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DYNAMIC SIMULATION MODEL OF A HYBRID POWERTRAIN AND CONTROLLER USING CO-SIMULATION–PART II: CONTROL STRATEGY

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ABSTRACT–The topic of this study is the control strategy of a mild hybrid electric vehicle (HEV) equipped with a continuously variable transmission (CVT). A brief powertrain and vehicle configuration is introduced followed by the control strategy of the HEV with emphasis on two key parts. One of them is an ideal operating surface (IOS) that operates the CVT powertrain optimally from the viewpoint of the tank-to-wheel efficiency. The other is a charge sustaining energy management to maintain the battery state of charge (SOC) within an appropriate level. The fuel economy simulation results of the HEV over standard driving cycles were compared with those of the baseline vehicle. Depending on the driving cycle, 1.3–20% fuel saving potential is predicted by the mild hybridisation using an integrated starter alternator (ISA). The detailed energy flow analysis shows that the majority of the improvement comes from the idle stop function and the benefits for electrical accessories. Additionally, the differences between the initial and the final SOC are in the range −1.0 ~ +3.8% in the examined cycle.

KEY WORDS : Fuel economy, Hybrid electric vehicle, Continuously variable transmission, Ideal operating surface, Charge sustaining energy management, Integrated starter alternator

NOMENCLATURE

J_{EM} : rotating inertia of electric machine
J_{ENG} : rotating inertia of engine
$J_{TX,in}$: rotating inertia of transmission input
$\dot{m}_f$: mass flow rate of fuel
$P_{ACC,mech}$: mechanical accessory power
P_{VEH} : vehicle power
R_{FD} : final drive ratio
R_{TX} : transmission ratio
r_{WHL} : wheel radius
T_{ENG} : engine torque
$T_{TX,loss}$: equivalent transmission loss torque
$T_{TX,out}$: transmission output torque
v_{VEH} : vehicle velocity
η_{FD} : final drive efficiency
θ_a : accelerator pedal position
θ_b : brake pedal position
ω_{EM} : electric machine speed
ω_{ENG} : engine speed
$\omega_{TX,in}$: transmission input speed

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1. INTRODUCTION

It is well established that future automobiles must minimize their environmental impact. If this input fulfilled by a reduction in carbon dioxide emissions then will also satisfy the increasing concerns on fossil fuel supply. The hybrid electric vehicle (HEV) is seen as a ready-to-use solution, considering the technical and infrastructural limitations.

The authors suggested a step-by-step approach of the mild hybridization of a compact SUV in the previous study (Cho and Vaughan, 2006). In the parallel mild HEV, the integrated starter alternator (ISA) is connected to the engine crankshaft and can be used as a motor to assist the engine or as a generator to charge the battery. Therefore, there are many complex compromises in the interactions between mechanical design and control algorithms, since they involve several energy storage and power transfer components. As a result, the control strategy has a key role to reduce the fuel consumption and the harmful emissions.

The objective of this paper is the development of the control strategy for a mild hybrid vehicle with a continuously variable transmission (CVT) and the demonstration of the fuel economy improvement. The simulation model of the powertrain is briefly introduced, followed by the detailed explanation of the control strategy. The battery state of charge (SOC) correction control and the predicted fuel economy improvement of the HEV over standard driving cycles are illustrated with the analysis of the energy flow and efficiency.

2. MODELLING AND SIMULATION

The powertrain models used in this study are based on the authors' previous work (Cho and Vaughan, 2006). A compact SUV equipped with a spark ignition direct injection (SIDI) engine and an infinitely variable transmission (IVT) was chosen as the baseline. For the hybridization, 15 kW ISA was adopted as the electrical machine (EM). The baseline and the hybrid vehicle specification is summarised in Table 1.

In addition, this study uses a forward-facing simulation model presented in the previous work. It is developed in the AMESim-Simulink co-simulation environment. Combining the advantages of the intuitive physical modelling environment of AMESim and the efficient control logic implementation of Simulink, the full dynamic model shows not only convenient but also time-efficient simulation performance.

3. CONTROL STRATEGY

There are multiple power sources and sinks in parallel HEVs. The engine and the EM can propel the vehicle with fuel and electric energy in the battery, and the EM and the brake can reduce the vehicle speed by absorbing the kinetic energy. To harmonise these components effectively, an additional supervisory controller (Laguitton *et al.*, 2002; Larsen *et al.*, 2002) or vehicle system controller (Phillips, 2002; Phillips *et al.*, 2000) is positioned on the logically higher level of the local controllers and responsible for organising them. The supervisory controller calculates the required control actions including the engine torque, the ratio of the transmission, the engagement of the transmission clutch, and the brake torque. The local controllers translate the required values into the real actuator signals considering the scaling and the saturation of the actuators.

Table 1. Specification of vehicles.

	Baseline	HEV
Engine	3.3 L SIDI	←
Transmission	IVT	←
EM	–	15 kW ISA
Battery	–	6.0Ah/144V
Mechanical accessory	1 kW	–
Electric accessory	–	1 kW
GVWR	2200 kg	2220 kg
Tyre size	235/70 R16	←
Frontal area	2.7 m^2	←
Drag coefficient	0.38	←

Table 2. Control mode transition criteria.

From \ To	Idling	Braking	Propelling
Idling	x	x	$\theta_a > 1\%$
Braking	$V_{VEH} < 0.5$ km/h	x	$\theta_a > 1\%$
Propelling	$\theta_b > 1\%$, $V_{VEH} < 0.5$ km/h	$\theta_b > 1\%$, $V_{VEH} > 0.5$ km/h	x

For the hybrid vehicle, there are three functional enhancements in the control algorithm from the non-hybrid conventional powertrain. The first is the idle stop which turns off the engine when the vehicle is stopped. Secondly, regenerative braking is implemented, which is the most important energy source of the HEV. The final is the torque assist and the battery charging with a charge sustaining energy management strategy. Operation in a pure electric mode is appropriate for parallel hybrid systems but not practical for the mild hybrid with ISA considered in this study.

3.1. Operating Mode

Control strategies should be changed taking account of the vehicle status and the driver's request. In this study, 3 different control modes, the idling, braking, and propelling modes, are defined and determined by the supervisory controller. The control actions are different in each mode and the change criteria are summarised in Table 2.

The default mode is idling in which the engine is turned off. When the accelerator pedal position is over a certain threshold level, the mode transition to the propelling mode occurs. In the propelling mode, the mode transition to the braking or the idling mode occurs depending on the vehicle speed. From the braking mode, pressing the accelerator pedal makes the transition to the propelling mode, or the mode is changed to the idling when the vehicle speed is reduced under a pre-defined

Table 3. Control actions at each mode.

Control parameter	Idling	Braking	Propelling
Engine torque	0	Controlled	Controlled
EM torque	0	Controlled	Controlled
CVT ratio	0	Controlled	Controlled
CVT clutch	Off	Controlled	on
Brake force	100%	Controlled	0%

low value. For each mode, the control actions of the local controllers are listed in Table 3.

