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Design and simulation of a TTRH-EV supervisory controller for a proton SAGA 1.3

Sajjad Abdollahzadeh Anbaran[1], Nik Rumzi Nik Idris[1], Mohd Junaidi Abdul Aziz[1], Tole Sutikno[2,3]
[1]Power Electronics and Drives Research Group, Universiti Teknologi Malaysia, Skudai, Malaysia
[2]Master Program of Electrical Engineering, Faculty of Industrial Technology, Universitas Ahmad Dahlan, Yogyakarta, Indonesia
[3]Embedded System and Power Electronics Research Group (ESPERG), Yogyakarta, Indonesia

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ABSTRACT

This paper presents modeling and control design steps towards the vehicle hybridization process. The objectives are: a) to model a retrofitted proton SAGA, which is a through-the-road HEV; and b) to design and implement a supervisory control unit for this vehicle. The electric powertrain components required for conversion are sized using the ADVISOR software package. Physical models of both powertrains were modeled using the MATLAB Simscape toolbox and validated for their fidelity. A supervisory controller design and implementation for retrofitted TTRH-EV SAGA is based on the BSFC map and OOL of the engine. The control objective is to restrict engine operation within its optimum window. The controller was implemented using the MATLAB Stateflow toolbox. The complete model of the retrofitted TTRH-EV SAGA, together with the supervisory controller, was tested using standard drive cycles, and the results are presented.

Corresponding Author:

Sajjad Abdollahzadeh Anbaran
Power Electronics and Drives Research Group, Universiti Teknologi Malaysia
81310 Skudai, Johor, Malaysia
Email: sajjad.abdollah@gmail.com

1. INTRODUCTION

Motivated by global warming and climate change, we witness a rapid increase in the number of electric vehicles (EVs) around the world. However, there are still problems that make the transition to EVs sluggish, and Malaysia is no exception. The most notable obstacles to mass adoption of EVs are: i) Electric grid capacity: the present grid is not designed to accommodate power demand when large number of EVs are plugged in. Thus, it requires major adjustments; ii) Battery charging time is still long; iii) Battery cost which constitutes 40% of vehicle price; and iv) EVs won't be as effective if the power required to charge its batteries isn't obtained from green or renewable energy sources. Thus, new power-plants are needed.

Given this, HEVs appear to be one of the best short-term solutions for facilitating the transition to full EV transport. In the meantime, HEVs provide the time needed to address issues inhibiting EVs mass adoption. HEVs combine the benefits of both EVs and conventional vehicles while make-up for their shortfalls. It also serves as tool that gradually alters consumer behavior and tilt it towards EVs. Among various types of HEVs, through-the-road hybrid electric vehicle (TTRH-EV) stands out as one candidate to be incorporated in Malaysia's green mobility plans. This particular type of HEV can serve Malysia best on accomplishing both its national and global commitments. This technical solution is vastly studied in literature for its conversion ability where a conventional vehicle can be transformed into a HEVs. This can save cost, eliminates the need to scrap existing vehicles hence reduce GHG emission and boost Malaysia's progress speed towards pure EV mobility.

TTRH-EVs are available commercially from several prominent auto manufacturers; Volvo [1] and BMW [2] have already introduced their TTRH-EVs to the market. Moreover, this topic was well received by automotive research groups at universities, as TTRH-EV offers the prospect of converting a conventional car into a hybrid, a.k.a. a retrofitted TTRH-EV. The University of Salerno in Italy [3]–[5] has extensively worked on retrofitted TTRH-EVs. They developed and patented a proposal for hybridizing cars with solar panels to recharge the battery [6]–[11]. The hybrid kit includes two in-wheel motors, an extra Lithium-ion battery, solar photovoltaic modules installed on the car body, and a control unit for the electric powertrain. A schematic depiction of the hybridization kit is available at the LifeSave website [12]. Simulation analysis using validated models has shown that the solar hybrid vehicle can achieve significant fuel consumption reductions, up to 20% in typical urban driving. The analysis has also confirmed that the most significant benefits are achieved in urban driving, and there is a trade-off between the level of complexity used for hybridization and fuel savings. Real-time models can detect active gear and neutral gear conditions without using additional sensors and using only low-frequency OBD data. Studies show that the solar hybridization technology has good potential to be adopted by users [13]–[17].

In another piece of research, a group at University Technology Petronas (UTP) in Malaysia, in partnership with H2E Technologies Sdn. Bhd., transformed a Proton WAJA into a hybrid car. The proposal is similar to one from the University of Salerno, involving the use of IWMs and a battery placed in the car's trunk. The original vehicle structure had to be changed in order to make it suitable for IWM's installation. Moreover, the team replaced the cable-driven engine throttle with an electronic device for two reasons: it disconnects the accelerator pedal command from the engine throttle, and it allows the driver's torque request to be processed and divided between the internal combustion engine and the electric motors [18]–[22]. The UTP team conducted a simulation study to investigate the impact of internal combustion engine (ICE) sizing on fuel economy and NOx emissions in TTRH-EV technology [18]. For this purpose, two TTRH-EVs with different ICE maximum output powers were compared with a conventional vehicle in a simulation environment. The two TTRH-EVs had a 30% and 50% degree of hybridization and were optimized for powertrain cost by generating potential optimal design solutions for the size of the electric motor [23], battery pack, and gear ratio. It has been established that the battery capacity is determined by the energy required to satisfy the all-electric range (AER) restriction of the vehicle. Additionally, the battery size is influenced by the maximum power of the electric motor (EM), which is linked to the powertrain's maximum power limit. Furthermore, the minimum acceptable size of the EM is dependent on the limitations of the 0-100 km/h acceleration time and maximum vehicle velocity. The study also shows that both TTRH-EVs are slightly heavier than conventional vehicles owing to the additional weight of the battery pack, electric motor, and so on.

This paper intends to develop a vehicle model, both for conventional and retrofitted Proton SAGAs, and design a supervisory controller for the retrofitted SAGA. First, the vehicle and system architecture are described. Next, vehicle modeling and development using MATLAB and Simscape are explained. Then, a vehicle control strategy and its design using MATLAB/stateflow are presented. Finally, the system model and its controller were tested against standard driving cycles.

2. VEHICLE AND SYSTEM DESCRIPTION

2.1. Proton SAGA 1.3 L specification

In this paper, an internal combustion engine-based Proton SAGA 1.3 L will be used for the conversion study. The Proton Saga 1.3 L is a popular subcompact car manufactured by Proton Holdings Berhad, a Malaysian automaker. The Saga has been in production since 1985 and is currently in its third generation. The car is known for its practicality, affordability, and reliability, making it a popular choice among budget-conscious consumers. Table 1 presents the vehicle specification for the SAGA 1.3 L.

Table 1. Proton SAGA technical specification

Engine	Transmission	Body
- 1.3-liter inline-four-cylinder engine - Max power: 95 hp at 5,750 rpm - Max torque: 120 Nm at 4,000 rpm	- 5-speed manual or 4-speed automatic	- Length: 4,331 mm - Width: 1,689 mm - Height: 1,491 mm - Wheelbase: 2,465 mm - Weight: 1,045-1,110 kg (depending on model and options)

2.2. TTRH-EV system architecture

TTRH-EV, conceptually speaking, is a post-transmission PHEV; nonetheless, the way the TTRH-EV powertrain is configured distinguishes it from conventional PHEVs. The main difference between TTRH-

EVs and PHEVs is the absence of mechanical coupling between power sources in TTRH-EVs. This particular configuration of HEV has received a few different names by different researchers, such as split-axle parallel HEV [24], split-parallel HEV, and TTRH-EV [8], [25]. Different names stem from the researcher's viewpoint and focus on matter; nonetheless, this work will use TTRH-EV only. Figure 1 is a conceptual demonstration of the TTRH-EV powertrain.

One of the possible ways to realize TTRH-EVs is by retrofitting a conventional vehicle into a HEV. It is also one of the appealing features of this particular configuration of HEVs, in which an existing fuel-based vehicle is converted into a TTRHEV. There are two proposed schemes to accomplish a retrofitted TTRH-EV, depending on the details of the electric propulsion system. A retrofitted TTRH-EV can be constructed by installing a single electric motor to run both rear wheels or by using in-wheel motors (IWM). The architecture for both designs is presented in Figure 2.

