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The effect of 48V mild hybrid technology on fuel consumption of a passenger car by using simulation cycle

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A R T I C L E I N F O

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Fuel consumption
48V mild Hybrid
NEDC
RDC
BAS system

A B S T R A C T

The ASEAN's legislation has become more regulatory towards electric vehicles for automotive manufacturers to ensure the environment is preserved better for future generations. The ASEAN roadmap 2025 requirement in optimizing a conventional vehicle's fuel consumption is implemented with hybrid technology in targeting the automotive industry worldwide to achieve energy-efficient vehicles. This research aims to develop a vehicle model via 1D simulation cycle and implement the 48V mild hybrid to lower vehicle fuel consumption considering perspective in drive cycles data. The vehicle model used in this research is a D-segment vehicle powered by a 1.8L TGDI engine. The base model will be created using a GT Suite software where data is compared and analyzed with actual vehicle measurement. There will be two models produced; with and without Belt-Alternator-Starter (BAS) system. They will be further investigated for their functions based on NEDC and RDC drive cycles for fuel consumption. However, implementing the add-on technology from this simulation improved overall vehicle fuel consumption by 7.7% in NEDC and 1.7% in RDC. The results obtained for the optimization of the vehicle have shown difference by the results of each engine characteristics such as engine fuel flow rate, speed, torque, the BAS functions, and state of charge. The research proposes its findings to understand the practical usage of 48V mild hybrid system in fuel reduction and provide reliable proof to use as a reference for initiative studies.

1. Introduction

The newest invention has been created to sustain better energy and environment. The growth of road vehicle stock will significantly produce more carbon dioxide on every vehicle that uses ICE. The total of CO2 and emissions made by the vehicle proclaims to be

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increasing by its high number of consumers. Mild hybrid not only reduces CO2 emission, but it also could increase in power by 20% using the belt starter generator [1–6]. Consequently, involving the evolution of new technology such as 48V mild hybrid to the vehicle could reduce fuel consumption. A mild hybrid is a vehicle that uses both ICE and partial electric. The 48V battery and a starter/-generator allow the engine to turn off while in idling and braking mode.

The ASEAN roadmap 2025 requirement in optimizing a conventional vehicle's fuel consumption is implemented with a 48V mild-hybrid technology in targeting the automotive industry worldwide to achieve energy-efficient vehicles. The implementation of engine stop-start is a somewhat complicated function. It extends far beyond just a simple component and benefits the fuel economy [1,2]. This research aims to develop a vehicle model via a 1D simulation cycle and optimize vehicle model by using 48V mild-hybrid to lower vehicle fuel consumption considering perspective in drive cycles data [7–9]. The subject used for this study is a D-segment vehicle with a 1.8L TGDI engine. The base model will be created using a GT Suite software where data is compared and analyzed with actual vehicle measurement. In GT Suite software, the baseline model correlation needs to be parallel with another vehicle model that uses the 48V system. It is aimed to develop a vehicle model via 1D simulation cycle and implement the 48V mild hybrid to lower vehicle fuel consumption considering perspective in drive cycles data in this research. D-segment vehicle powered by a 1.8L TGDI engine vehicle model is used to analyze the performance. And also the base model is created using a GT Suite software where data is compared and analyzed with actual vehicle measurement.

1.1. Functions of BAS in hybrid electric Vehicle(HEV)

Belt-Alternator-Starter (BAS) is a small component in a vehicle that acts as a generator and motor directly linked to the engine. BAS system's function stands with three standard terms, mainly considering the stop/start function, regenerative braking and torque booster/torque assist. These functions are found in any hybrid vehicle types to help give better fuel consumption to the vehicle. Below is the detailed explanation of each function.

Stop/start mode is well known in the HEV world to switch the engine off mode during idling. If the vehicle is stationary in this mode, the engine can be switched off to save idle fuel consumption [10–15]. The stop/start system helps in containing unnecessary fuel usage during the vehicle stop or idling condition. As for the starting mode of engine they have happened during the driver input ECU on acceleration pedal. When the engine is in the off state, the vehicle needs torque to crank the engine. For cranking back the engine, a 12V battery kicks in the BAS system to start operating the engine. The switching system completes a circuit in the on-state to connect the starter motor, motor/generator and first energy storage device (12V battery) to the second energy storage device (48V battery) operationally so that both the starter motor and the motor/generator are connected to both the first energy storage device and the second energy storage device operationally [16–18]. Each starting mode required a small amount of torque to crank engine; therefore, a 12V battery is used in the engine's starting operation. The first minimum voltage of the first energy storage system may be a total minimum voltage of 8 V, for a 2 V per cell, such as during the start of the key. During this mode assumes that there is enough energy for the battery to sustain the requisite electrical ancillaries' operation and the next request for engine cranking.