3.2. CVT Control

In vehicles equipped with stepped transmissions, the engine speed is directly related to the vehicle speed and only the engine torque is a control variable. On the other hand, CVTs provide an additional degree of freedom to isolate the engine speed from the vehicle speed. This is the reason why the CVTs have a potential to operate the engine more efficiently and the controller is more complex than the other cases.

Most of the CVT control algorithms proposed in other studies (Yasuoka *et al.*, 1999; Sakaguchi *et al.*, 1999; Kim and Kim, 2002) are based on the efficient operation of the engine at a given power. It is effective and easy to be implemented from the engine brake specific fuel consumption (BSFC) map, but not always true optimal in terms of the overall powertrain efficiency. More precisely, the important factor of the transmission ratio control is not the engine efficiency but the tank-to-wheel efficiency.

The concept of the ideal operating surface (IOS) is suggested in this study to control the powertrain efficiency optimally. The IOS consists of the operating points of the transmission ratio and the engine torque to minimise the fuel consumption at a given vehicle speed and power. The relationship of these variables can be expressed as:

$$\min_{R_{TX}} J = \min_{R_{TX}} \dot{m}_f(T_{ENG}, R_{TX}) \tag{1}$$

$$T_{ENG} = \frac{P_{ACC,mech}}{\omega_{ENG}} + T_{TX,loss}(R_{TX}, T_{TX,out}) + R_{TX} T_{TX,out} \tag{2}$$

$$T_{TX,out} = \frac{R_{FD} P_{VEH} r_{WHL}}{\eta_{FD} \quad v_{VEH}} \tag{3}$$

$$R_{TX} = \frac{v_{VEH}}{r_{WHL} R_{FD}\, \omega_{ENG}} \tag{4}$$

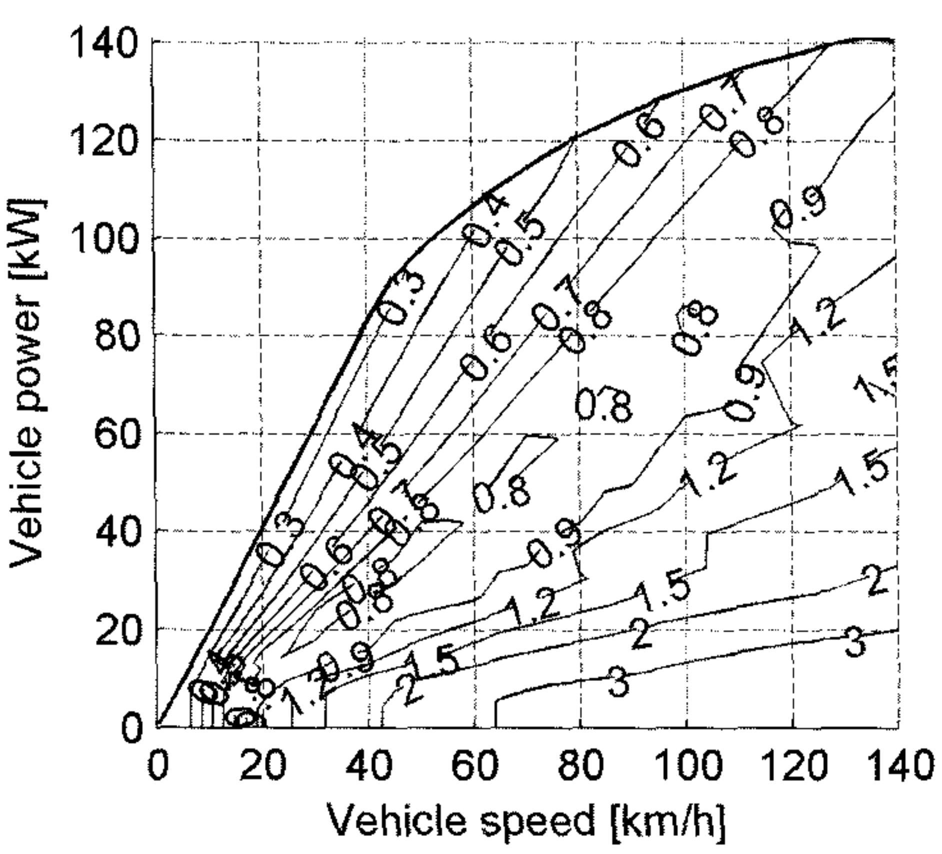

Figure 1. IOS-Transmission ratio.

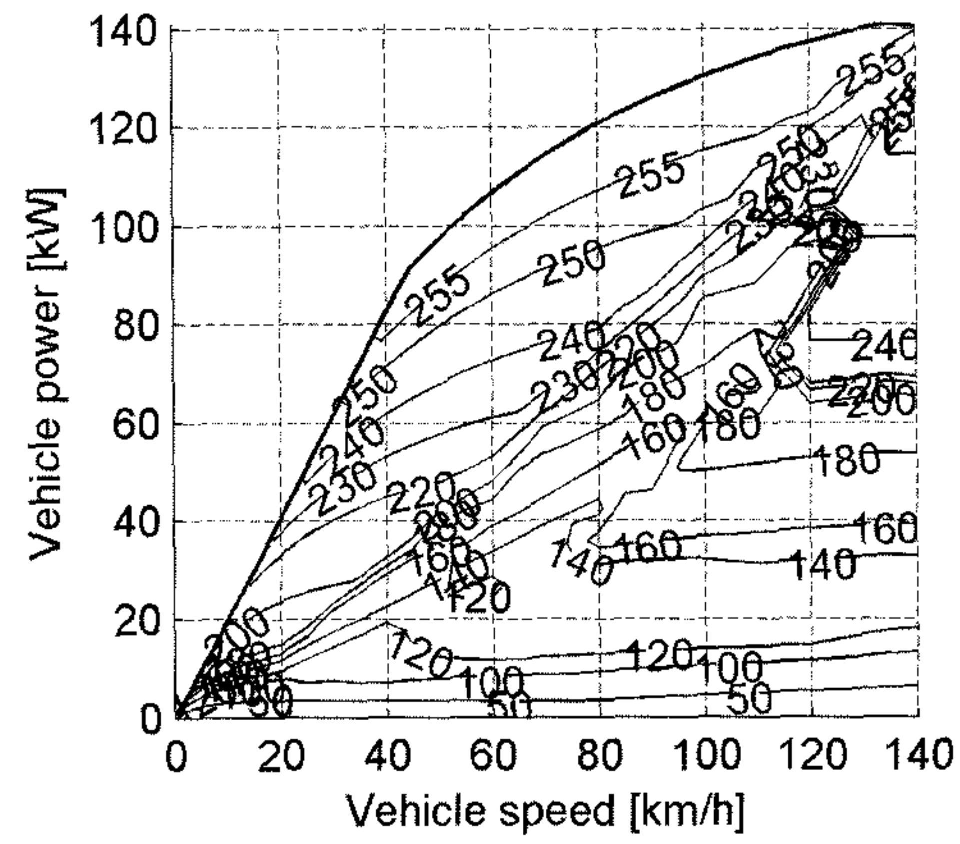

Figure 2. IOS-Engine torque.