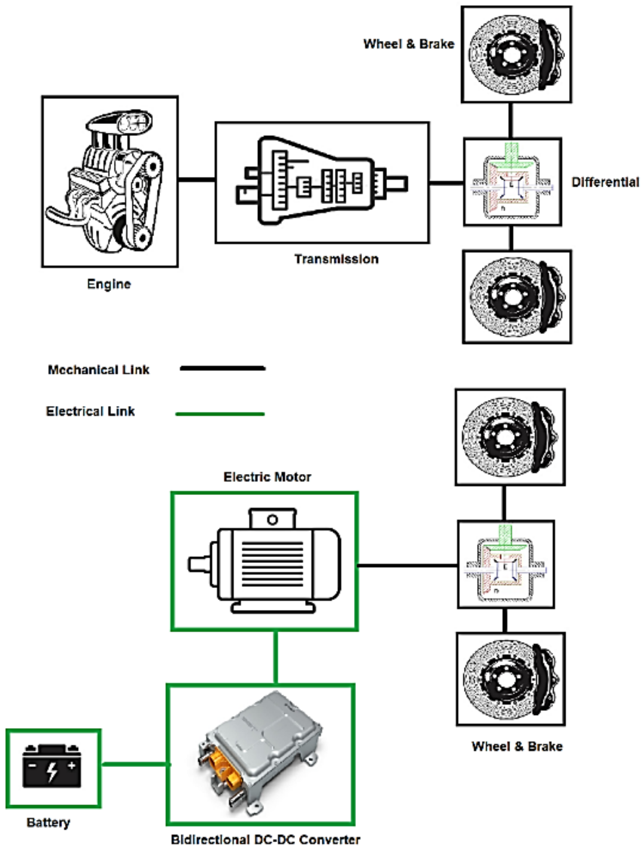

Figure 1. Conceptual illustration of TTRH-EV powertrain

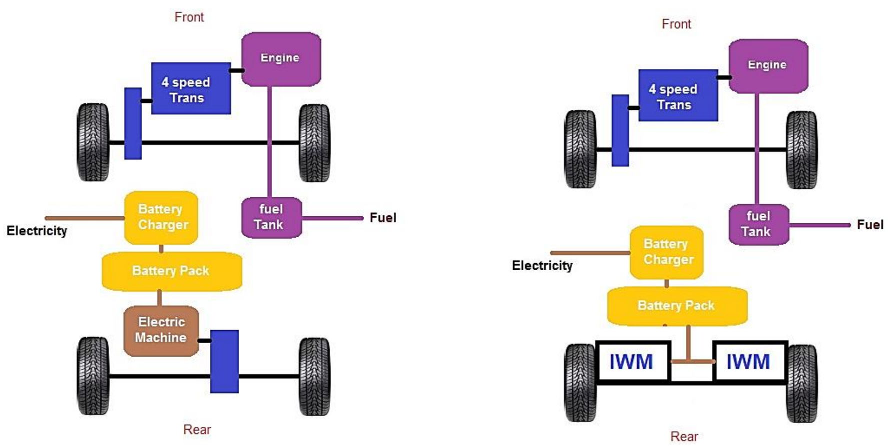

Figure 2. Possible configurations of retrofitted TTRH-EV

3. MODELING AND SIMULATION

3.1. SAGA electric powertrain

An effective modeling and simulation environment is an indispensable tool for automotive engineers and designers to study and manage the interaction between various components of a HEV. For the purpose of this study, the vehicle is modeled using MATLAB and Simscape. This particular toolbox in MATLAB enables the physical modeling of various systems in multiple domains. It is based on causal modeling techniques, in contrast to causal techniques, which reflect the realistic behavior of systems and their components. Moreover, the TTRH-EV powertrain is modeled at system level, which is adequate for control system design studies.

To hybridize Proton SAGA, an electric propulsion system must be designed. In other words, the size of the main components of the electric powertrain, i.e., the battery and motor, must be determined. Since the design is intended to be a full HEV, the main consideration in the component sizing process is that the electric powertrain should overcome all forces acting on the body of the vehicle and load, such as rolling resistance, aerodynamic drag, and resistive force due to climbing an incline. To determine the electric motor and battery size, the ADVISOR software package is used. The technical specification of SAGA was fed to the software package. Table 2 shows the motor and battery pack sizes.

The data for these components is available in ADVISOR. They are then deployed in the Simscape environment to construct an electric powertrain model based on the Proton SAGA 1.3 L, as shown in Figure 3. Next, the model is validated against multiple driving cycles such as FTTP75, EUDC, and ECE15. Figure 4 shows the vehicle's actual speed versus FTP75, which demonstrates the electric powertrain is able to perform standalone to run SAGA as an EV.

Table 2. Electric Propulsion component size from ADVISOR

Electric Motor	Battery
- AC62 Induction Motor	- Lead-Acid Battery
- 62 kW, 595 volts	- 25 Module at 308 volts

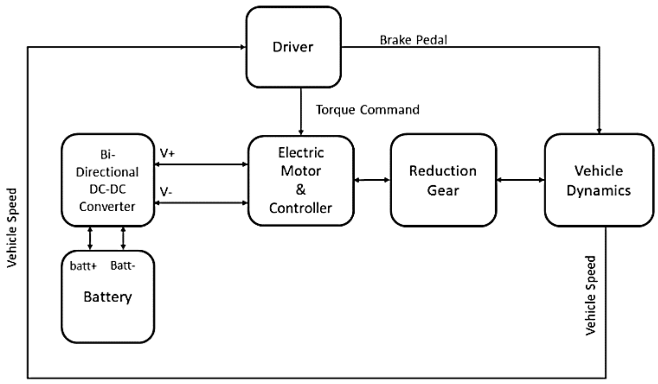

Figure 3. SAGA-electric powertrain model IN Simscape

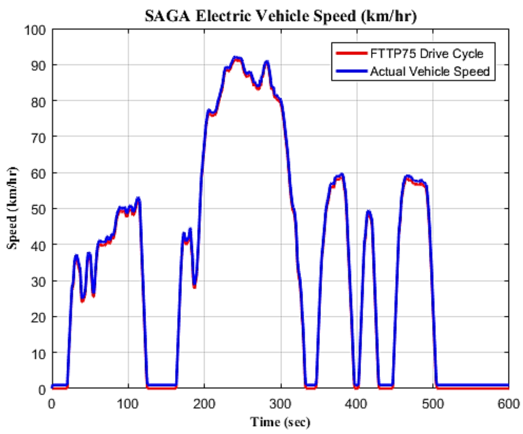

Figure 4. SAGA electric powertrain tested with FTTP75

3.2. SAGA internal combustion engine powertrain

Conventional SAGA powertrain components are the internal combustion engine, four-speed transmission, transmission control logic, and vehicle body. To have a realistic SAGA model, real measured data are used to model the engine and transmission system with a gear-shift controller, as shown in Figure 5. Figure 6 shows the SAGA engine brake specific fuel consumption (BSFC) map superimposed by the engine optimal operating line (OOL). OOL is the line along which an engine operates at its maximum fuel efficiency. This line is obtained by solving an optimization problem that returns the corresponding speed and torque vectors at which fuel efficiency is at its maximum. This data is required to control the engine such that engine operating points are restricted to optimal regions within the BSFC map.