1.1.1. Regenerative braking

The energy of the vehicle's kinetic movement is regenerated from braking to recharge battery purposes. The vehicle's energy is well used and not wasted when it is in free-wheeling mode or idling. The regenerative braking happened during the braking of the vehicle or low acceleration pedal position by the driver. When the driver is either in the low accelerator pedal position or presses the brake pedal during deceleration, the recovery mode is on [17–19]. Furthermore, it regains energy from the braking, but the engine is also switched off in this state. They are thus explaining in the free-wheeling condition made by the vehicle. For this recharging process, the battery will then use back its energy in a cycle mode to apply the vehicle electricity or even assist vehicle restarting mode. Other than that, the powertrain's efficiency increases by maximizing the amount of energy recovered.

1.1.2. Torque booster/torque assist

The component in hybrid is lesser compared to a conventional. BAS has a much compact system that can distribute many functions to the vehicle. Torque assist is one of them. In a hybrid, the torque assist mainly occurs during the starting of the engine. In braking or stopping vehicle's mode, the engine will switch off automatically depending on the ECU input towards the driver's accelerator pedal position. Suppose the engine is automatically in the off state. In that case, it requires a sufficient torque to crank the engine for a starting mode. The starter motor assists with the restart during the higher torque, the lower rpm of the restart and the motor/generator to assist with the restart during the lower torque, the latter part of the restart at a higher rpm. The e-machine supplies additional torque to boost vehicle performance in the 48 V mild hybrid configuration. There are different researches related to enhance in environmental issues and, the motor/generator can be configured to provide only relatively low torque, allowing cost savings over motor/generators that provide a higher torque output [19–24].

2. Materials and methods

The study in this research is to implement the 48V system to the vehicle. The drive cycle was studied for its characteristic and condition to prove for the comparison of the results. The method used in creating the 1D simulation is a GT Suite Software. Where two distinct design was created; conventional and mild hybrid.

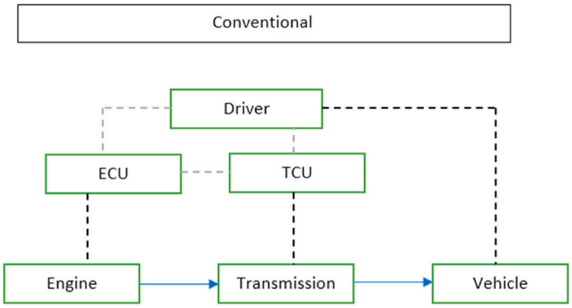


Fig. 1. Schematic vehicle model in GT Suite (without BAS).

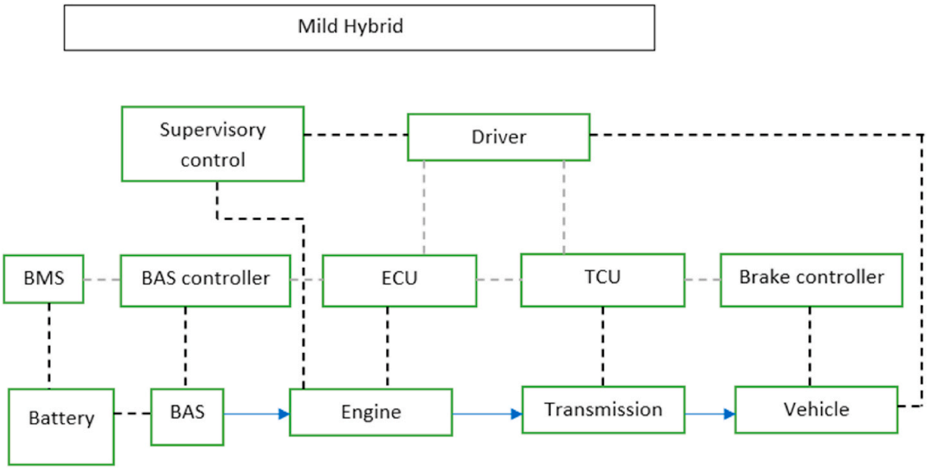


Fig. 2. Schematic vehicle model in GT Suite (with BAS).