The calculation results of the transmission ratio and the engine torque are shown in Figure 1 and Figure 2. The thick solid lines on both indicate the maximum available power at the wheel. Increasing the vehicle speed at a given power, the ratio is increased and the engine torque is decreased which means the overall powertrain efficiency is higher for low engine speed. There is a large gap of the ratio between 0.8 and 0.9, and the engine torque is locally decreased in this area because the efficiency of the CVT used in this study reaches maximum around this ratio.

The tank-to-wheel specific fuel consumption is illustrated in Figure 3. The lowest value is less than 305 g/kWh which implies 26.8% tank-to-wheel efficiency. The important point is that the quite broad high efficiency area is positioned in the mid-power range, and this advantage comes from the combination of the SIDI engine and the CVT.

Figure 4. Improvement of tank-to-wheel specific fuel consumption by IOS. illustrates the improvement of the tank-to-wheel specific fuel consumption by the IOS against the traditional optimal operating line, which considers

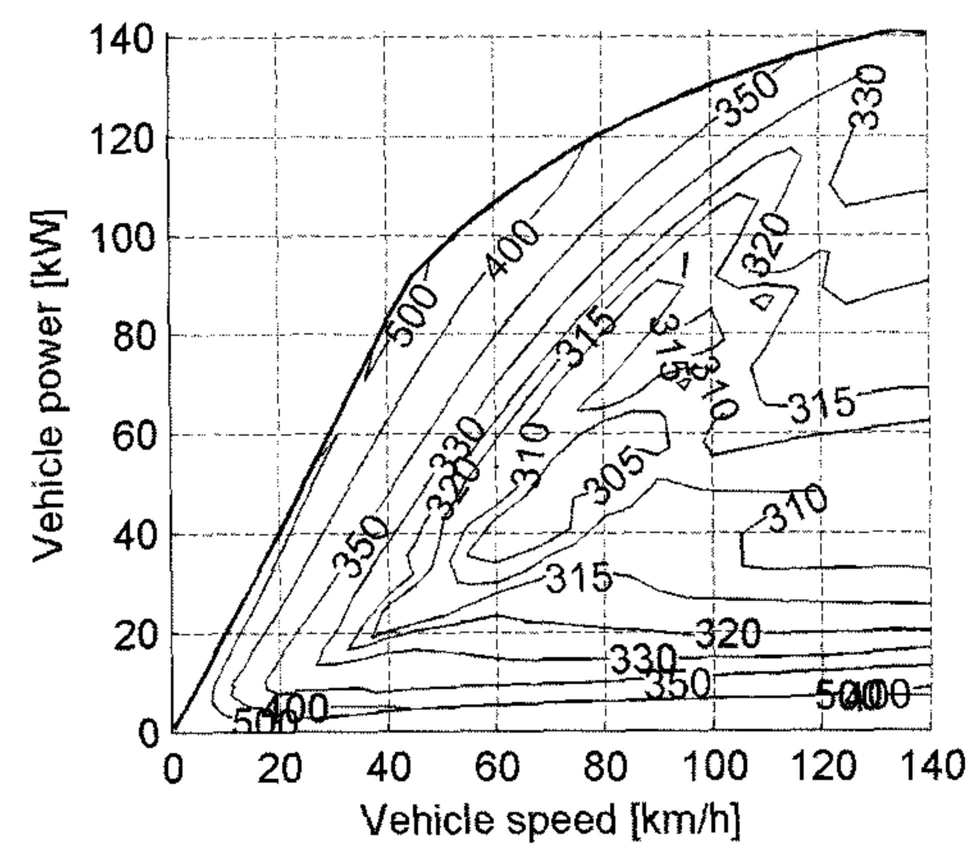

Figure 3. Tank-to-wheel specific fuel consumption.

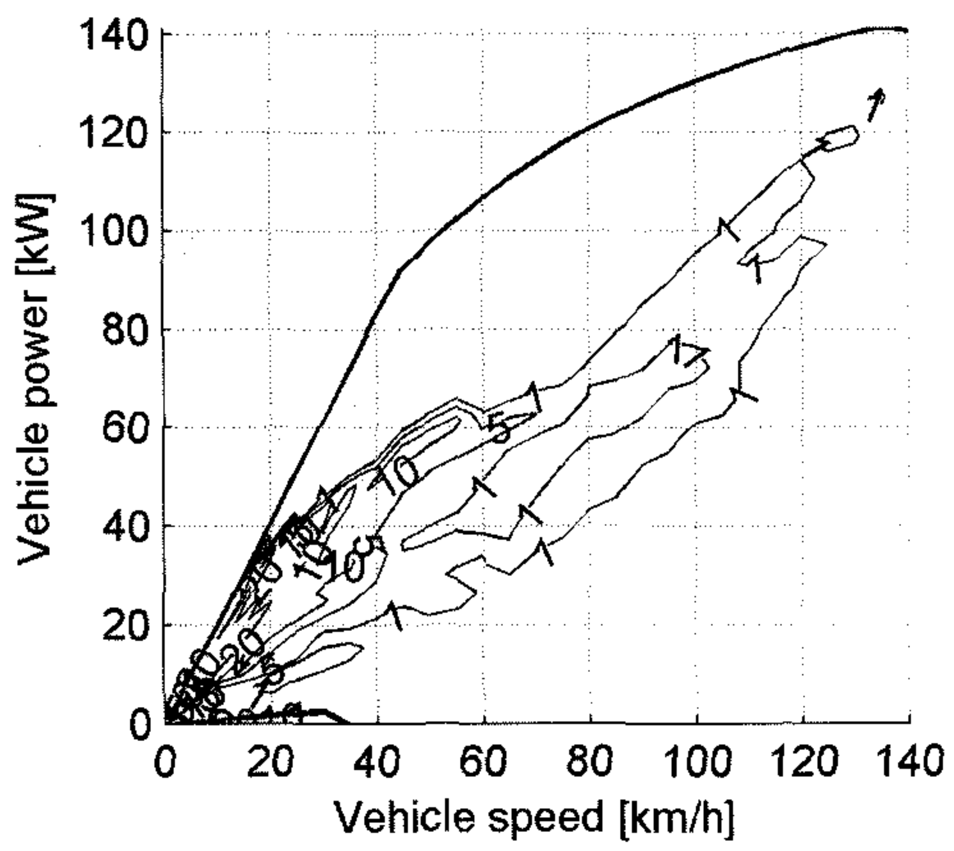

Figure 4. Improvement of tank-to-wheel specific fuel consumption by IOS.

only the engine efficiency. Comparing with Figure 1, IOS shows the advantage in the efficient transmission ratio 0.8–0.9, and more than 5% improvement in low speed and mid to high torque region. It implies that the transmission efficiency is more important than the engine efficiency in this area.

