Simulation of Series and Parallel Hydraulic Hybrid Myvi

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School of Mechanical Engineering
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Universiti Sains Malaysia

DECLARATION

This journal article is a presentation of my original research work. Wherever contributions of others are involved, every effort is made to indicate this clearly, with due reference to the literature, and acknowledgement of collaborative research and discussions. The work was done under the guidance of Dr. Muhammad Iftishah Ramdan, at the Universiti Sains Malaysia, Engineering Campus.

Leong Yong Sheng

Date: 5th June 2017

In my capacity as supervisor of the candidate's journal article, I certify that the above statements are true to the best of my knowledge.

Dr. Muhammad Iftishah Ramdan

Date: 5th June 2017

ACKNOWLEDGEMENT

I am using this opportunity to express my gratitude to everyone who supported me throughout the course of this final year project. I am thankful for their guidance, advice and critism during my project work. I would like to express my deepest gratitude to my advisor, Dr. Muhammad Iftishah Ramdan, for his excellent guidance, caring, forgiveness, and providing me with an excellent atmosphere for doing research. I take this opportunity to express my gratitude to all the School of Mechanical Engineering members for their help and support. I also thank my parents for the all the support.

Thank you,

Yong Sheng

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

SOC : State of charge

BSFC : Brake specific fuel consumption

ABSTRACT

The paper compares the fuel economy of Perodua Myvi with 2 different architectures of hydraulic hybrid vehicle which are parallel and series architectures. The simulation was done to predetermine the feasibility of transforming conventional Myvi to a hydraulic hybrid Myvi. The fuel economy was simulated with backward-facing model on the Malaysian drive cycle using MATLAB coding. A rule-based control strategy was manipulated manually to fulfill the requirement with respect to the drive cycle. The parallel architecture shows a good improvement on fuel economy which is 97% while 47% in series architecture. However, even the parallel hybrid would take 12.4 years for the return of investment costing which is infeasible.

ABSTRAK

Kertas ini membandingkan ekonomi bahan api Perodua Myvi antara 2 jenis seni bina hibrid hidraulik iaitu selari dan siri seni bina. Simulasi ini dijalankan untuk menentukan kemungkinan mengubahkan Myvi konvensional menjadi Myvi hybrid hydrolik. Ekonomi bahan api telah disimulasi dengan menggunakan model menghadap dari belakang. Simulasi ini menggunakan pengekodan MATLAB dan kitaran memandu Malaysia sebagai input. Strategi kontrol berbasis aturan telah dimanipulasi sehingga ia memenuhi kebutuhan dalam kitaran memandu. Seni bina selari menunjukkan kemajuan sebanyak 97% sementara 47% dalam seni bina siri. Namun, hibrida selari akan mengambil selama 12.4 tahun untuk mengembalikan investasi yang mana tidak berlayak.

INTRODUCTION

Most of the internal combustion engines use fuel which is a non-renewable resource. There are millions of vehicles running daily and the fuel consumption is immense, as well as the waste produced from the combustion such as carbon dioxide. In 2013, transportation sector had contributed 43.3% of energy consumption of petroleum in Malaysia [1]. Most of the vehicles use internal combustion engine and therefore it is crucial to increase the fuel economy.

In general, we waste a lot of energy in driving such as during braking. Most of the time, the engine is operating out of its efficient region such as low torque and high speed. Hydraulic hybrid vehicle(HHV) was invented to reduce the issues stated. The concept is similar with hybrid electric vehicle(HEV) which utilizes the energy by capturing and reuse the braking energy. In addition, the alternative source of energy can assist the engine in some cases to reduce the load and thus efficiency of engine is higher. The benefit of using HHV over HEV is that HHV is able to capture braking energy more efficient [2].

The vehicle encounters mainly 4 forces (air drag, rolling friction, inertia and gravity on inclined road) on moving. In this simulation, the gradient of road is assumed to be zero all the time in the Malaysian drive cycle as the slope angle of road could not be measured and recorded in real time on road. The net force is then translated to required wheel torque. The inertial force increases due to the additional components' weight of hydraulic system. Therefore, a control strategy is designed to fulfill the requirement vehicle speed from the Malaysian drive cycle.

There are 2 architectures of hydraulic hybrid system in this study – parallel and series hydraulic hybrid systems. The configuration of parallel hydraulic hybrid system is as shown in Figure 1. The hydraulic system is connected in parallel to the drive shaft and the hydraulic pump can assist engine whenever needed and regenerate power from the excess power in drive shaft. A clutch is placed after the engine so that the engine can be decoupled and turned off while the hydraulic system provides full power to the wheels based on the control strategy [3]. Since the components are all connected directly as same as conventional vehicle, installation of parallel hydraulic hybrid system to a conventional vehicle is feasible [4]. The advantage of this architecture is the high transmission efficiency where the components are coupled mechanically while the disadvantage is that the engine must run accordingly to the wheel speed and thus, no full engine control and lower brake thermal efficiency.

