In this simulation, the comparisons of results between the base models with the HEV model were presented. The simulation was customized and consisted of two continuous events. In the first 10 seconds of the events; the HEV vehicle model which initially was cruising at 90 km/h underwent a single lane change manoeuvre and then for the remaining time the model was driven in a reference to a drive cycle of the Urban Dynamometer Driving Schedule (UDDS). The selected drive cycle represents the driving behaviour of a vehicle in an urban driving condition where during the simulation; the vehicle will experience the stop and go driving conditions. The duration of the driving is 1369 seconds which covers a distance of 11.69km with a maximum speed of 91.3km and average speed of the whole drive cycle of about 31.5km. The first event was intended for vehicle dynamics analysis while the second event was meant for energy management analysis.

The results of the energy management simulations are shown in Fig. 11 for the velocity profile, the torque produce by the ICE, the SoC and the fuel consumption throughout the whole simulation. As for the vehicle dynamics simulation, a zoomed in results of the yaw rate of the vehicle at time less than 10 seconds was shown in Fig. 12.

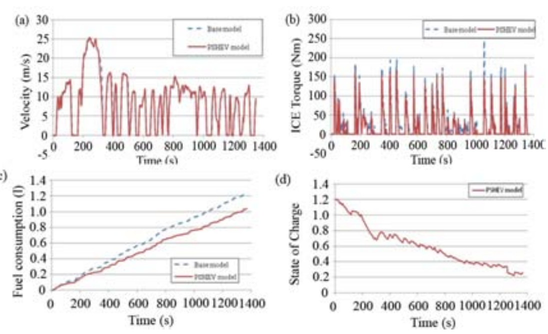

Fig. 11. Combined simulation results (a) Velocity profile comparison (b) ICE torque comparison (c) Fuel use comparison (d) SoC of HEV model

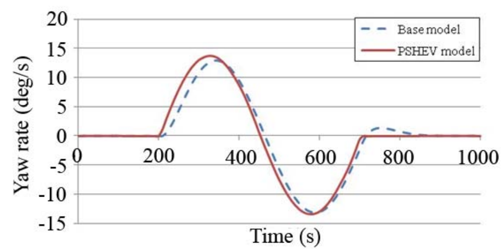

Fig. 12. Yaw rate comparison

As observed from Fig. 11(a), both vehicle models have managed to maintain the target velocity profile. However, there is a slight difference in the amount of torque produced by the ICE (Fig. 11(b)). The amount of torque produced by the base vehicle model was higher at certain time as compared to the HEV model.. The HEV model has been assisted by the IWM at the programmed condition and because of this the amount of torque produced by the HEV model is less. Due to the amount of reduced torque, the fuel consumption has also decreased. It can be seen in Fig. 11(c) that the amount of fuel used by the base model is higher as compared to the HEV model. Another improvement that HEV model has managed to achieve was in term of vehicle stability. It can be observed from Fig. 12 that the HEV model was able to maintain the vehicle path and reduce the overshoot when returning to a straight ahead position.

5.5 Fuel consumption effect during cornering

This simulation was conducted specifically to study the effects of fuel consumption during a cornering event and to assess the significant of having a vehicle dynamic controller. To demonstrate this situation, a cornering event simulation was selected. Initially, the vehicle model was travelling in a straight line at a speed of 90km/h for 2 seconds. The model then started to negotiate a 90o corner having a radius of curvature of 60 meters within 6 seconds. The results for the simulation are shown in Fig.13.

Fig. 13(b) reveals that the amount of fuel consumed during the manoeuvre has reduced when the IWM was assisting the vehicle during cornering. The assistance of IWM in turning the rear wheels has helped to

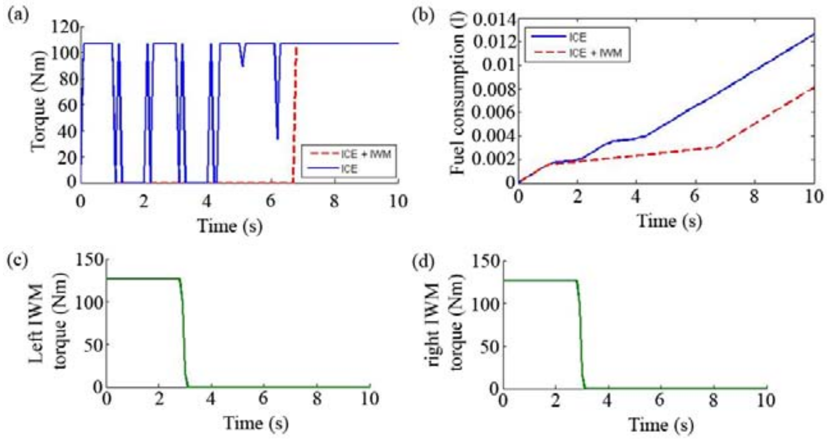

Fig. 13. Fuel consumption during cornering results (a) ICE torque comparison (b) Fuel use comparion (c) Left IWM torque (d) Right IWM torque

reduce the cornering forces acting on the rear tyres, and hence ease the manoeuvre. In addition, the explanation can also be found from Fig. 13(a) where, without the assistance of IWM, the vehicle requires some amount of torque to move the car. Both IWM have been assisting the movement of the vehicle since the beginning of the simulation (Fig. 13(c) and 13(d)). But after 3 seconds, the torque produced by the IWM reduced since the IWM would only assist based on the conditions set up in the controller. It can be concluded that the vehicle dynamics controller is also significant in reducing the fuel consumption as well as providing good vehicle handling.