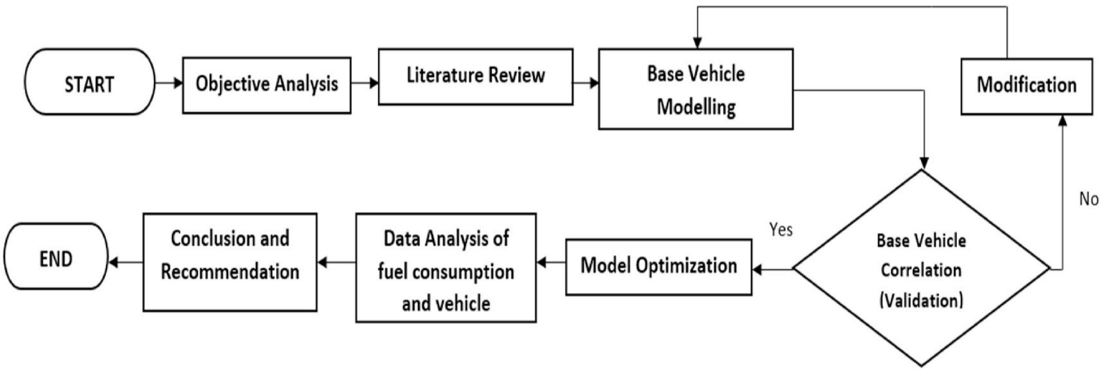


Fig. 3. Methodology flowchart.

2.1. Vehicle modelling in GT suite

In this paper, mild hybrid fuel consumption is determined through a complete simulation run in various driving cycles. Since a conventional vehicle model is used for this research, it consists of a powertrain that has a four-cylinder with TGDI 1.8L engine. The accuracy of data and information was ensured; the vehicle data and specifications were identified from the software and drive cycle used. Figs. 1 and 2 show the schematic base model of the vehicles used in the GT-Suite simulation.

Table 1
Vehicle base model specification.

Item	Description
Engine	1.8L Turbocharged and Gasoline Direct Injection (TGDI)
No. of cylinders	4-cylinder
Induction	Forced, Turbocharged
Transmission	6-speed AT
Total displacement	1801 cc
Min. Engine Speed	750 rpm
Max. Engine Speed	5500 rpm
Max. BMEP	23.4 bar @ 4000 rpm
Max. Power	173 kW @ 5000 rpm
Max. Torque	335N-m @ 4000 rpm
Weight	1500 kg

Table 2
Parameter of NEDC and RDC.

Parameter	NEDC	RDC
Cycle Time [s]	1180	2644
Distance [km]	11.0	34.8
Maximum Vehicle Speed [km/h]	120.0	135.5
Average Velocity [km/h]	33.6	47.2

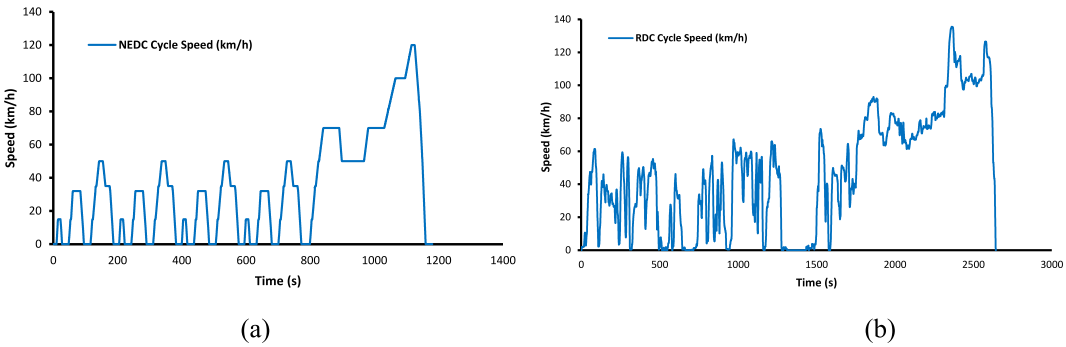


Fig. 4. Cycle profile for (a) NEDC (b) RDC.