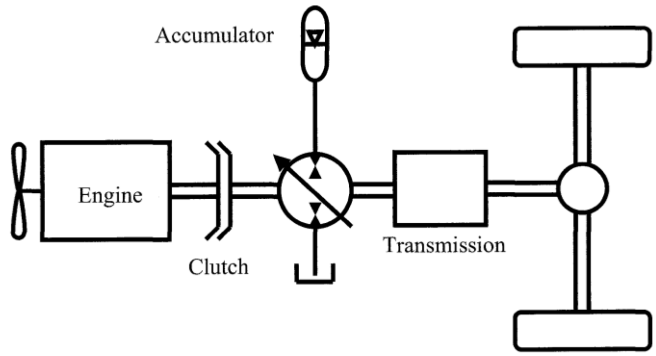


Figure 1: Schematic diagram of parallel hydraulic hybrid system [3]

In series hydraulic hybrid system, the hydraulic system replaces the mechanical drive train as shown in Figure 2, where engine is able to operate at different speed with the wheels. This allows a full engine control where operating parameters can be controlled to give higher brake thermal efficiency of engine. However, this architecture suffers a low transmission efficiency due to the higher loss through the hydraulic system. Moreover, if the hydraulic system breaks down, the vehicle is unable to move unlike the parallel architecture.

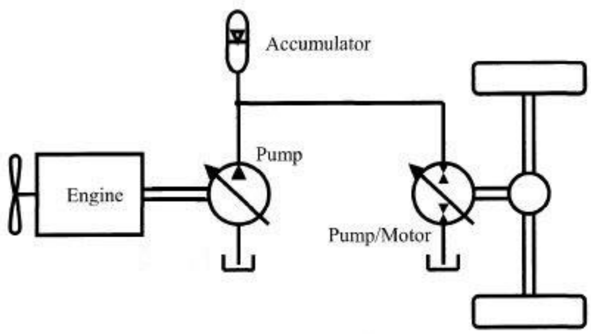


Figure 2: Schematic diagram of series hydraulic hybrid system [3]

COMPONENTS SIZING OF HYDRAULIC SYSTEM

The parts were chosen from Rexroth, Bosch Group where the type of pump is axial piston variable pump, A4VG and the accumulator is hydro-pneumatic bladder-type accumulator. The major specifications of pump and accumulator chosen is shown in Table 1 and Table 2. The nominal pressure of accumulator was set as large as possible and larger than the nominal operating pressure of pump (400bar) as to store more energy. The volume of accumulator was determined by size of Perodua Myvi's available space. The size of pump was chosen based on the minimum torque at maximum displacement, the torque must be able to perform the maximum torque of engine (100Nm) so that it could meet the drive cycle requirement all the time.

Table 1: Specifications of A4VG pump selected

Nominal maximum pressure	400bar
Displacement/revolution (D)	71cm^3
Torque @Δp=400bar, D	452Nm
Torque @Δp=100bar, D	113Nm
Approximate mass	50kg

Table 2: Specifications of hydro-pneumatic bladder-type accumulator selected

Nominal volume	20liters
Maximum operating pressure	414bar
Approximate mass	94kg

SIMULATION

MATLAB coding is used to simulate the fuel economy using backward facing modelling and discretization of time into time step of 1s each. Desired speed of vehicle from drive cycle [5] is the input to a vehicle model producing transmission speed and torque required. The transmission speed and torque are then gone through a transmission model (including hydraulic model) to compute the engine speed and torque. Myvi's engine map which Lim Zhi Wey (colleague) has done experimentally is used to determine the fuel consumption based on the engine speed and torque. The backward-facing modelling is visualized as shown in Figure 3.

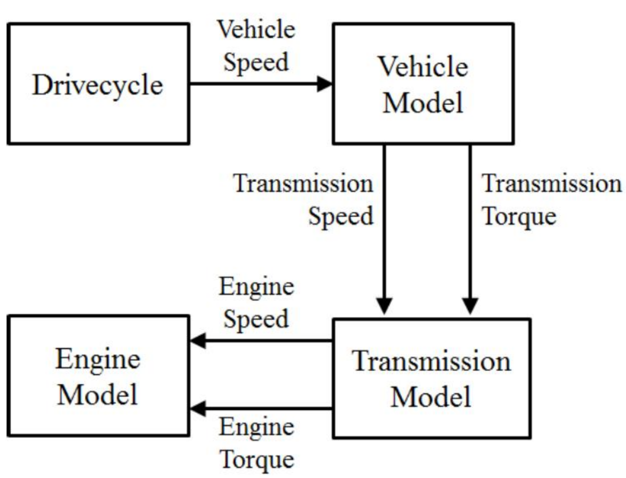


Figure 3: Backward-facing vehicle model [6]

SIMULATION EQUATIONS

The vehicle encounters four forces on moving which are air drag (F_D), rolling friction (F_r), inertia (F_a) and gravity on inclined road (F_g). Therefore, the net force required to drive the wheel is the sum of these 4 forces.