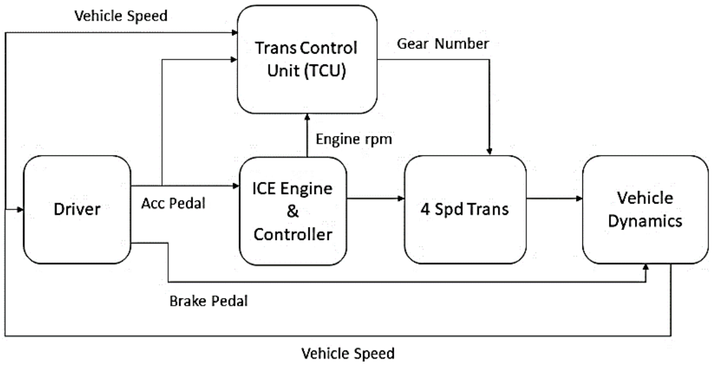

Figure 5. SAGA internal combustion powertrain

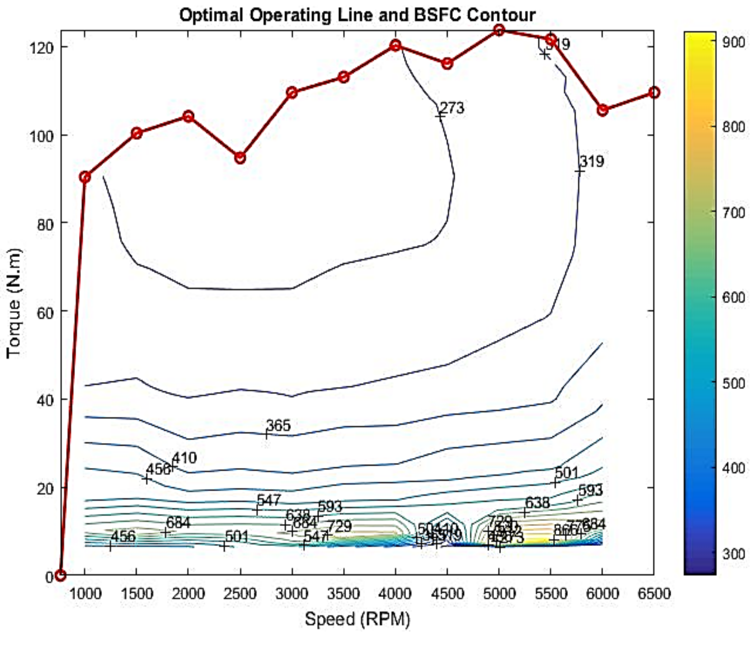

Figure 6. SAGA- engine BSFC map and optimal operating line (OOL)

The transmission system for SAGA is a four-speed automatic (4-AT) system. It is modeled with a torque converter coupled to a variable transmission system (CVT). This structure, conceptually speaking, demonstrates similar behavior to that of a geared automatic transmission; moreover, there is gearshift logic implemented in the model to ensure the CVT behaves like an AT, as shown in Figure 7.

The gearshift logic is implemented using the MATLAB/state flow toolbox. It uses SAGA gearshift maps to calculate a speed threshold at which gear changes need to take place. The gearshift logic also decides whether the gear should shift up or down, as illustrated in Figure 8. Similar to the SAGA electric powertrain, the engine-based powertrain is also tested against a few standard driving cycles. Figure 9 shows the vehicle speed of the engine-based powertrain and gear change process during drive.

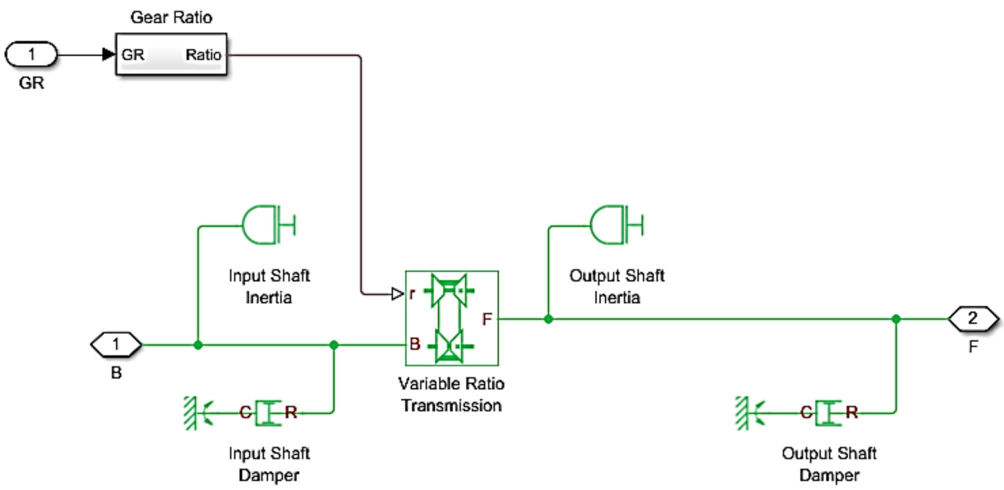

Figure 7. SAGA, 4-speed automatic transmission in Simscape environment

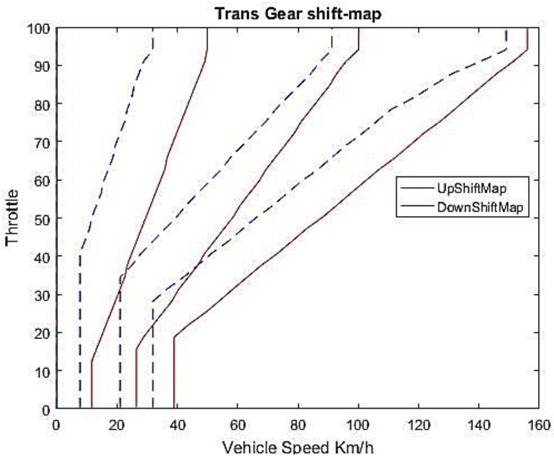

Figure 8. SAGA, 4-speed AT gearshift map

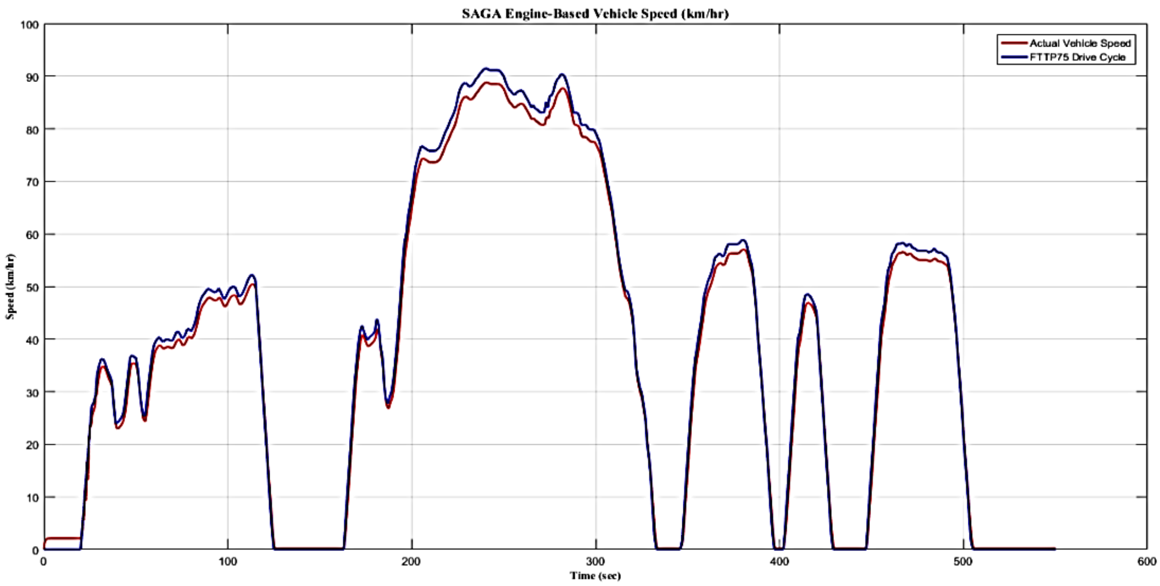

Figure 9. SAGA, engine-based powertrain model test with FTTP75

As the final step in modeling and controlling a retrofitted SAGA (TTRH-EV), the two separate powertrains are combined in a single model to form the TTRH-EV powertrain, as shown in Figure 10. In contrast to powertrain models for electric propulsion and engine-based systems where the vehicle dynamics subsystem includes either the front or rear wheel, the vehicle dynamics subsystem in the TTRH-EV model includes all four wheels. The front wheels are propelled by the engine's propulsion system, and the rear wheels are attached to the electric motor. Subsequently, a 4WD vehicle is realized, which is one of the key features of the TTRH-EV system. Figure 11 presents the vehicle dynamics subsystem constructed using Simscape-driveline.