2.2. Methods

1D simulation is used to design a vehicle compatible with the software to see data obtain reached the required result. During this study, the vehicle used is a D-Segment vehicle with an automatic transmission of a 1.8L TGDI engine. Below shows Fig. 3 methodology flowchart during the entire process of the making of an actual model in a GT Suite until the achieving objectives:

2.3. Vehicle model specification

The list of the description below is the base model specification used in this study. Both vehicle models have the same specification showed in Table 1 below. The base model will be created in GT Suite software, and data will be obtained from GT Post.

3. Results and discussion

The simulation involved were two types of vehicles; conventional and mild HEV. The result's data will be compared by two drive cycles to investigate the similarities and the differences obtained throughout.

3.1. Drive cycles

The drive cycles used in this study were NEDC and RDC. Drive cycles were used to provide a strong perspective for both sides of the results. NEDC has a more distinguished pattern compared to RDC, which is much irregular pattern. Due to the driving pattern set by NEDC whilst RDC has a much more random pattern for its depending on random real driving cycles. The real driving cycle (RDC) is

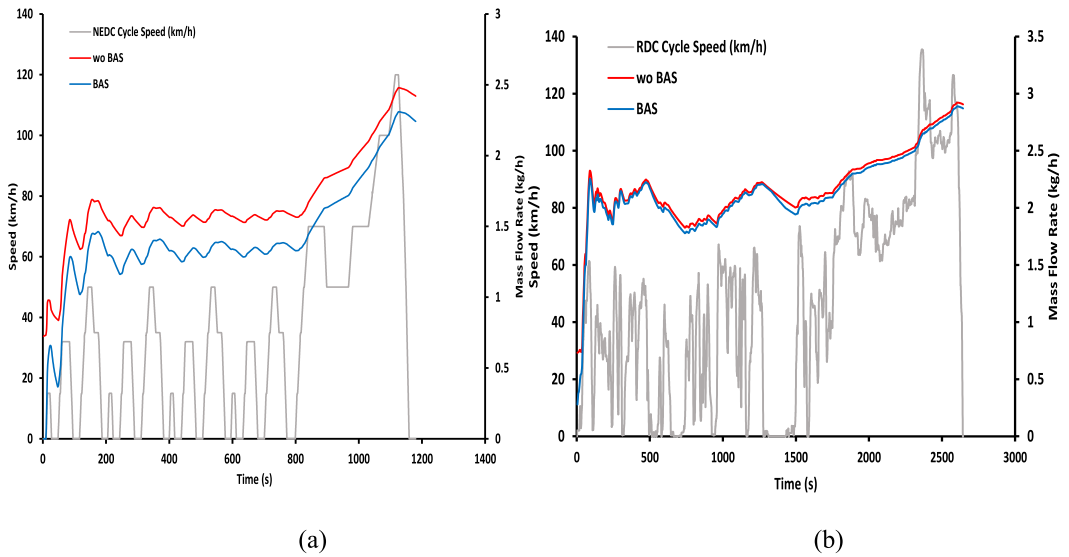


Fig. 5. Fuel flow rate with vs without BAS (a) NEDC (b) RDC.

generated from a conclusive part of gears such as gear WLTP, gear CADC, gear NEDC, gear Dynamic NEDC. The data for RDC is mainly from a random cycle generator software by TNO. The generator comes with a set of calculation to obtain a series of random outcome for RDC. For instance, road styles require the presumption that the driver would not act the same when travelling on a rural road or driving on a motorway [7]. Thus, to represent an actual world driving conditions towards the simulation. The different outcome of data from NEDC and RDC is as in Table 2 and Fig. 4.

In this study, a conventional vehicle was used as a reference for comparison purposes with mild HEV. The results can see the fuel consumption of each engine's vehicle characteristics such as engine fuel flow rate, speed, torque, the BAS functions and state of charge.