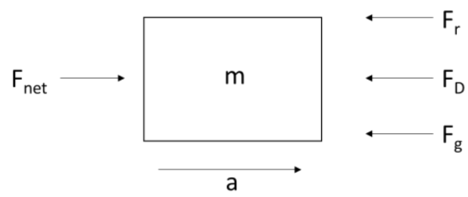


Figure 4: Force body diagram of vehicle

$$\sum F = F_a$$

$$F_{net} - (F_D + F_r + F_g) = F_a$$

$$F_{net} = F_D + F_r + F_a + F_g \qquad (1)$$

where F_{net} is the net force (N)

$$F_D = 0.5\rho C_D A v^2 \qquad (2)$$

where ρ is density of air (kg/m^3), C_D is the drag coefficient, A is the frontal area (m^2) and v is the vehicle speed (m/s)

$$F_r = C_r m_T g \qquad (3)$$

where C_r is the coefficient of rolling resistance, g is the gravitational acceleration (m/s^2), m_T is the sum of mass of vehicle, driver and additional components of hydraulic system (kg)

$$F_a = m_T a \qquad (4)$$

where a is the vehicle linear acceleration (m/s^2)

$$F_g = m_T g \sin\alpha \qquad (5)$$

where α is the slope angle corresponding to the road (°). Since there is no slope angle data from the drive cycle, α is assumed to be 0 all the time, thus $F_g = 0$

From the net force, the wheel torque (T_w)(N) and the flywheel torque ($T_{flywheel}$)(N) can be calculated using equation 6 and 7

$$T_w = F_{net} r \qquad (6)$$

where r is the radius of wheel (m)

$$T_{flywheel} = T_w G \qquad (7)$$

where G is the gear ratio.

The wheel angular speed (S_{wheel})(rad/s) and flywheel angular speed ($S_{flywheel}$)(rad/s) can be calculated from vehicle speed using equation 8 and 9.

$$S_{wheel} = \frac{v}{r} \tag{8}$$

$$S_{flywheel} = S_{wheel}G \tag{9}$$

The pressure in accumulator is calculated by assuming it is an adiabatic process and using gas law as below.

$$PV^{\gamma} = constant \tag{10}$$

where P is the pressure of nitrogen gas (Pa), V is the volume of nitrogen gas (m^3) and γ is the gas constant of nitrogen gas.

The pump torque (T_p)(N) and volumetric flow rate of oil (Q)(m^3/s) are obtained using equation 11 and 12.

$$T_p = PDx \tag{11}$$

$$Q = \omega Dx \tag{12}$$

where x is the position of swash plate, D is the volume displacement per angular displacement and ω is the angular speed of pump (rad/s).

The volume of nitrogen gas can then be determined from the volume flow rate of oil and the previous volume of nitrogen gas. The pressure is then calculated using the gas law in equation 10.

Throughout the system, the power or torque experiences some losses. The efficiencies of series and parallel hydraulic hybrid systems are illustrated in Figure 5 and Figure 6. The arrow shows the direction of power transmitted with the efficiency it can transmit. The power can be transmitted in two way between hydraulic pump and wheel with the efficiency in each transmission. η_h is the hydraulic efficiency while η_m is the mechanical efficiency.

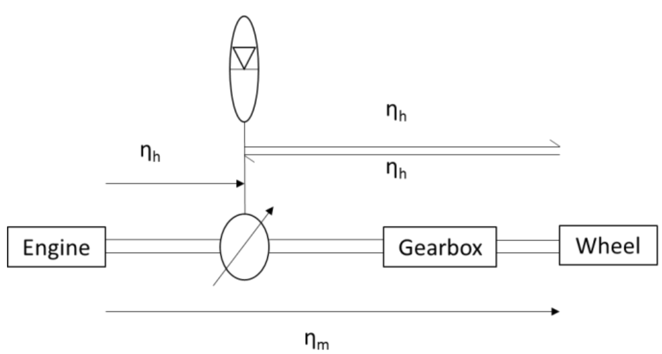


Figure 5: Efficiency of power transmitted in parallel hydraulic hybrid system

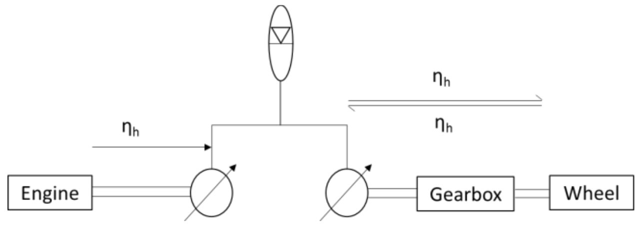


Figure 6: Efficiency of power transmitted in series hydraulic hybrid system

At the end, torque and speed of engine are calculated and used to determine the fuel consumption from the engine fuel consumption map. The fuel economy (km/L) is then calculated using equation 13.

$$Fuel\ economy = \frac{Distance}{fuel\ consumption} \tag{13}$$

The parameters used in this simulation are shown in Table 3. The frontal area was calculated using the dimension data as shown in equation 14. The mass of the vehicle is obtained from the kerb weight while the driver is estimated to be 80kg which is an average male adult weight.