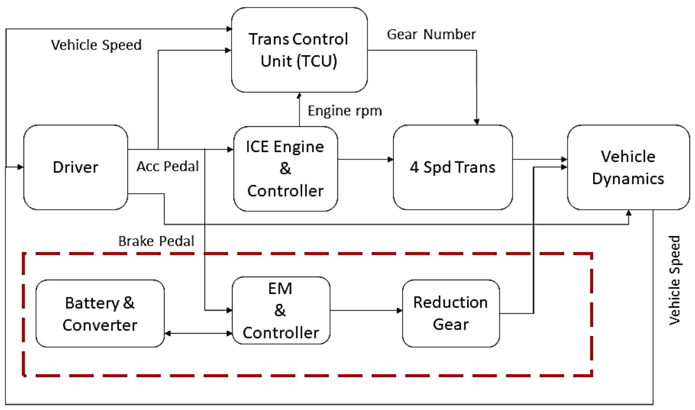

Figure 10. SAGA TTRH-EV powertrain model

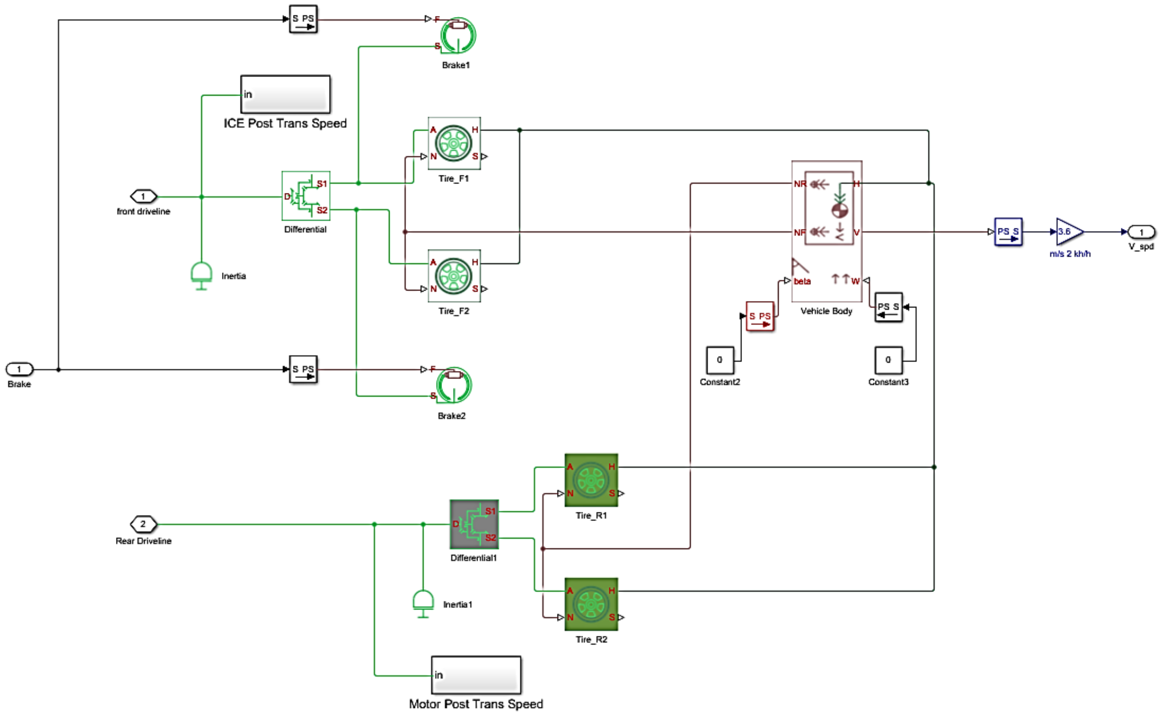

Figure 11. 4WD subsystem in TTRG-EV SAGA

At this stage, the model does not include a supervisory control system. Instead, the power demand is equally divided between the engine and electric motor, and the model is validated against standard drive cycles. Figure 12 shows the TTRH-EV speed profile versus the FTTP75 drive cycle while the engine and electric motor equally supply power to the wheels (TTR = 50%). It can be seen from Figure 12 that vehicle model fidelity is good and performs well under FTTP75, and engine and motor together are able to meet the power demanded by the driver.

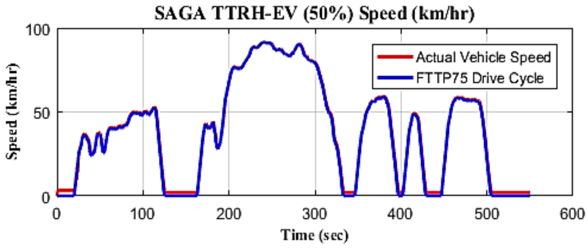

Figure 12. SAGA TTRH-EV model (TTR=50%) tested with FTTP75

4. SUPERVISORY CONTROLLER DESIGN

A typical control structure of a HEV consists of three layers: system-level, component-level, and physical layer. In some literature, the system-level layer is called the high-level controller, and the component-level layer of the control structure is called the low-level controller, as depicted in Figure 13. These two together formed the supervisory control unit (SCU). The supervisory system in an HEV computes the instantaneous amount of power for each energy source present in the HEV powertrain to deliver at each instant while satisfying several constraints.

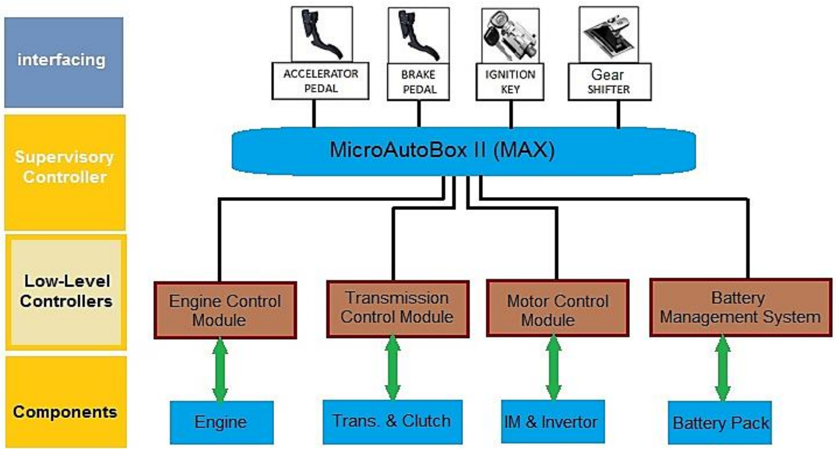

Figure 13. Control system architecture of a HEV

A system-level or high-level controller performs supervisory control tasks where it is responsible for: i) selecting the appropriate operating point, ii) coordination between energy sources onboard, iii) power management, and iv) regenerative braking control. This layer of control aims at optimizing the energy flow of the powertrain while maintaining SOC within an admissible range. It receives information from the driver and main components of the driveline and outputs the operating point and operating condition (set point) of driveline actuators to be executed by the low-level control layer.

4.1. Supervisory control logic

In general, there are nine operating modes for a HEV [18], out of which TTRH-EV, restricted by its structure, can avail itself of five operating modes. These operating modes are: i) EV only; ii) ICE only; and iii) TTRH-EV, iv) regenerative braking, v) stationary charging. The design of the vehicle in this study has to comply with Malaysian Green Mobility Plans [26], [27], hence the retrofitted SAGA must have plug-in capability and is not allowed to operate in charge-sustaining mode. For this reason, the supervisory control design for retrofitted SAGA has four operating modes (1-4).

The supervisory controller is expected to decide operating modes, partition power demand between electric and engine powertrains, and improve vehicle fuel economy. Engine BSFC maps are incorporated to determine areas where engines have low fuel efficiency and use electric motors to run. Moreover, the engine OOL presented in Figure 6 gives the torque and speed values at which the engine has high fuel efficiency. The supervisory controller should run the engine along this line. The area in which engines have low fuel efficiency can be determined by studying the BSFC contour, and the power value below which engines operate inefficiently can be determined from the same map, which is shown in Figure 14.

From Figure 14, it can be seen that the engine's inefficient region is below the 17.8 kW power hyperbola. Thus, this is the region where the engine should run and an electric motor should supply it instead. Further investigation of the map shows that the engine leaves its optimal region after a 50-kW power hyperbola. Therefore, these two values determine the engine's optimal operation window [17.8–50 kW]. The supervisory controller should operate the electric motor outside this region where engine operation is not optimal. Table 3 summarizes the operating mode region for SAGA TTRH-EV. From Table 3, it can be seen that both the electric motor and engine are active in TTRH-EV mode, where the engine and electric motor together propel the vehicle. This would allow the implementation of a supervisory controller in MATLAB/state flow to be simpler Figure 15.