Basically, the IOS is derived from the steady state efficiency of the driveline components but the required engine torque includes a dynamic load to accelerate or decelerate the engine and the transmission input side inertia by changing gear ratio in transient. Therefore, the total required torque at the engine can be expressed as;

$$T_{ENG}=\frac{P_{ACC,mech}}{\omega_{ENG}}+T_{TX,loss}(R_{TX},\ T_{TX,out})+R_{TX}T_{TX,out}$$
$$+J_{ENG}\dot{\omega}_{ENG}+J_{EM}\dot{\omega}_{EM}+J_{TX,in}\dot{\omega}_{TX,in} \quad (5)$$

The dynamic torque on the second line is independent of the transmission ratio and the efficiency. Moreover, it is hard to predict offline the calculation of the IOS. As a result, the engine operating points can only be on the IOS in the steady state condition.

3.3. HEV Control

3.3.1. Idle stop

To save the fuel burnt during idling, the controller stops the engine when the vehicle is fully stopped. This idle stop functionally occupies a large portion of the HEV benefit, especially in mild hybrids. To restart the engine from rest, the ISA is switched on when the mode is changed from idling to propelling, cranking the engine as quickly as possible. When the crankshaft speed reaches the minimum level to operate the engine and the CVT properly, the engine is turned on and the output clutch of the CVT is engaged to launch the vehicle. It takes less than 0.2 second, so the driver should not feel the response delay. Even though high EM torque is necessary, it is for a short period with relatively little energy taken from the battery.

3.3.2. Regenerative braking

When the mechanical brake is involved to reduce the vehicle speed, the kinetic energy is dissipated as heat. A HEV saves this energy to the battery by using the EM as a generator. An additional advantage of the hybrid vehicle in braking mode is the fuel shutoff during decelerating. When a vehicle is decelerating, the engine has to spend a small amount of fuel to maintain the proper combustion conditions and control harmful emissions. However, it is possible to shut off the fuelling of the engine in HEVs because the EM can control the operating conditions of the engine and maintain the idling speed even though the transmission is in the geared neutral or the clutch is opened. Therefore, most of the fuel spent in the braking mode can be saved by the hybridisation.

When entering the braking mode, the controller fixes the transmission ratio at the current state. If the engine speed is reduced below the idle speed, the ratio is decreased to maintain the idle speed. From the transmission ratio and the current vehicle speed, the maximum regenerative braking torque at the wheel can be calculated as shown in Figure 5. If the required braking torque exceeds the maximum regenerative braking torque, the remainder is assigned to the mechanical brake torque request. On the other hand, if the required braking torque is less than the engine drag torque, the ISA supplies the torque to drive the engine, the accessory and the transmission loss. This study accounts for only the longitudinal motion of the vehicle, so the braking torque distribution between the front and rear wheels is not considered and the available kinetic energy can be absorbed by the EM as much as possible within the power and torque limit. This assumption is quite reasonable in the case of a front wheel drive SUV with an active braking control system,

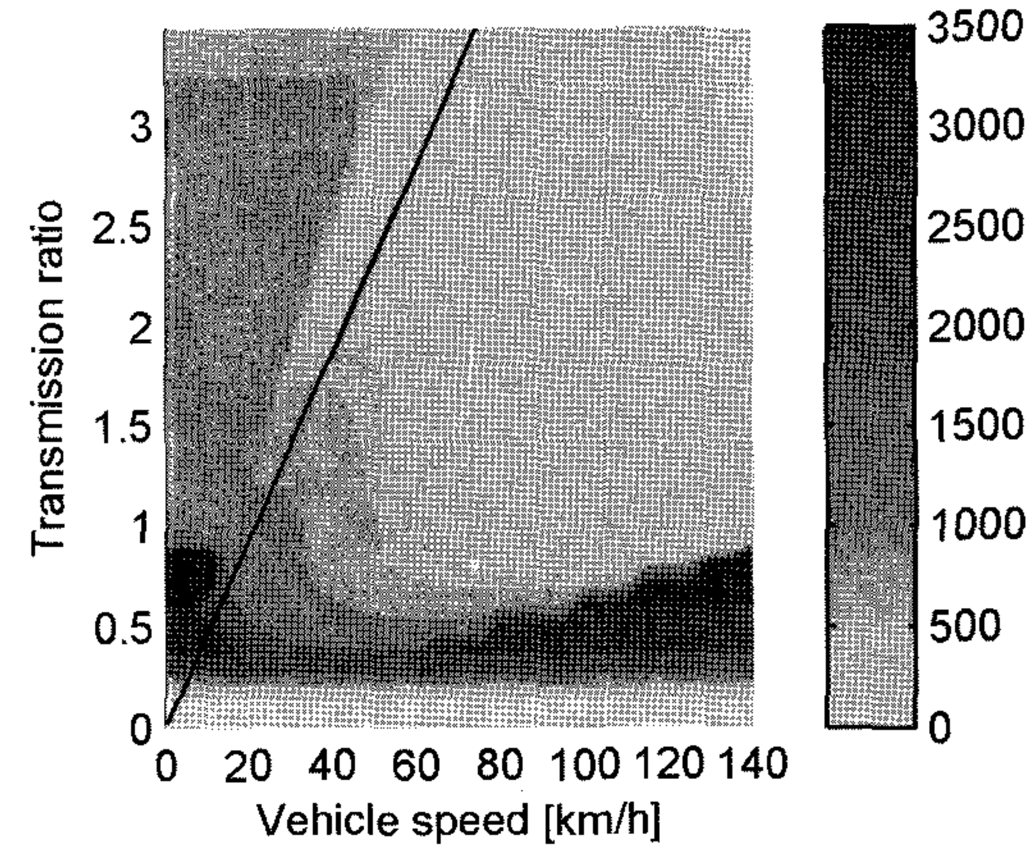

Figure 5. Maximum regenerative braking torque at the wheel.

because the maximum deceleration in the standard driving cycles is around 0.15 g and is achievable from only the front wheels without stability problem. According to the regenerative braking study of a large SUV (Cacciatori *et al.*, 2005), this value of deceleration is possible by the front wheel with the friction coefficient 0.3 which is much less than the standard value, 0.8, for the typical road condition.

3.3.3. Charge sustaining energy management

The control of the battery SOC is an important factor for the charge sustaining HEVs. Deep charging or discharging affects the battery life and performance. Therefore, the SOC of the battery should be maintained in the proper level. In this study, the target SOC is set as 60% and the high and low limits for charging and the discharging control are +/−10% from the target SOC. Additionally, the hardware limit of the battery is assumed as 20 to 80%. To avoid a low SOC, the engine may have to drive the ISA to generate the electric power. However, the ISA can assist the engine more at the high SOC level. There are many kinds of charge sustaining control strategies but the main factors to decide the EM torque are the engine efficiency and the battery SOC (Johnson *et al.*, 2000).