$$A = (wheel\ height - clearance\ height) \times width \tag{14}$$

Table 3: Parameters used in simulation

Parameter	Symbol		Value
Total gear ratio [7]	G	1st gear	11.01
		2nd gear	6.15
		3rd gear	4.03
		4th gear	2.81
Tire radius [7]	r		0.2915m
Frontal area [7]	A		2.31435m^2
Drag coefficient [7]	C_D		0.35
Density of air	ρ		1.225kg/m^3
Density of fuel (Wan Dun Ye, Colleague)	ρ_f		716.0755kg/m^3
Mass of vehicle + driver [7]	m		1020kg
Gravitational acceleration	g		9.81
Coefficient of rolling resistance [8]	C_r		0.01
Gas constant of nitrogen gas	γ		1.4
Mechanical efficiency [9]	η_m		0.96
Hydraulic efficiency [10]	η_h		0.75

The gear selection depends on the vehicle speed as shown in Table 4 **[5]** and the engine torque required. When the engine torque required at the gear ratio is higher than the maximum torque of engine at the engine speed, the gear is shifted down to a lower gear.

Table 4: Gear selection rules

Vehicle speed (m/s)	Gear
< 7.73	1
7.73 to 13.83	2
13.83 to 21.09	3
> 21.09	4

CONTROL STRATEGY

For the parallel hydraulic hybrid system, the engine is always running at the torque with minimum BSFC accordingly to the engine speed. The excess torque from the engine will charge the accumulator and vice versa, the hydraulic motor will assist engine when engine provides insufficient torque. The engine is turned off and vehicle is fully driven by hydraulic pump when the accumulator reaches SOC of 0.85. The engine is turned on when the SOC falls lower than 0.1. The algorithm flowchart of the parallel hydraulic hybrid control strategy is shown in Figure 7.

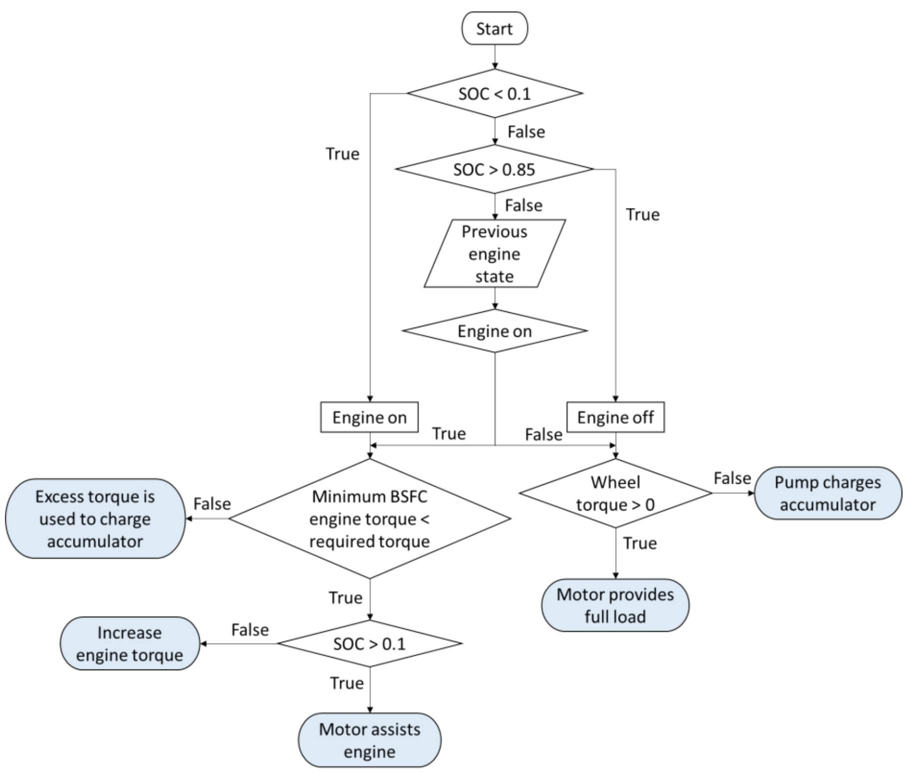


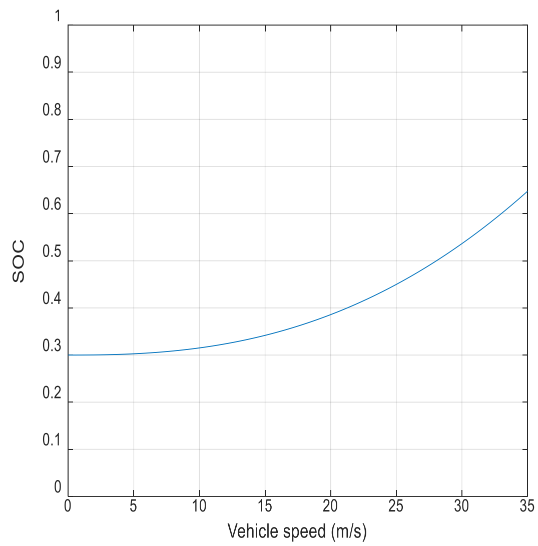
Figure 7: Algorithm flowhart of parallel hybrid