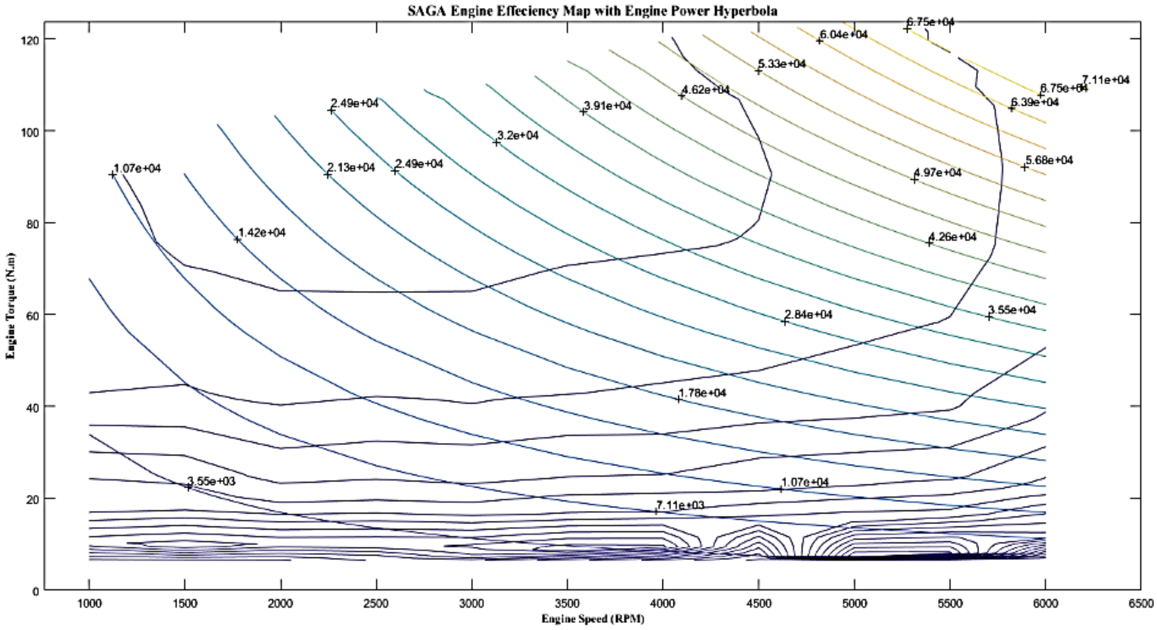

Figure 14. SAGA BSFC map with engine power hyperbola

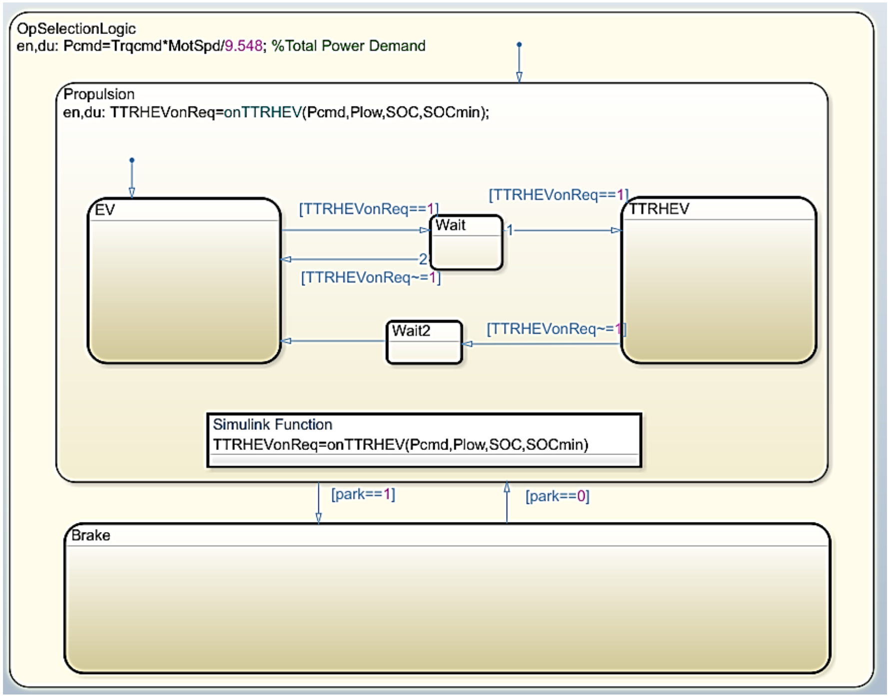

Figure 15. SAGA TTRH-EV supervisory control implementation with MATLAB/state flow

Table 3. SAGA TTRH-EV operating modes

Operating mode	Electric Motor	ICE
EV	On if power demand below 17.8 kW	Off
ICE	Off	On if power demand is between 17.8-50 kW
TTRH-EV	On	On
Regenerative Braking	Motor functions as generator	Off

There are two super-states: Propulsion and braking, and within the propulsion super-state, the vehicle's operating mode is decided. The vehicle first starts in EV mode and continues in that state until the power demanded by the driver exceeds the 17.8 kW threshold. In EV mode, the engine and transmission control systems are off, so the engine-based powertrain is not supplying any power to the front wheels. The propulsion super-state is simultaneously monitoring power demand and using the *TTRHEVonReq* function to decide if the engine should run or stay off. The vehicle would enter the TTRHEV if the *TTRHEVonReq* function is ON (equal to 1). In the new state, supervisory control will calculate how much power the engine should provide. If the power demand is more than 50 kW, an electric motor will supply that surplus power demand, which is illustrated in Figure 16.

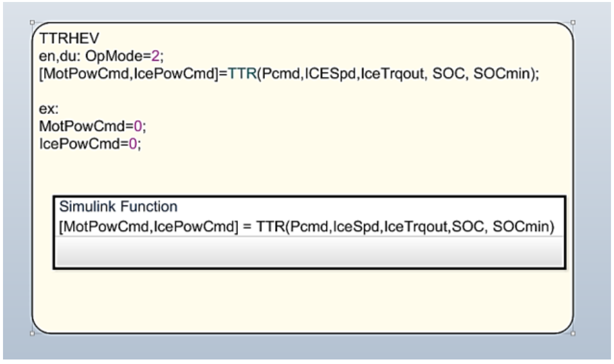

Figure 16. SAGA TTRH-EV control in hybrid mode

4.2. Total torque and calculation

The supervisory controller computed total power demand by multiplying torque by the motor speed measured at the wheel (post-transmission), Figure 17. The amount of torque demanded by the driver is calculated in the torque demand subsystem, Figure 18. Rear and front wheel speeds are measured and given to two lookup tables that contain optimal torque-speed characteristics of the engine and motor. The output of these two lookup tables is summed to determine the total amount of torque. This is where TTR (through-the-road) technology realizes itself. Finally, this value is multiplied by the accelerator pedal value and fed to the supervisory controller state flow chart to compute total power demand.

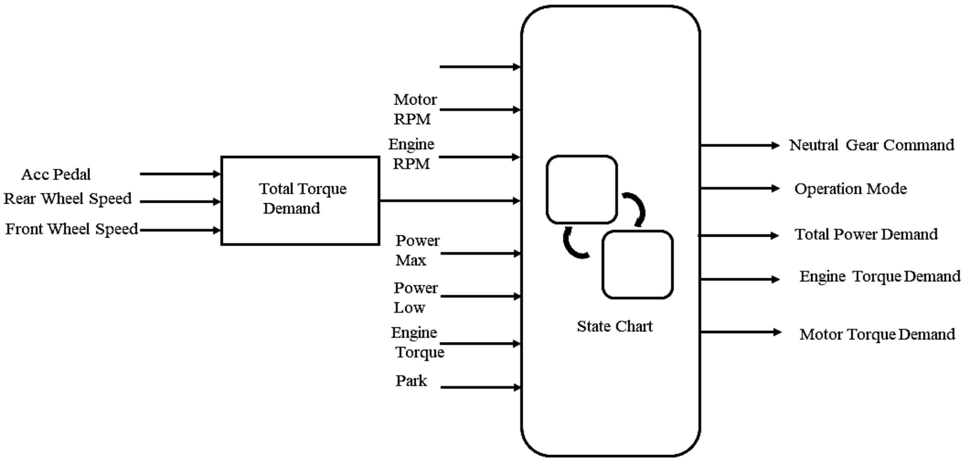

Figure 17. SAGA TTRH-EV supervisory controller implementation via MATLAB/State flow