6 Conclusion

A HEV model built from a converted conventional vehicle (Proton WAJA) was developed in a co-simulation environment between ADAMS/Car and MATLAB/Simulink. The HEV model was initially validated with the real vehicle data obtained from experiments prior to performing further analysis. The model was aimed to possess improved characteristic in term of fuel consumption and vehicle handling as compared to the base model. The developed model was firstly tested to examine its handling characteristics through simulations. The VDC simulation concluded that the controller has managed to improve the handling characteristic of the HEV model as compared to the base model. The EMS controller was validated with the ADVSIOR and it was found that the controller was able to produce almost equal results as the ADVISOR results. To test both controllers simultaneously, a combined simulation (both VDC and EMS) was performed and the results showed that the controller was able to manage both conditions within the same simulation. Finally, a specific simulation that studied the usage of fuel when negotiating a corner was performed. The results revealed that the HEV model had improved the fuel consumption of the vehicle compared to base model. Based on the simulations performed, it can be concluded that the HEV model built from conventional vehicle is successful in view of the fact that the proposed HEV model was able to perform both in EMS and VDC simulation and managed to improve the fuel consumption and the driving characteristic of the base model. It is hoped that the conversion of conventional vehicles into HEV would be the choice of the future as this helps to reduce the amount of world road vehicles, and hence reduce pollution in general.

References

[1] Energy management studies for a new generation of vehicles. *Technical Report*, Technical Report, Department of Electrical System Engineering, School of Engineering and Computer Science, Oakland University, Rochester, MI, Mar, 1998.

[2] The Poulsen Hybrid Power Assist System, 2010. Http://www.poulsenhybrid.com/PoulsenHybrid.php: http://www.poulsenhybrid.com.

[3] REVOLO, 2010. Http://revolo.kpitcummins.com/about-revolo.htm: http://revolo.kpitcummins.com/.
[4] MIRA, 2010. Http://www.mira.co.uk/About_MIRA/: http://www.mira.co.uk/About_MIRA/What_is_MIRA.htm.
[5] About Us: Race technology, 2010. Http://www.race-technology.com/about_us_2_1.html.
[6] B. Baumann. *Intelligent control strategies for hybrid vehicles using neural networks and fuzzy logic*. Master's thesis, Department. Of Electrical Engineering, Ohio State University, Columbus, 1997.
[7] B. Baumann. *Modeling and Simulation of A Hybrid Electric Vehicle Using MATLAB/Simulink and ADAMS*. Master's thesis, Department of Mechanical Engineering, University of Waterloo, Canada, 2007.
[8] H. Hannoun. Energy management strategy for a prallel hybrid electric vehicle using fuzzy logic. *International Symposium on Power Electronic, Electric Drives, Automation and Motion*, 2006, 34–40.
[9] N. Jalil, N. Kheir. Energy management studies for a new generation of vehicles. *Technical Report*, Department Electrical System Engineering, School of Engineering and Computer Science, Oakland University, Rochester, MI, Mar, 1998.
[10] C. Jeongyun. Cornering stability improvement for 4 wheel drive hybrid electric vehicle. *IEEE International Symposium on Industrial Electronics*, 853–858.
[11] J.Niels, M. Schouten. Energy management strategies for parallel hybrid vehicle using fuzzy logic. *Control Engineering Practice*, 2003, **11**: 171–177.
[12] H. Kada. Electronic differential with direct torque fuzzy control for vehicle propulsion system. *Turkish Journal of Electrical Engineering and Computer Sciences*, 2009, **17**: 21–38.
[13] F. Khoucha. An optimal fuzzy logic power sharing strategy for parallel hybrid electric vehicles. *Vehicle Power and Propulsion Conference*, 2010, 1–5.
[14] D. Kim. Optimal brake torque distribution for a four-wheel drive hybrid electric vehicle stability enhancement. *Proceedings of the Institution of Mechanical Engineers*, **221**: 1357–1366.
[15] H. Kono. *Fuzzy control for hybrid electric vehicles*. Master's thesis, Department of Electrical Engineering, The Ohio State University, 1998.
[16] F. Li. Motor torque based vehicle stability control for four-wheel-drive electric vehicle. *Vehicle Power and Propulsion Conference*, 2009, 1596–1601.
[17] S. Motoki. Independent wheel torque control of small-scale electric vehicle for handling and stability improvement. *JSAE Review 24*, 2003, 449–456.
[18] A. Poursamad. Design of genetic-fuzzy control strategy for parallel hybrid lectric vehicle. *Control Engineering Practice*, 2008, **16**: 861–873.
[19] S. Sakai. Motion control in an electric vehicle with four independently driven in-wheel motors. *IEEE/ASME Transactions on Mechatronic*, 1999, 9–16.
[20] N. Schouten. Fuzzy logic control for parallel hybrid vehicles. *IEEE Transactions on Control Systems Technology*, 2002, 460–468.