For the series hydraulic hybrid system, the engine is always running at the engine torque and speed with minimum BSFC. When the vehicle speed is high, the engine speed increases to produce more power to charge the accumulator as shown in Figure 8. When the SOC is running low, and required power is higher than the engine power produced at minimum BSFC, the engine will increase torque or speed which increases the power to sufficiently charge the accumulator to maintain the SOC. The timing to turn on the engine depends on the speed of vehicle as power required is usually proportional to the vehicle speed and the hydraulic efficiency is low. The condition to turn on the engine is shown in equation 15. This is a trial and error method to prevent negative SOC value in simulation.

$$SOC < 0.3\left(\frac{v}{33}\right)^{2.5} + 0.3 \tag{15}$$

The SOC set to turn on the engine against the vehicle speed is shown in Graph 1. The engine accelerates in 3 time steps during startup (1000rpm) until it reaches the speed with minimum BSFC (2000rpm) to ensure a practical condition of engine. The engine is turned off when the SOC reaches 0.8.

Graph 1: SOC to turn on the engine with respect to vehicle speed



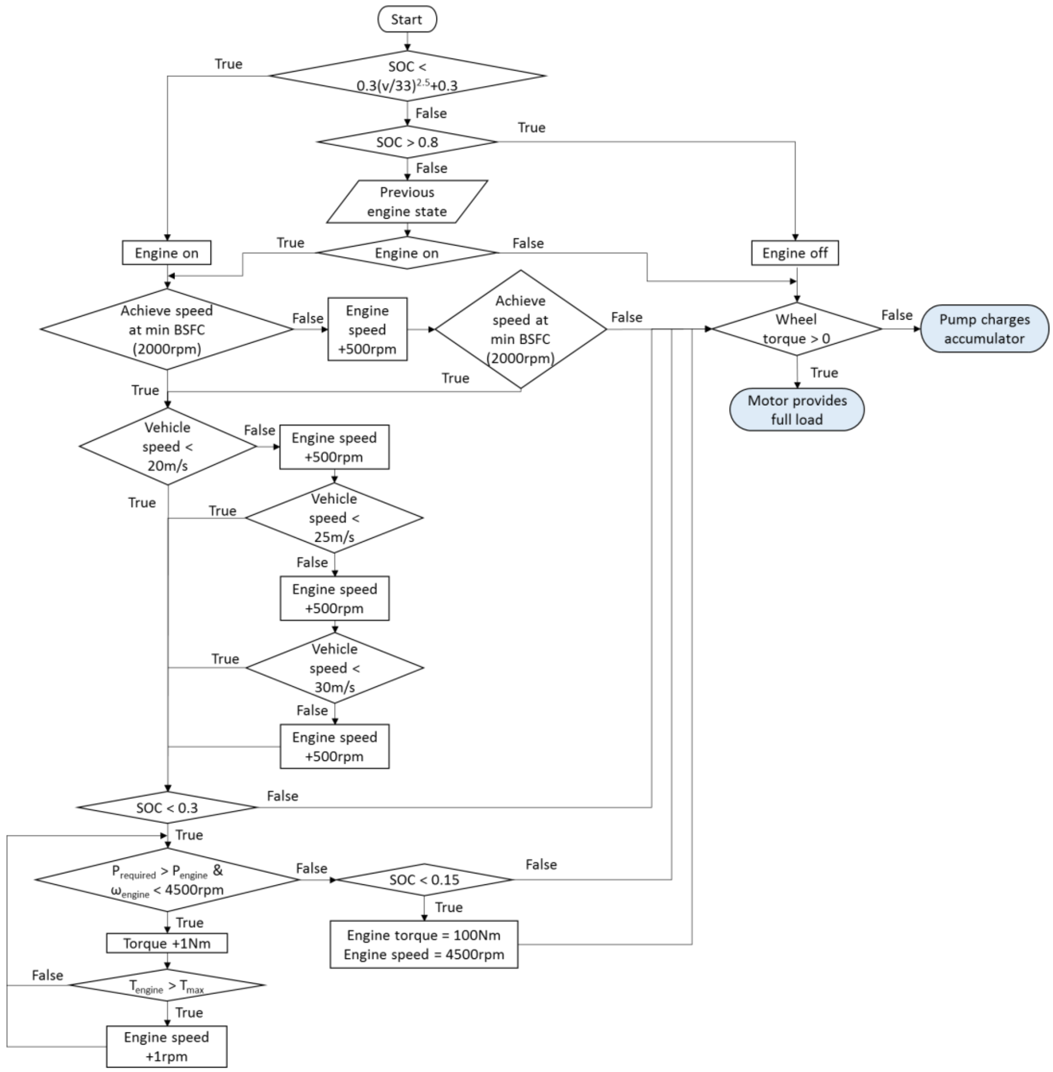


Figure 8: Algorithm flowchart of series hybrid

RESULTS

The fuel economy simulated is compared to the experimental results of conventional Myvi [5] and shown in Table 5, Graph 2 and Graph 3 while the comparison with simulation results of conventional Myvi (Ong Horng Neng, colleague) is shown in Table 6. The simulation of conventional Myvi was done using forward-facing vehicle model. The simulation results of each drive cycle are shown in Appendix. In overall, parallel architecture has better fuel economy than series architecture as series architecture suffers higher transmission loss though the engine was used mostly at highest efficiency. The hybrid system improves