To simplify the problem, only the engine efficiency is considered at first. The thick solid line in Figure 6 represents the ideal operating line (IOL) which consists of the best efficiency points at a given speed on the engine BSFC map. The additional two dashed lines above and below the IOL are the ideal assist and the charging lines respectively. These lines have an efficiency of 80% of the IOL. If the required torque is over the assist line, the ISA assists the engine to boost the torque as much as possible. On the other hand, if the required torque is below the ideal charging line, the engine produces the extra torque to charge the battery within the limitation of the ISA.

If the assist and the charging lines are fixed based on the engine efficiency, the SOC cannot be maintained within the required limits over arbitrary driving conditions. To level the SOC, the assist and the charging torque must be controlled according to the SOC. To implement these features, the controller moves the assist and the charging line related to the current SOC as illustrated in Figure 7. At the high or low SOC, the assist and the charging torque are on the best efficiency points respectively. If the SOC is out of the limits, power exchange with the battery is prohibited.

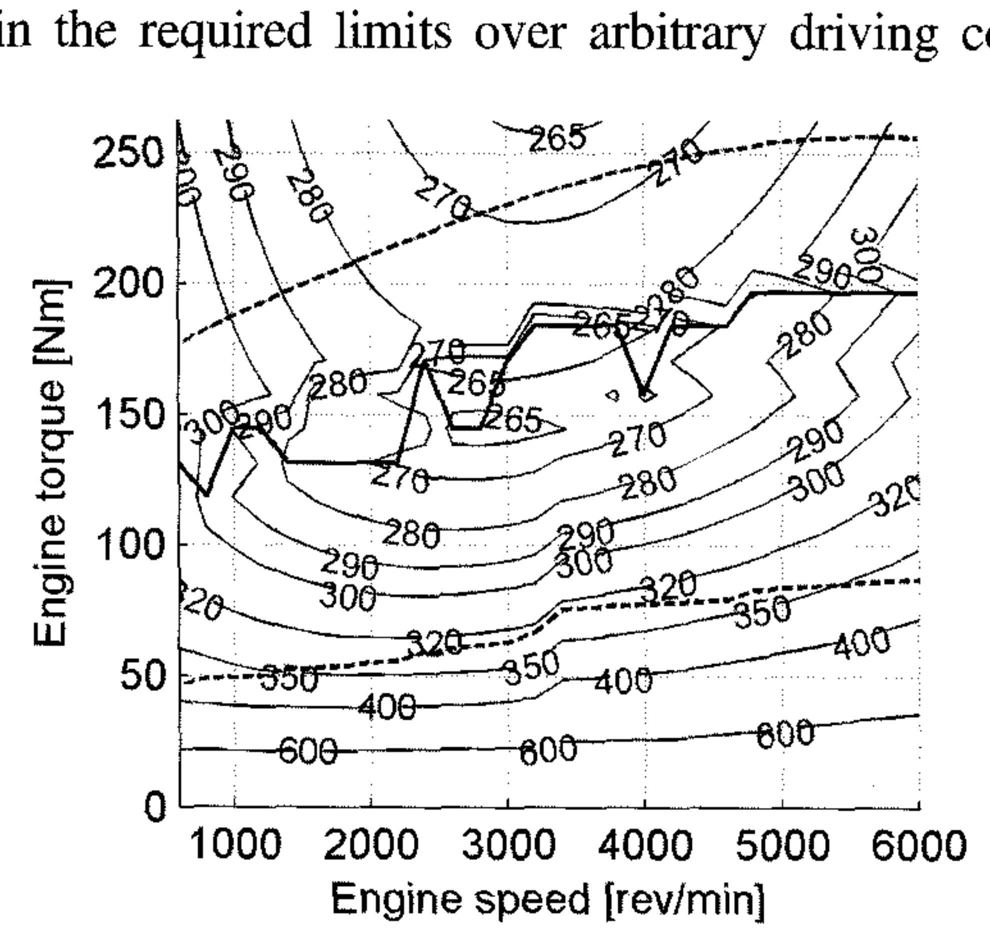

Figure 6. IOL on engine BSFC.

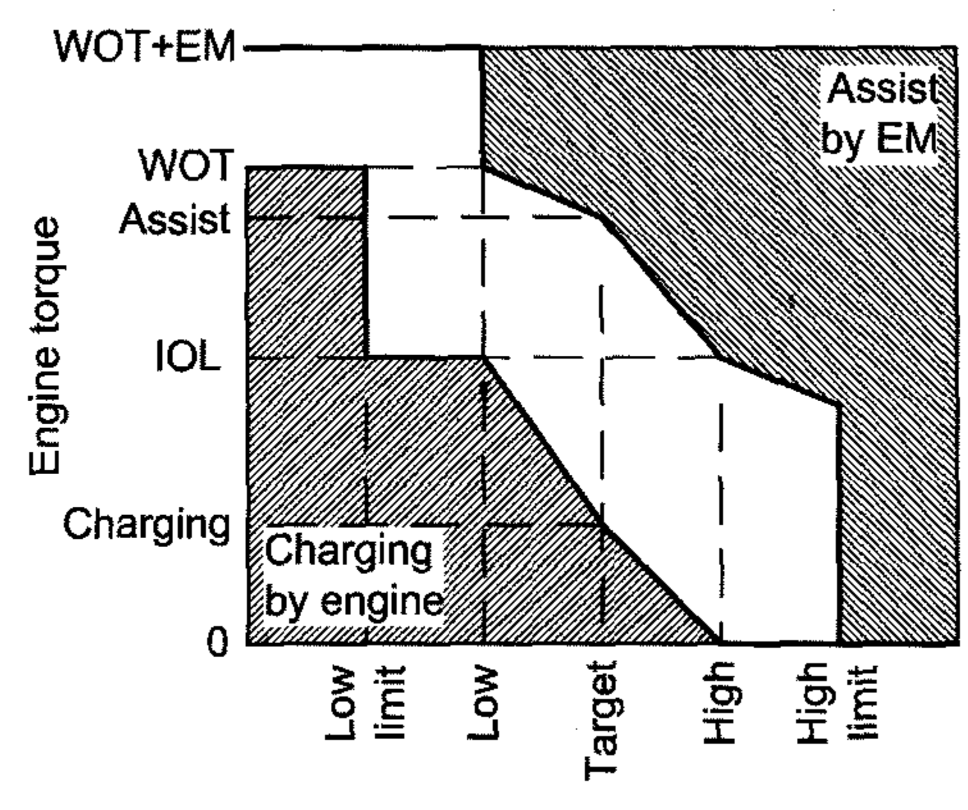

Figure 7. Charge sustaining energy management.