3.2. Fuel flow rate (with vs without BAS)

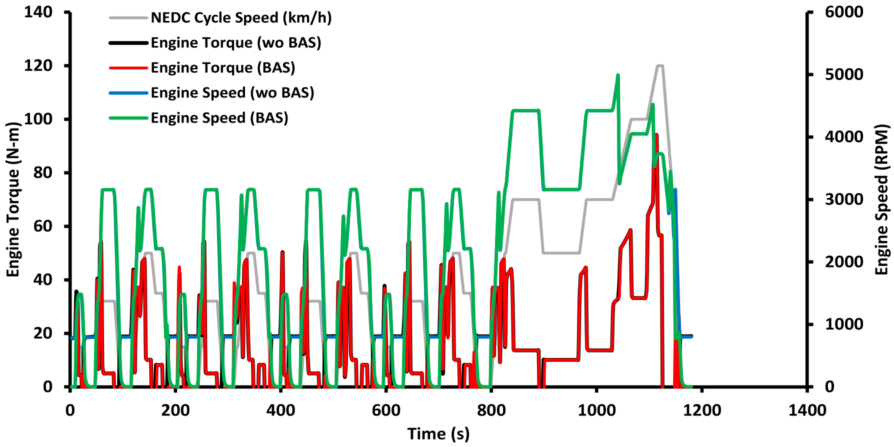
The hybrid uses BAS that develop fuel reduction following to its engine movement. In Fig. 5, we could see that the fuel flow rate varies between the two models. A vehicle with the BAS system has a slightly lower gap than the one without the BAS system. Mass of fuel is affected as the engine is still running, but the mass of fuel is less than a standard ICE as for the BAS system. Fig. 5 shows that the fuel flow rate for a hybrid was started at 0 kg/h; this indicates that the engine's condition is in an off state. When the engine is off, no torque presence thus no fuel required.

Engine stop-start cuts the fuel when it is not used to propel the car to the engine. Part of the explanation for lower fuel consumption for hybrid electric vehicles is that they allow the internal combustion engine to work at more effective speed-load points [8]. When the engine needs start, the motor will apply its torque via the accessory belt and cranks engine without using the starter motor due to the BAS that serves as a generator and motor. A belt-alternator-starter may be referred to as the motor/generator and may be designed to be powered by 12 V. The conventional vehicle graph (without BAS) has a starting point of 0.72 kg/h of fuel flow rate as the start state engine. When a conventional vehicle is in a stationary state, there will be torque and fuel presence to keep the engine running, explaining why a conventional has a higher starting point than a mild hybrid.

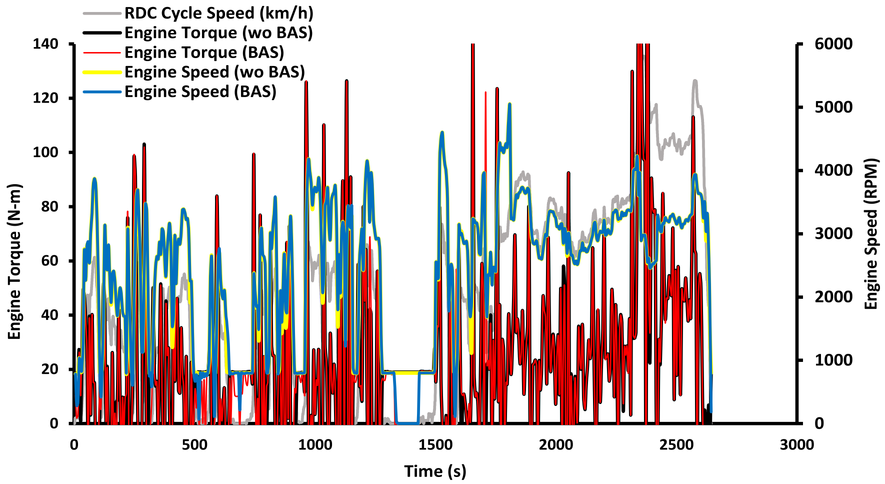
3.3. Engine speed and engine torque (with vs without BAS)

Much of the fuel's energy goes to the exhaust and the coolant (radiator) in a typical vehicle powered by an internal combustion engine, either SI or CI, with around a quarter of the energy doing mechanical work to propel the vehicle. In relating to the driving pattern, as the vehicle is in an urban area, it consumes more fuel due to braking. The pattern will show an inconsistent up and down pattern. From the profile, changes happen during each set of braking, and vehicle idling which speed indicated is 0 km/h in constant time. In an urban area, for BAS system shows the engine speed and engine torque varies. As when in urban, BAS complies in being the most effective in continuous braking. Therefore, leading to the engine speed and engine torque to a much efficient use than the one without BAS. Fig. 6 shows the engine shut off in each braking set for the vehicle with the BAS system. The stop/start system enrols its purpose to shut off the engine during any vehicle stop at a traffic area.