the fuel economy better in city compared to highway as there is less braking event in highway driving where the hydraulic hybrid saves fuel by regenerating the braking power. In addition, vehicle travels faster in highway thus higher power required, engine has to operate out of efficient region to provide power when the accumulator is running low. This affects more on the series architecture since series architecture suffers more transmission loss, as the result series architecture did not improve the fuel economy in highway. For parallel architecture and in highway driving, the hybrid driving system could be turned off and engine should work inside high efficient region. However, due to the increase in total weight of vehicle, the vehicle requires more torque and sometime gear needs to be lowered down to provide higher torque, causing high engine speed which has high fuel consumption rate. Therefore, the hydraulic system should always assist the engine whenever needed.

Table 5: Fuel economy results comparing to conventional (experiment)

Course	Time	Fuel economy (km/L)				
		Conventional (experiment) [5]	Parallel hybrid	Percentage difference	Series hybrid	Percentage difference
City 1	Afternoon	8.168	23.770	191%	18.879	131%
	Morning (a)	9.770	23.216	138%	17.943	84%
City 2	Afternoon	9.767	22.214	127%	18.339	88%
	Morning (a)	10.960	24.853	127%	18.760	71%
City 3	Afternoon	14.030	22.205	58%	17.098	22%
	Morning (a)	7.480	21.812	192%	16.045	114%
City 4	Afternoon	10.180	18.961	86%	14.234	40%
	Morning (a)	10.490	21.016	100%	15.401	47%
Highway	Afternoon	12.770	18.163	42%	12.077	-5%
	Morning (a)	14.740	16.874	14%	10.931	-26%

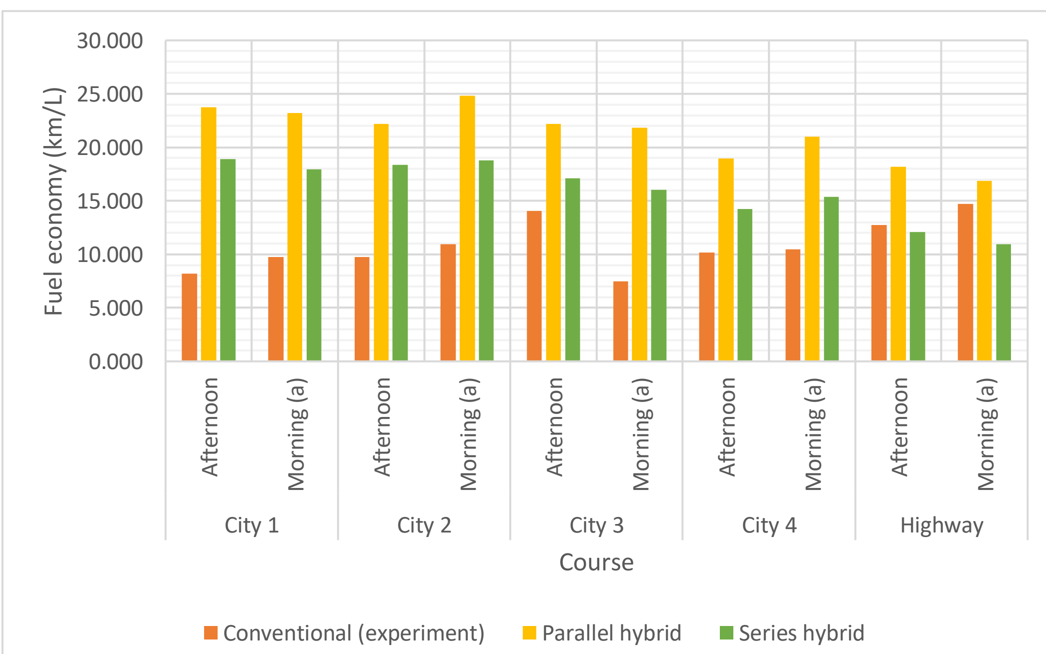
Table 6: Fuel economy results comparing to conventional (simulation)

Course	Fuel economy (km/L)				
	Conventional (simulation)	Parallel hybrid	Percentage difference (%)	Series hybrid	Percentage difference (%)
City 5	12.744	20.151	58%	16.345	28%