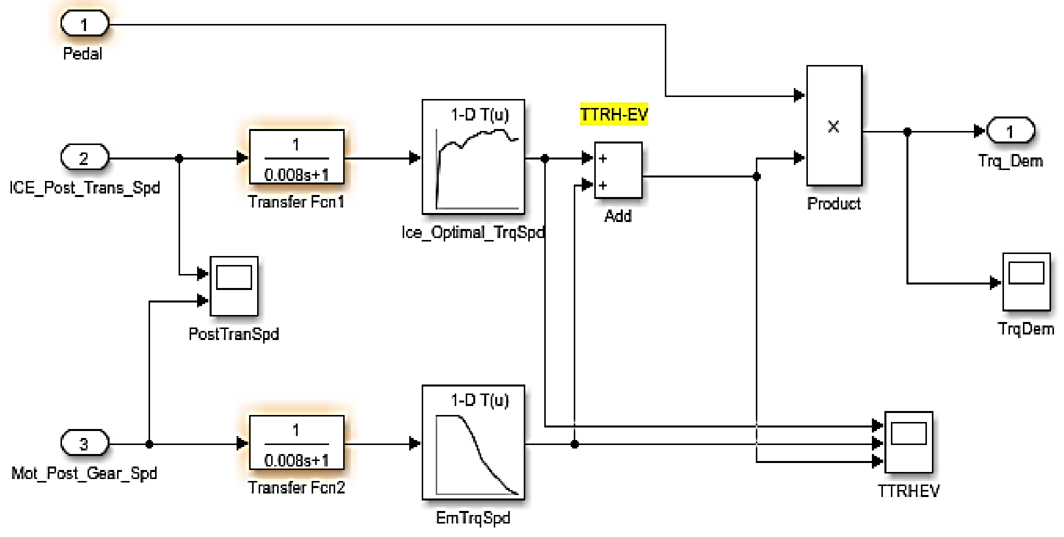

Figure 18. SAGA TTRH-EV total torque calculation

5. RESULTS AND DISCUSSION

The control architecture for SAGA TTRH-EV implemented in Simulink is presented in Figure 19. It receives feedback data from low-level components of the vehicle and uses it to decide hybrid vehicle operating modes as well as the partitioning of power demand. The supervisory controller outputs necessary signals to the low-level controllers, i.e., the engine controller, electric motor controller, and transmission control unit (TCM), which contains gearshift logic for the 4-AT transmission.

A complete model of the retrofitted TTRH-EV SAGA has been tested using various drive cycles such as FTTP75, EUDC, and ECE 15. However, only the results for FTTP75 are presented in this paper. The transition between different operating modes of vehicles is presented in Figure 20. The SAGA TTRH-EV controller switched between EV mode and TTRHEV mode. In TTRHEV mode, the engine is always on, and the controller switches on the electric motor when there is a surplus of power that must be met by the electric motor.

Engine outputs of retrofitted SAGAs are presented in Figure 21. It can be seen that it supplies power to the wheels when it is required in TTRHEV mode and runs idle during EV mode. Figure 22 shows electric motor speed, torque, and power measurements. It can be seen that the motor is always on throughout the drive and supplies most of the power required by the driver. This in turn shows its effect on battery SOC, which causes it to deplete quickly and shorten the distance that can be traveled in EV mode, as shown in Figure 23.

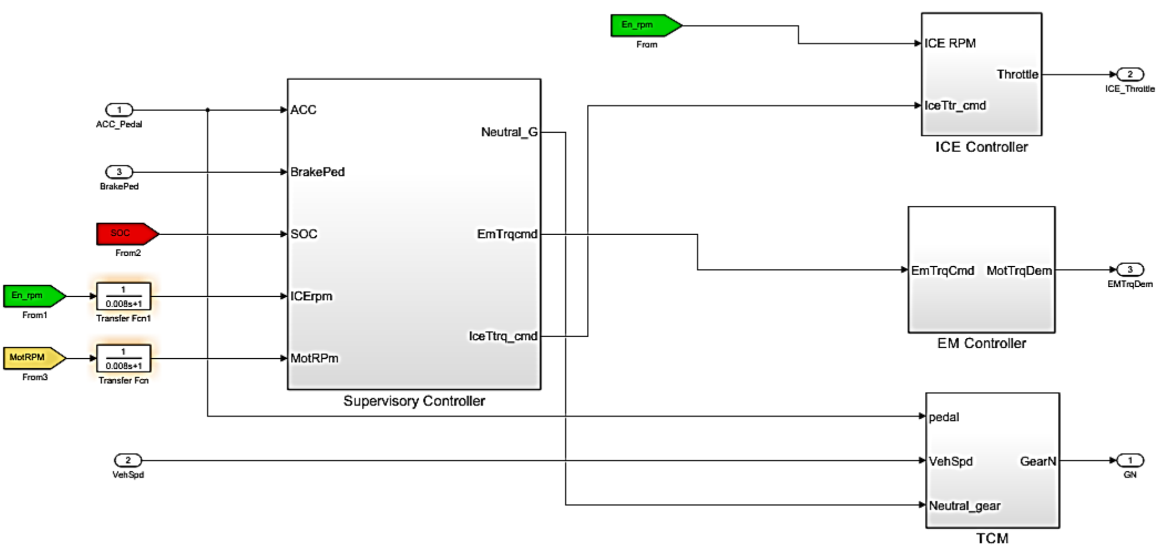

Figure 19. SAGA TTRH-EV control architecture including high-level (supervisory) and component level controllers

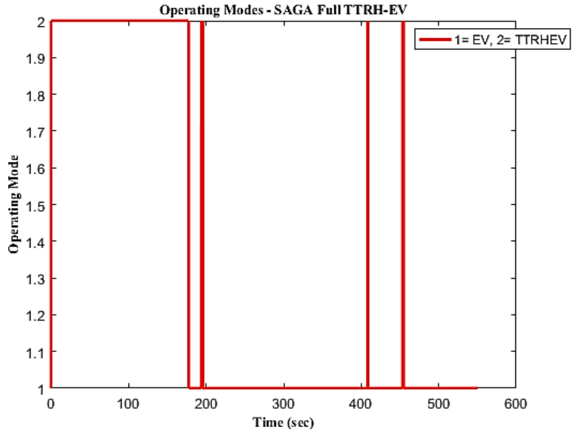

Figure 20. Supervisory controller operating modes (1= EV, 2= TTRHEV)