4. FUEL ECONOMY STUDY

4.1. Fuel Economy

Four standard driving cycles are used for the fuel economy study. Table 4 shows the comparison of the fuel consumption between the baseline and the hybrid vehicle. Basically, the simulation result of the baseline vehicle shows much better fuel economy than the reference vehicles which is the same class of SUVs (Cho and Vaughan, 2006). Omitting the cold start might partly affect the result in the FTP-75 cycle, but it can be seen that use of the SIDI engine and the CVT has a good potential of the fuel economy improvement in itself.

The hybridisation further improves the fuel economy considerably from the baseline. In the 10–15 mode cycle the improvement is 20%, and 1.3% in HWFET which is the worst case. These differences arise from the characteristics of the driving cycles. The 10–15 mode has

Table 4. Fuel consumption.

Vehicle	Fuel consumption [L/100 km] (Improvement [%])			
	NEDC	FTP-75	HWFET	10-15
Reference		12.0	9.3	
Baseline	10.0	10.2	7.9	11.0
Hybrid	8.8 (12.0)	8.8 (13.7)	7.8 (1.3)	8.8 (20.0)

relatively long idle time and low average speed. On the other hand, HWFET has little idling and high average speed. The mild hybrid gains most of the advantages from the idle stop and the regenerative braking. Therefore, it is hard to get a significant improvement in HWFET cycle. In the NEDC and FTP-75, the improvements are 12.0% and 13.7% respectively, and these values are anticipated from other recent studies of the mild hybridised SUV (MacBain, 2002; Simopoulos *et al.*, 2001).

4.2. Variation of State of Charge

Charge sustaining HEVs should maintain the SOC regardless of the driving conditions. It means that the control strategy should be designed to recover the SOC more actively if it is far from the target value. In the standard driving cycles, it is preferable that the final SOC is as close as possible to the initial value, because there are few clear methods to convert the difference of the energy stored in the battery to the equivalent fuel consumption.

The SOC variation over the driving cycles is illustrated in Figure 8 along with the vehicle speed. The initial SOC level is set at the same target SOC, 60%. In all cases, the SOC is controlled within the normal operating boundaries, +/–10%. The lowest point is 52% in HWFET cycle, and the highest value is 65% in FTP-75. The SOC is generally decreased when there is no energy flow to or from the ISA because the electric accessory extracts energy from the battery. Additionally, the hard acceleration during vehicle launch requires a large power instantaneously. All of these energy consumptions are recovered mainly and rapidly by the regenerative braking. Over these 4 standard driving cycles, the charge sustaining control strategy is working well as the design intension.

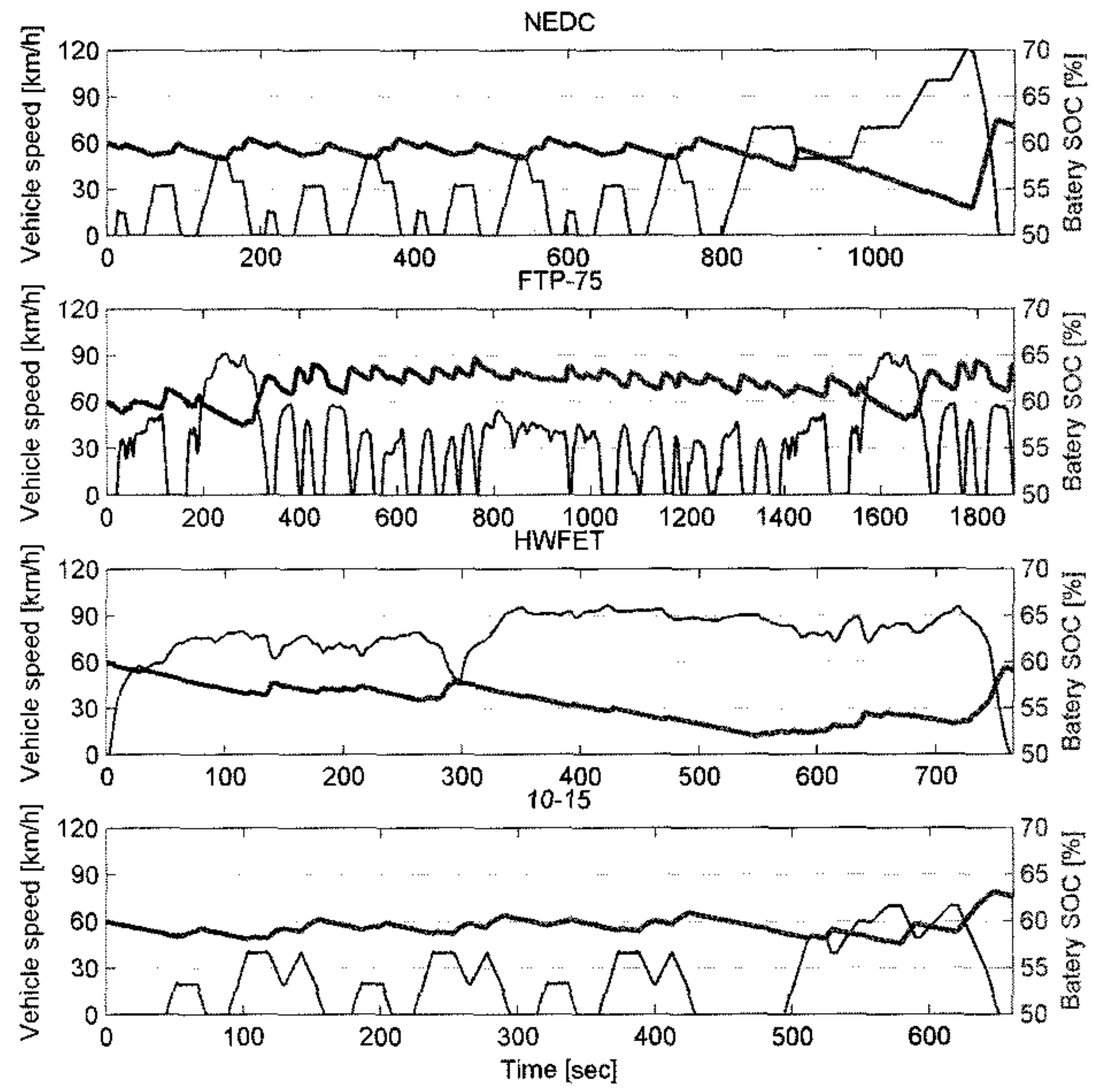

Figure 8. Variation of SOC.

Table 5. Battery SOC change.

	Battery SOC [%]			
	NEDC	FTP-75	HWFET	10-15
Initial	60.0	60.0	60.0	60.0
Final	61.8	63.8	59.0	62.7
Change	+1.8	+3.8	−1.0	+2.7
Tolerance	±10.1	±16.4	±13.5	±3.9

The SOC change over the driving cycles are summarised in Table 5 with the allowable tolerances which are 1% of the total consumed fuel energy as suggested in

Table 6. Consumed fuel.