Fig. 6, the torque characteristic proves that a conventional vehicle has a consistent torque applied to its engine, while a mild hybrid is mainly in no torque applied. When the engine's torque and speed are reduced, the fueling will decrease as well. The presence of torque simplifies the presence of work applied. For a conventional vehicle, its engine will remain running and affect fuel consumption even when the vehicle is in idle. Meanwhile, for a hybrid vehicle, constant idling will automatically shut down the ICE and start free-



(a)



(b)

Fig. 6. Engine Speed and Torque with vs without BAS (a) NEDC (b) RDC.

wheeling. Thus, no fuel consumed. Fig. 6 proves that the vehicle that uses BAS, most of the braking and starting point duration, can be seen in a 0 km/h of engine speed and torque.

3.4. BAS states

The 48V system has four times more power than the 12V, which the energy can be used for different drive states. Engine off or vehicle stopped mode activates the BAS system when the programming/ECU catches acceleration less than 0%. Fig. 7 and Table 4 shows each BAS state's function. From state 1 can be identified when the engine is in an off state which the speed located is at 0 km/h. The fuel cutting occurred during this phase since the engine is off. If the ECU obtain acceleration pedal is more than 0%, the signal is transferred to start the engine. For starting engine state 2, it happened at the increase of the spike on the graph. Proves that acceleration occurs as the graph starts to be in an increment phase. Eventually, the engine will act as regular conventional ICE when the engine speed reaches more than 800 RPM. As vehicle speed continues to increase, the engine will work in state 3, which is 'engine only' shown in the graph. The phase of regular ICE has taken place during travel. Following state 4 is the regenerative braking. The electric is gained from the vehicle's kinetic energy, which is from the deceleration process. When the driver is either in the low accelerator pedal position or presses the brake pedal during deceleration, the recovery mode is on. The green coloured graph indicates vehicle idling or decelerates, which then to regenerate energy from braking until the engine goes to a fully off state. Table 3 shows that each state's percentage was obtained to compare each state's occurrence frequency. From the table, we can acknowledge that each state has served its purpose in fueling. Since state 3 is engine only, almost more than 30% of the remaining states, which is part of the BAS system, have

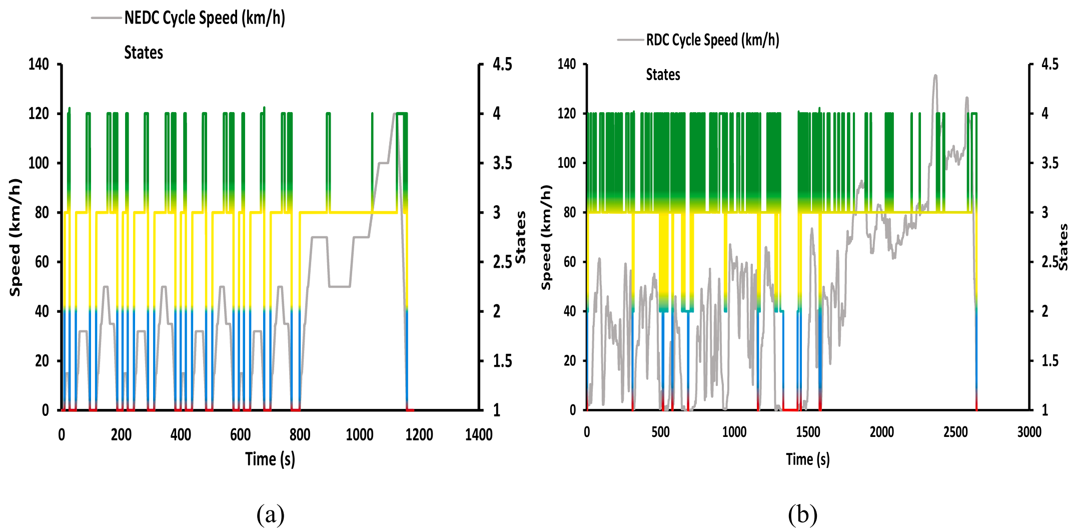


Fig. 7. BAS states (a) NEDC and (b) RDC

Table 3
Percentage of each States.