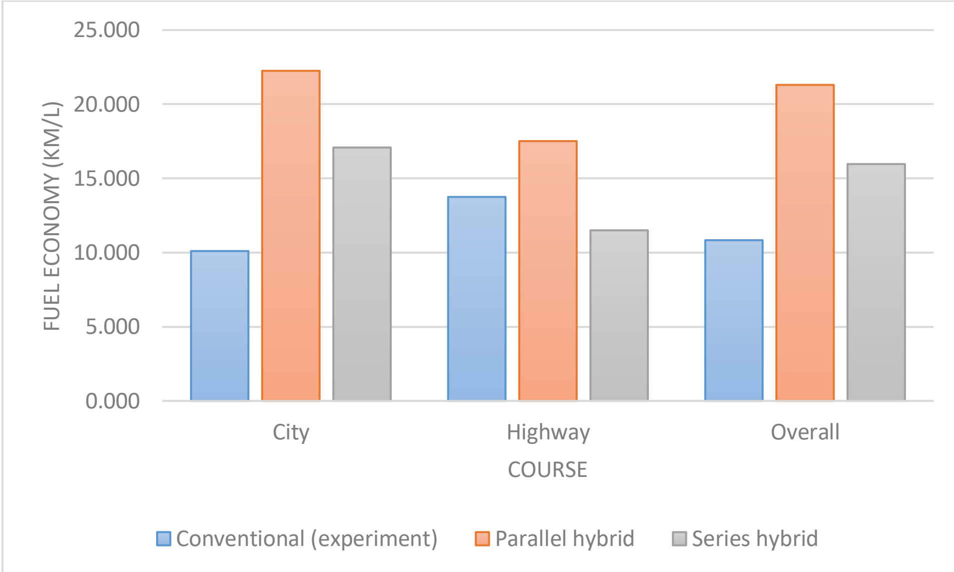
Table 7: Fuel economy results in City, Highway and Overall

Course	Fuel economy (km/L)				
	Conventional (experiment)	Parallel hybrid	Percentage difference (%)	Series hybrid	Percentage difference (%)
City	10.106	22.256	120%	17.087	69%
Highway	13.755	17.518	27%	11.504	-16%
Overall	10.836	21.308	97%	15.971	47%

Graph 2: Fuel economy in different course



Graph 3: Fuel economy in City, Highway and Overall



The positive improvements of fuel economy come along with the increase of vehicle's cost. The hydraulic components' cost is shown in Table 8. The price shown is the quotation in March 2017. The relationship between investment cost and fuel cost saved is analyzed by using an average annual mileage of vehicle in Malaysia of 24,129km/year [11] and estimated constant fuel price of RM2.20/L. The average fuel economy is not accounting the City 5 as it is simulation based result in conventional vehicle. The hydraulic hybrids show significant values of fuel cost saved, however, the time taken to cover back the investment cost is still long which is shown in Table 9.

Table 8: Cost of hydraulic components in parallel and series architectures

Part	Cost/unit (RM)	Unit	
		Parallel	Series
A4VG pump	23,778	1	2
HAB accumulator	3,032	2	2
	Total cost (RM)	29,842	53,620

Table 9: Cost analysis

	Unit	Conventional	Parallel hybrid	Series hybrid
Average fuel economy	km/L	10.836	21.308	15.971
	L/km	0.0923	0.0469	0.0626
Fuel saved	L/km	-	0.0454	0.0297
Cost saved annually	RM	-	2,407.83	1,575.23
Cost of hydraulic parts	RM	-	29,842.00	53,620.00
Time taken to return the investment cost	year	-	12.4	34.0

CONCLUSION

In series architecture, the ability of full control of engine did not give a better fuel economy than parallel architecture due to higher loss in transmission. In addition, the engine did not always operate at highest efficiency region for when the SOC is low. The parallel architecture gave a better fuel economy by the control strategy of using torque at lowest BSFC each speed. However, both of series and parallel architecture did not use optimized control strategy, thus, there is still room for improvement. It was infeasible for both parallel and series architecture as it will take 12.4 years and 34 years for the return. However, the fuel economy for parallel hybrid could be further improved by optimizing the control strategy and the cost could be reduced by mass ordering the hydraulic components. Moreover, the parallel hybrid can have bigger torque which is bigger acceleration when both the engine and hydraulic work together.