Vehicle	Operating mode	Consumed fuel [L] (Portion [%])			
		NEDC	FTP-75	HWFET	10-15
Baseline	Idling	0.096 (8.8)	0.116 (6.4)	0.001 (0.1)	0.071 (15.6)
	Braking	0.019 (1.7)	0.051 (2.8)	0.018 (1.4)	0.010 (2.2)
	Propelling	0.975 (89.4)	1.634 (90.7)	1.283 (98.5)	0.374 (82.0)
	Total	1.090 (100.0)	1.801 (100.0)	1.302 (100.0)	0.456 (100.0)
Hybrid	Idling	0.000 (0.0)	0.000 (0.0)	0.000 (0.0)	0.000 (0.0)
	Braking	0.003 (0.3)	0.007 (0.5)	0.004 (0.3)	0.002 (0.5)
	Propelling	0.948 (99.7)	1.543 (99.5)	1.268 (99.7)	0.365 (99.5)
	Total	0.951 (100.0)	1.550 (100.0)	1.272 (100.0)	0.367 (100.0)
Baseline - Hybrid	Idling	0.096 (69.1)	0.116 (46.2)	0.001 (3.3)	0.071 (80.0)
	Braking	0.016 (11.5)	0.044 (17.5)	0.014 (46.7)	0.008 (9.0)
	Propelling	0.027 (19.4)	0.091 (36.3)	0.015 (50.0)	0.009 (10.1)
	Total	0.139 (100.0)	0.251 (100.0)	0.030 (100.0)	0.089 (100.0)

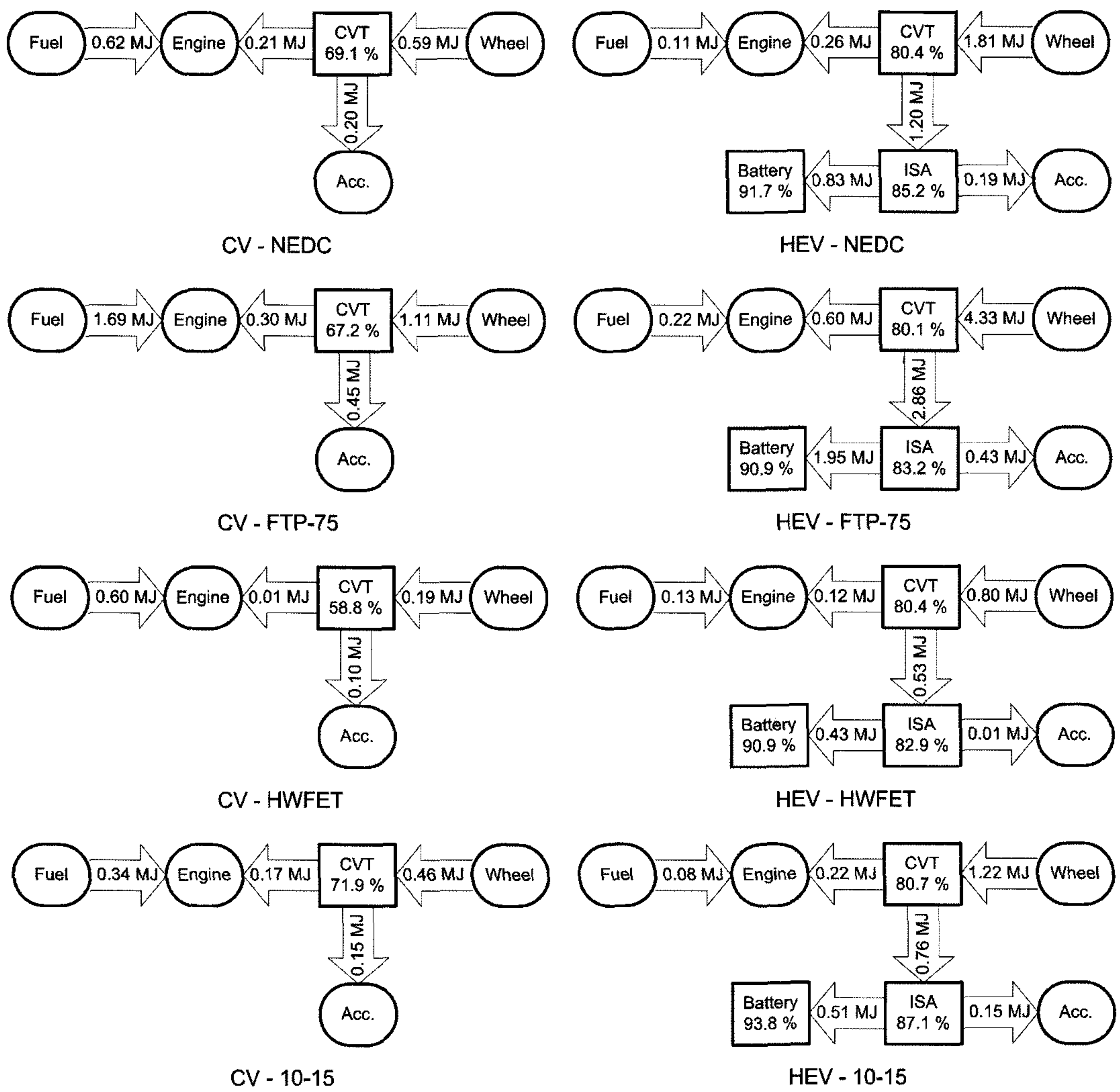

Figure 9. Energy flow and efficiency in braking mode.

the guideline from SAE (1999). The final SOC after the operation of the driving cycles is within these tolerances in all cases and slightly higher than the initial values except for the case of the HWFET mode. Actually, the final deceleration of the vehicle at the end of the cycles can offer the sufficient energy to recover the lost SOC. In HWFET, the final SOC is just 1% below the target, which is the worst case. Therefore it is clear that the fuel economy improvement of the HEV does not depend on the consumption of the pre-charged battery energy.

4.3. Energy Flow and Efficiency Analysis

The main purpose of this section is to reveal the pros and cons of the mild hybridisation in detail. To analyse the benefit of the HEV, the amount of the consumed fuel in each operating mode is summarised in Table 6. To define the operating mode, the simulation output signals from the vehicle are used. When the vehicle speed is zero the mode is classified as idling, for braking and propelling it depends on the sign of the wheel torque.

It is quite clear that there is a big difference between the synthetic cycles and the real world cycles. In the synthetic cycles, NEDC and 10–15 mode, the majority of the fuel saving is extracted from idling. These driving cycles consist of the constant acceleration and deceleration phases with the long idling and steady state cruising. Therefore the ISA does not have much opportunity to assist the engine or generate electric energy. Whereas more dynamic torque to accelerate or decelerate the inertia of the powertrain is needed in FTP-75 and HWFET. This requires the active role of the ISA and the fuel economy is improved in the braking and the propelling mode. This result also implies that the synthetic cycles are not suitable to examine the HEV benefits. The source of improvement in idling is clear because the HEV stops the engine when the vehicle is fully stopped.