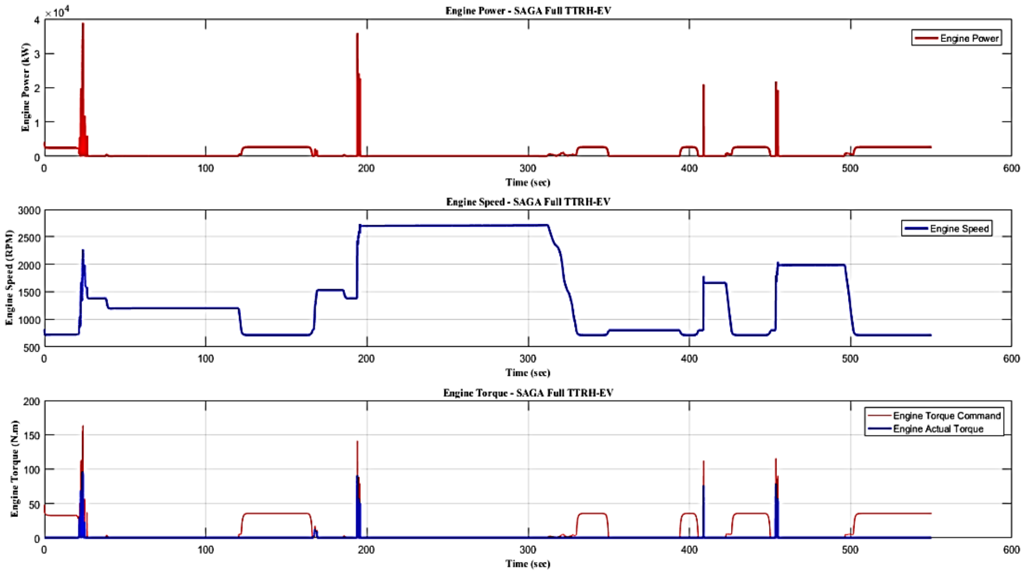

Figure 21. Engine torque, speed and power of retrofitted SAGA

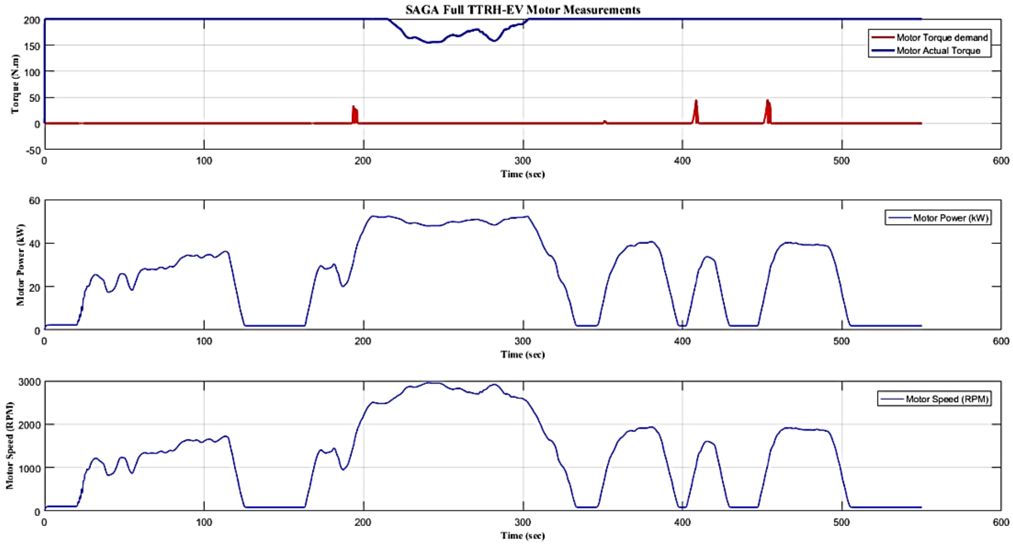

Figure 22. Electric motor measurements of retrofitted SAGA

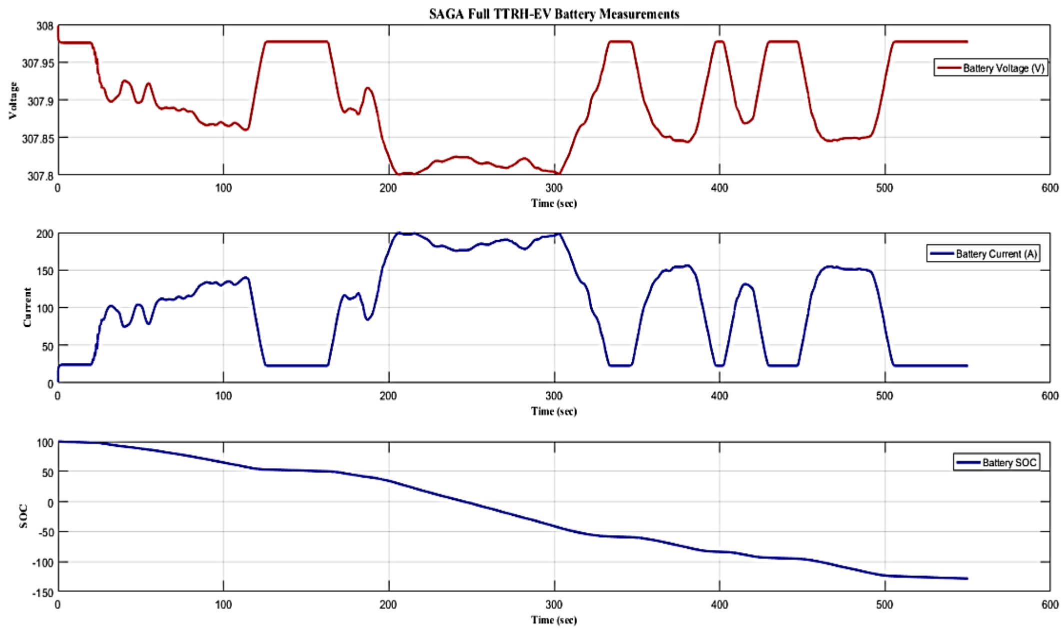

Figure 23. Battery output measurement for retrofitted SAGA

6. CONCLUSION

The conversion of a Proton SAGA into a through-the-road hybrid electric Vehicle (TTRH-EV) is discussed. The electric powertrain components to run SAGA in electric mode were sized using the ADVISOR software package, and their physical model was developed using the MATLAB Simscape physical modeling toolbox. Finally, the model was validated against standard driving cycles. Similarly, the original vehicle, which is a Proton SAGA, was modeled using real, measured data. The physical model includes the engine, transmission system, controller, and vehicle dynamics systems. The engine-based physical model was tested against standard drive cycles, and results were presented. Next, the two models (EV and Engine-based) were combined to form the TTRH-EV. This model was also validated using multiple drive cycles, and results for FTTP75 were presented. Next, a supervisory controller was designed for the retrofitted SAGA TTRH-EV. This control strategy was based on the engine's BSFC map and its optimal operating line (OOL). The objective of the control is to operate the engine at its optimum operating window. The control values for the supervisory controller were obtained from the engine BSFC map, and the controller was implemented using the MATLAB state flow toolbox. In line with supervisory controllers, controllers for low-level components such as engines, electric motors, and transmissions were developed. Finally, results were presented to assess the performance of the supervisory controller of the retrofitted TTRH-EV. Based on the results presented, the supervisory controller manages to accommodate the power demanded by the driver and track the reference speed cycles. However, the supervisory controller needs further tuning, and its performance on fuel economy needs to be investigated. In hindsight, it is expected that the retrofitted SAGA TTRH-EV will demonstrate good fuel economy performance since the supervisory controller uses an electric motor throughout the drive cycle and to meet power demand. This means the engine is seldom used, which can be translated as low fuel consumption.

REFERENCES

[1] Volvo, "Volvo XC90 Recharge – Our luxury plug-in hybrid SUV," 2023, [Online]. Available: https://www.volvocars.com/us/cars/xc90-hybrid/.

[2] T. X5, "BMW X5 (G05): Models, Technical Data & Prices | BMW.com.my," 2023, [Online]. Available: https://www.bmw.com.my/en/all-models/x-series/X5/2021/bmw-x5-highlights.html.

[3] G. Rizzo and F. A. Tiano, "Life cycle assessment study for different options of sustainable mobility, including vehicle conversion," *International Journal of Powertrains*, vol. 9, no. 1–2, pp. 122–149, 2020, doi: 10.1504/IJPT.2020.108431.

[4] J. Meisel, W. Shabbir, and S. A. Evangelou, "A practical control methodology for parallel plug-in hybrid electric vehicle powertrains," *2013 9th IEEE Vehicle Power and Propulsion Conference, IEEE VPPC 2013*, pp. 30–35, 2013, doi: 10.1109/VPPC.2013.6671659.

[5] G. Rizzo, M. Sorrentino, C. Speltino, I. Arsie, G. Fiengo, and F. Vasca, "Converting conventional cars in mild hybrid solar vehicles," *IFAC Proceedings Volumes (IFAC-PapersOnline)*, vol. 44, no. 1 PART 1, pp. 9715–9720, 2011, doi: 10.3182/20110828-6-IT-1002.03319.

[6] F. A. Tiano, "Transformation of vehicles into plug-in or electric hybrid-solar cars," *LIFE-SAVE*, 2022. https://www.life-save.eu/en/conversion-into-plug-in-solar-hybrids-or-in-electric-cars/.

[7] F. A. Tiano, G. Rizzo, G. De Feo, and S. Landolfi, "Converting a Conventional Car into a Hybrid Solar Vehicle: a LCA Approach," *IFAC-PapersOnLine*, vol. 51, no. 31, pp. 188–194, 2018, doi: 10.1016/j.ifacol.2018.10.035.

[8] G. Rizzo, M. Naddeo, and C. Pisanti, "Upgrading conventional cars to solar hybrid vehicles," *International Journal of Powertrains*, vol. 7, no. 1–3, pp. 249–280, 2018, doi: 10.1504/IJPT.2018.090352.

[9] G. Rizzo *et al.*, "A prototype mild-solar-hybridization kit: Design and challenges," *Energy Procedia*, vol. 45, pp. 1017–1026, 2014, doi: 10.1016/j.egypro.2014.01.107.

[10] J. Meisel, W. Shabbir, and S. A. Evangelou, "Evaluation of the through-the-road architecture for plug-in hybrid electric vehicle powertrains," *2013 IEEE International Electric Vehicle Conference, IEVC 2013*, 2013, doi: 10.1109/IEVC.2013.6681143.

[11] J. Meisel, W. Shabbir, and S. A. Evangelou, "Control of PHEV and HEV Parallel Powertrains Using a Sequential Linearization Algorithm," *SAE Technical Papers*, vol. 2015-April, no. April, 2015, doi: 10.4271/2015-01-1219.