States	NEDC (%)	RDC (%)
1	8.95	1.61
2	0.58	3.87
3	69.98	66.73
4	20.49	27.79

Table 4
Color coding for BAS States.

Item	Color	States
1	Red	Engine Off
2	Blue	Starting
3	Yellow	Engine Only
4	Green	Regen Braking

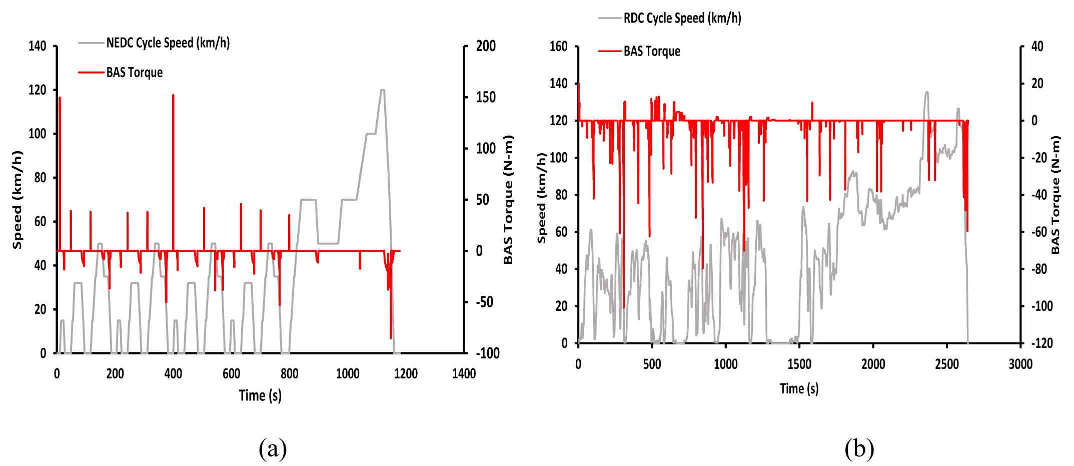


Fig. 8. BAS torque (a) NEDC and (b) RDC

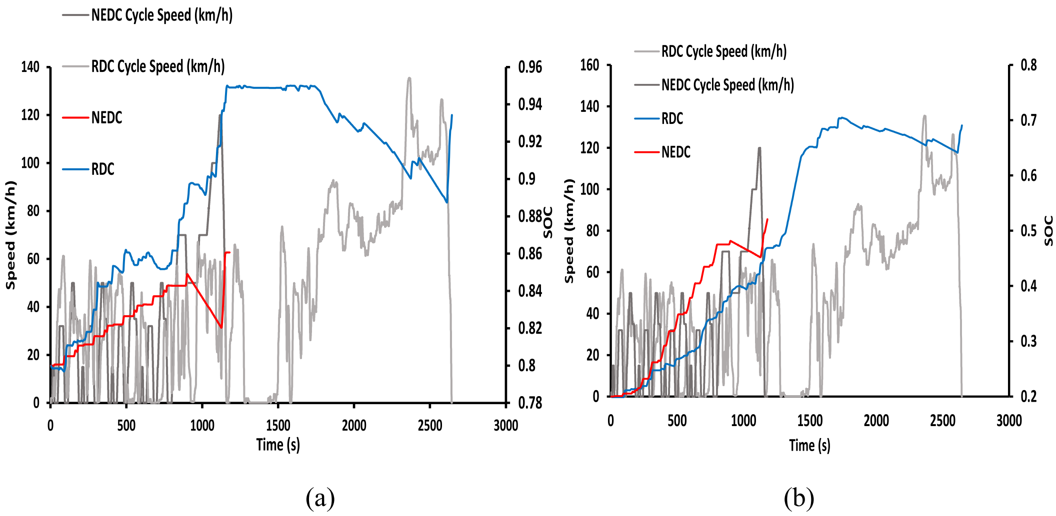


Fig. 9. State of charge for NEDC and RDC (a) 80% (b) 20%.

contributed to reducing fuel consumption during the travel.