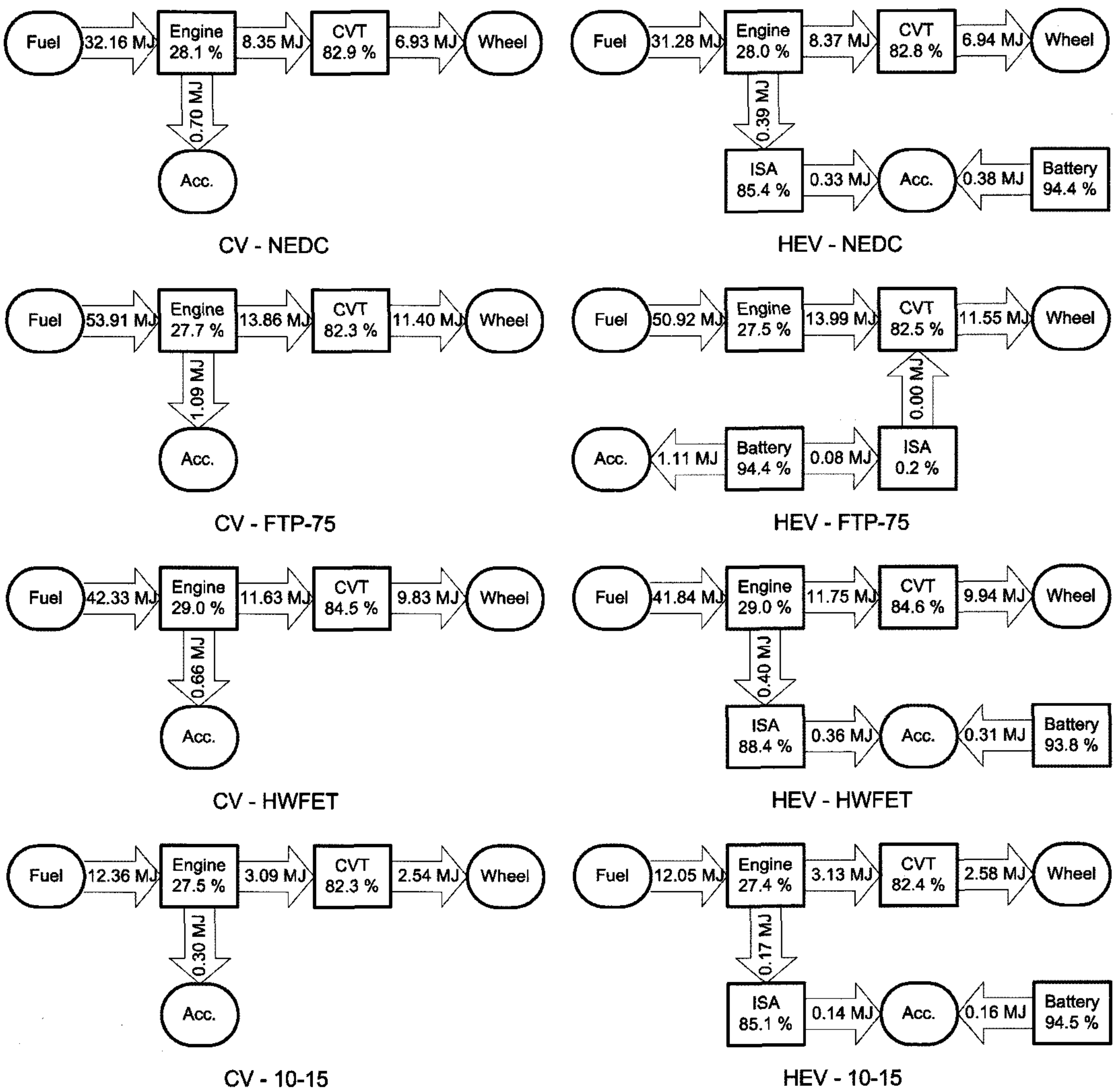

Figure 10. Energy flow and efficiency in propelling mode.

However, the braking and the propelling mode need more detailed analysis through the energy flow and conversion efficiency calculation of the powertrain components.

The energy flow diagram in the braking mode is displayed in Figure 9. The circular and squared symbols indicate the energy source or sink and the transmission components respectively. The energy flow between these components is shown by the arrows. As expected, the regenerative braking from the wheel absorbs much energy in the case of the HEV. This energy is used to drive the electric accessory and the rest is saved in the battery. A small amount of fuel is consumed because the engine should produce the energy to drive itself and overcome the driveline loss when the required braking torque is not sufficient. However, the ISA can assist this torque, so less fuel is used in the HEV.

The propelling mode consumes most of the fuel, more than 99% for the HEV. This fact means that the improvement in the propelling mode is the important factor of the HEV. Figure 10 depicts the energy flow and conversion efficiency in the propelling mode with the same convention as the braking mode diagram. The interesting point is that there is little difference of the engine and the transmission efficiency between the baseline vehicle and the HEV. That indicates the mild hybridisation hardly moves the powertrain operating points to the better efficient region. It is partly caused by the fact that the combination of the SIDI engine and the CVT is already operated very efficiently, so there is little room to improve the fuel economy by the mild hybridisation. Consequently, the fuel saving mainly comes from the accessory driving. In the baseline vehicle, 5–10% of the engine output energy is used to drive the mechanical accessory. On the contrary, much less energy from the engine is used to drive the ISA to supply the electric accessory driving in the HEV. In this study, the same value is assumed for the mechanical accessory in the baseline vehicle and the electric accessory in the HEV. However, as the battery supplies more than 50% of the electric accessory energy in the case of the HEV, the load to the engine by the accessory is much less than the baseline vehicle even though energy is lost in the ISA and battery. In the extreme case, HWFET cycle, the engine load by the accessory is zero and the battery supplies all of the energy.

5. CONCLUSIONS

The following are drawn from this study as the conclusions.

- The IOS concept was introduced to maximise the powertrain efficiency with the CVT. The baseline vehicle showed much better fuel economy than the same class of SUVs in FTP-75 and HWFET cycle. Therefore, the suggested powertrain and the CVT control strategy have a good fuel saving potential.
- The SOC level during the driving cycles was well controlled within the preset bounds, and the differences between the initial and the final SOC are in the range $-1.0 \sim +3.8\%$ in the examined cycle. This indicates that the proposed charge sustaining energy management algorithm is properly designed.
- The fuel economy improvement of the HEV was 1.3–20% in standard driving cycles against the baseline vehicle, which already showed considerable benefit with the combination of the SIDI engine and the CVT.
- The energy flow analysis indicated that the idle stop and the electrified accessory load driven by the regenerative braking energy occupied the majority of the improvement. Consequently, the fuel saving potential of the mild hybrid SUV was considerable in the urban cycles but relatively small in the highway cycle.

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