[12] L. Renzo, "Landi Renzo is a LIFE-SAVE's project partner - HySolarKit," *LIFE-SAVE*, [Online]. Available: https://www.life-save.eu/en/landi-renzo-en/

[13] I. Arsie, M. D'Agostino, M. Naddeo, G. Rizzo, and M. Sorrentino, "Toward the development of a through-the-road solar hybridized vehicle," *IFAC Proceedings Volumes (IFAC-PapersOnline)*, vol. 46, no. 21 PART 1, pp. 806–811, 2013, doi: 10.3182/20130904-4-JP-2042.00157.

[14] M. D'Agostino, M. Naddeo, and G. Rizzo, "Development and validation of a model to detect active gear via OBD data for a Through-The-Road Hybrid Electric Vehicle," *IFAC Proceedings Volumes (IFAC-PapersOnline)*, vol. 19, pp. 6618–6623, 2014, doi: 10.3182/20140824-6-za-1003.01166.

[15] E. Galvagno, D. Morina, A. Sorniotti, and M. Velardocchia, "Drivability analysis of through-the-road-parallel hybrid vehicles," *Meccanica*, vol. 48, no. 2, pp. 351–366, 2013, doi: 10.1007/s11012-012-9606-6.

[16] V. Marano, H. Medina, M. Sorrentino, and G. Rizzo, "A model to assess the benefits of an after-market hybridization kit based on realistic driving habits and charging infrastructure," *SAE International Journal of Alternative Powertrains*, vol. 2, no. 3, pp. 471–481, 2013, doi: 10.4271/2013-24-0086.

[17] G. Rizzo, F. A. Tiano, V. Mariani, and M. Marino, "Optimal modulation of regenerative braking in through-the-road hybridized vehicles," *Energies*, vol. 14, no. 20, 2021, doi: 10.3390/en14206835.

[18] S. A. Zulkifli, N. Saad, S. Mohd, and A. R. A. Aziz, "Split-parallel in-wheel-motor retrofit hybrid electric vehicle," *2012 IEEE International Power Engineering and Optimization Conference, PEOCO 2012 - Conference Proceedings*, pp. 11–16, 2012, doi: 10.1109/PEOCO.2012.6230915.

[19] S. A. Zulkifli, S. Mohd, N. Saad, and A. R. A. Aziz, "Split-parallel through-the-road hybrid electric vehicle: Operation, power flow and control modes," *2015 IEEE Transportation Electrification Conference and Expo, ITEC 2015*, 2015, doi: 10.1109/ITEC.2015.7165774.

[20] S. A. Zulkifli, S. Mohd, N. Saad, and A. R. A. Aziz, "Operation and control of split-parallel, through-theroad hybrid electric vehicle with in-wheel motors," *International Journal of Automotive and Mechanical Engineering*, vol. 11, no. 1, pp. 2793–2808, 2015, doi: 10.15282/ijame.11.2015.54.0235.

[21] S. A. Zulkifli, S. Mohd, N. Saad, and A. R. A. Aziz, "Operation, power flow, system architecture and control challenges of split-parallel through-the-road hybrid electric vehicle," *2015 10th Asian Control Conference: Emerging Control Techniques for a Sustainable World, ASCC 2015*, 2015, doi: 10.1109/ASCC.2015.7244637.

[22] S. A. Zulkifli *et al.*, "Design and development of split-parallel through-the road retrofit hybrid electric vehicle with in-wheel motors," *IOP Conference Series: Materials Science and Engineering*, vol. 100, no. 1, 2015, doi: 10.1088/1757-899X/100/1/012039.

[23] S. A. Zulkifli, S. Mohd, N. Saad, and A. R. A. Aziz, "Influence of motor power and efficiency on fuel consumption of retrofit-conversion split-parallel hybrid electric vehicle," *2013 9th IEEE Vehicle Power and Propulsion Conference, IEEE VPPC 2013*, pp. 339–343, 2013, doi: 10.1109/VPPC.2013.6671715.

[24] K. V. Singh, H. O. Bansal, and D. Singh, "A comprehensive review on hybrid electric vehicles: architectures and components," *Journal of Modern Transportation*, vol. 27, no. 2, pp. 77–107, 2019, doi: 10.1007/s40534-019-0184-3.

[25] M. F. M. Sabri, M. H. Husin, M. I. Jobli, and A. M. N. A. Kamaruddin, "An overview of modeling and control of a through-the-road hybrid electric vehicle," *Lecture Notes in Electrical Engineering*, vol. 666, pp. 399–417, 2021, doi: 10.1007/978-981-15-5281-6_28.

[26] J. Lee, "RMK-12: Malaysia to be carbon neutral by 2050 – cleaner electricity to replace coal-fired power plants," *Paultan.Org*, 2021, [Online]. Available: https://paultan.org/2021/09/28/rmk-12-malaysia-to-be-carbon-neutral-by-2050-cleaner-electricity-to-replace-coal-fired-power-plants/.

[27] L. Anthony, "Malaysia's EV policy to offer tax-free cars, lower road tax, green parking, toll rebates, charging incentives," *Paultan.org*, 2021, [Online]. Available: https://paultan.org/2021/05/20/malaysia-ready-to-offer-handsome-tax-incentives-for-evs-new-policy-set-to-be-announced-in-june-madani/.

BIOGRAPHIES OF AUTHORS

Sajjad Abdollahzadeh Anbaran is currently a PhD student at Universiti Teknologi Malaysia (UTM). He has B.S and M.S degrees in Electrical Engineering from IAU-Iran and UTM-Malaysia. His research interests are in field of modeling and optimal control of Hybrid/Electric Vehicles. He can be contacted at email: saasajjad2@graduate.utm.my.

Nik Rumzi Nik Idris earned his B.Eng. degree in Electrical Engineering from the University of Wollongong, Wollongong, NSW, Australia, in 1989. He then pursued his M.Sc. degree in Power Electronics at Bradford University, West Yorkshire, U.K., in 1993. Later, in 2000, he obtained his Ph.D. degree from Universiti Teknologi Malaysia (UTM), Johor Bahru, Malaysia. He is a senior member of the Institute of Electrical and Electronics Engineers (IEEE) and served as the chair of the IEEE Power Electronics Society, Malaysia Chapter from 2014 to 2016. Currently, he holds the position of Professor at Universiti Teknologi Malaysia and serves as an Associate Editor for the IEEE Transactions on Power Electronics. From 2012 to 2023, he was the Head of the Power Electronics and Drives Research Group (PEDG) at UTM. With an extensive publication record of over 180 journals and conference papers, he has been invited as both a guest speaker and keynote speaker to several international and local programs and conferences. His research interests are in the field of high-performance control of AC drives, electric/hybrid electric vehicles, and power electronic systems. He can be contacted at email: e-nrumzi@utm.my.

Mohd Junaidi Abdul Aziz was born in Kuala Terengganu, Malaysia, in 1979. He received his B.S. and M.S. degrees in Electrical Engineering from the Universiti Teknologi Malaysia (UTM), Kuala Lumpur, Malaysia, in 2000 and 2002, respectively. He received his Ph.D. degree in Electrical Engineering from the University of Nottingham, Nottingham, ENG, UK, in 2008. Since 2008, he has been with the Faculty of Electrical Engineering, UTM, where he is presently working as an associate professor. His current research interests include power electronics and electric vehicles, with a special focus on battery management systems. He can be contacted at email: junaidi@utm.my.

Tole Sutikno is a lecturer, and serves as the head of the Electrical Engineering Department, as well as the head of the Master Program of Electrical Engineering within the Faculty of Industrial Technology at Universitas Ahmad Dahlan (UAD) in Yogyakarta, Indonesia. In 1999, 2004, and 2016, he graduated with a Bachelor of Engineering from Universitas Diponegoro, a Master of Engineering from Universitas Gadjah Mada, and a Doctor of Philosophy in Electrical Engineering from Universiti Teknologi Malaysia. All three degrees are in the field of electrical engineering. Since the year 2008, he has held the position of Associate Professor at the Universitas Ahmad Dahlan in Yogyakarta, Indonesia. He is among the top 2% of researchers named by Stanford University and Elsevier BV as the most influential scientists in the world for 2021–present. His research interests include the areas of digital design, industrial applications, industrial electronics, industrial informatics, power electronics, motor drives, renewable energy, FPGA applications, embedded systems, artificial intelligence, intelligent control, digital libraries, and information technology. He can be contacted at email: tole@te.uad.ac.id.