3.5. BAS torque

Based on Fig. 8 cycles profile NEDC and RDC, the speed varies with BAS torque as the speed goes from a 0 km/h. The BAS torque starts to spike when the vehicle speed is started. The red line from the graph indicates the torque of the BAS. The positive value shows a small amount of torque from when the vehicle begins to start moving. Still, when the torque is negative, basically it means the BAS is in regenerative braking mode. The e-machine provides additional torque in the 48 V mild hybrid system to boost vehicle performance (torque-assist). The BAS torque acts as a torque booster that assists the BAS system restart the engine by applying a little torque to its motor. Only the starter motor is driven at the beginning of the restart. In another embodiment, the motor/generator is powered during the restart event only after a predetermined period has elapsed after the restart initiation or after a predetermined speed has been reached by the motor. Each drive cycle has proven that the BAS system serves its function smoothly for each positive value of torque received. The torque can be identified at each starting point after braking.

3.6. State of charge (SOC)

For the state of charge in this study used as a starting point is at 80%. This study uses 80% as SOC of the battery because it is in a good health state. Data observed is the proof of ability charging and discharging of the battery. Based on Fig. 9, the state of charge is identified in two patterns: increase and decrease. The SOC's descending shows the discharge of the battery while the increasing shows the battery's charge. In an urban driving pattern, the battery will remain recharge as it undergoes braking. The pattern for NEDC in discharging can be seen in between 800 and 1200s while for RDC is in 1800–2600s. Due to constant vehicle acceleration, the power needs to propel the vehicle is decreased; thus, proving the SOC, not in use is decreased. As it accumulates mechanical energy and discharges by slowing down, it supplies the EPS(electric propulsion system, i.e. clutch) with mechanical energy. The flywheel is charged by speeding up. When a vehicle is in braking mode, the charging process will occur thus shows the ascending at 0–800s for NEDC and 0–1200s for RDC.

During braking, the battery will charge due to regenerative braking. The kinetic energy from the rotational torque will impose as the recharging system. By charging the flywheel, which is further used for battery charging, the power of regenerative braking can be recovered [6]. The pattern for SOC proves a good display of charging and discharging point. Consider replacing the battery SOC with a much lower SOC of 20% results of a disintegrate towards the HEV performance. Compared to the energy it had when it was completely charged, battery SOC calculates the amount of energy left in a cell, which gives the user an idea of how much longer a battery can last until it needs to be recharged. Mainly because during discharging the battery will remain in a charging mode and will not distribute its energy towards vehicle propelling nor electrification in a required time. The charging process is affected and has much shorter time life of charging. Fig. 9 shows the SOC of 80% and 20%. If SOC affected, the whole cycle of electrification in the vehicle is also affected. Battery enrols a significant impact on energy distribution in the BAS system and other battery resources. The result of using a much lower SOC will impose on using a standard conventional vehicle. Thus, no change in fuel consumption will be achieved.

4. Conclusion

Previous results showing a difference in conventional and mild HEV proves that the 48V system reduces fuel consumption. It may

Table 5
Overall Fuel consumption Improvement.

Drive Cycle	1.8L TGDI With BAS (L/100 km)	1.8L TGDI Without BAS (L/100 km)	Improvement
NEDC	8.87	9.61	7.70%
RDC	8.07	8.21	1.71%

not be a big change of improvement but still proves fuel consumption reduction. The mild HEV also showed the characteristic of effective stop and start mode of the vehicle. The torque-assist also contributes to achieving the vehicle's performance, when it serves as an electric assist to the vehicle during a short period of idling. Nevertheless, this study's objective reducing fuel consumption based on the two drive cycles and using the 1D simulation software was achieved. As seen in results, implementing the add-on technology from this simulation improved overall vehicle fuel consumption by 7.7% in NEDC and 1.7% in RDC. The overall fuel consumption for NEDC and RDC was improved, as shown in Table 5 below.

Author statement

All authors contributed to manuscript equally and declare that there is no conflict of interest and all authors have seen and approved the manuscript being submitted.

Declaration of competing interest

The authors declare that there is no conflict of interest and all authors have seen and approved the manuscript being submitted.

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