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APPENDIX

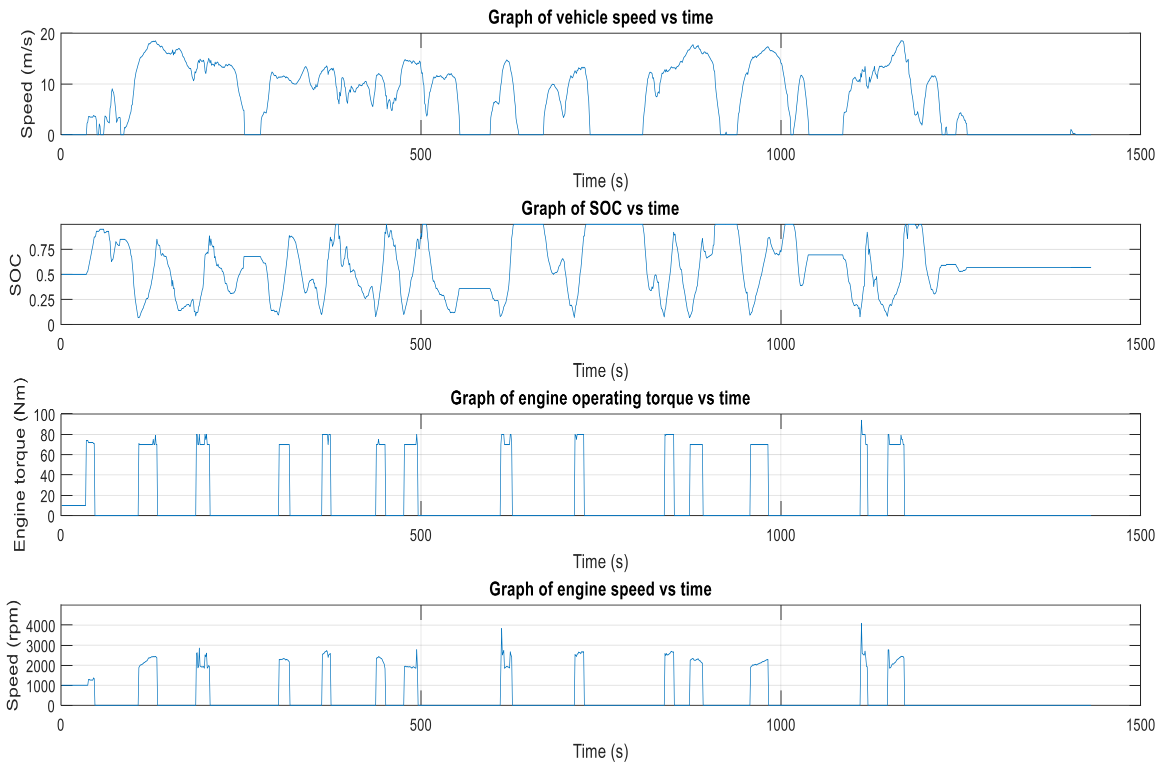

Figure 9: Parallel hybrid - City 1

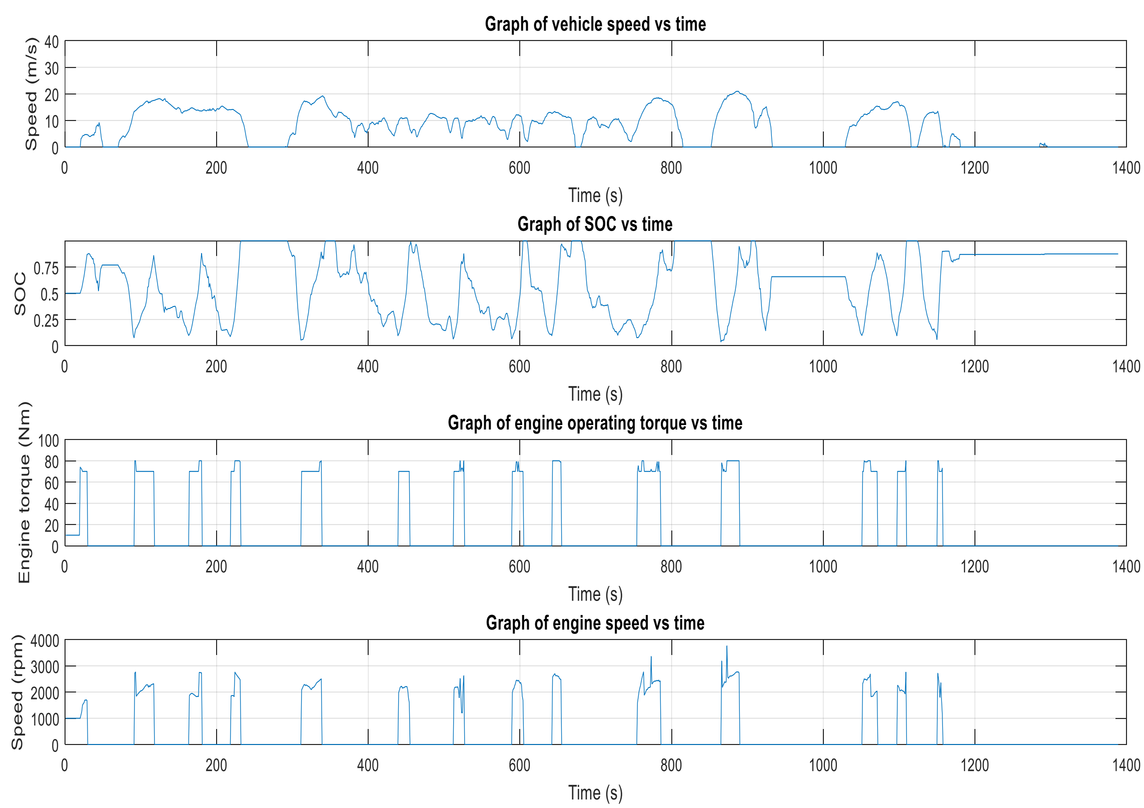

Figure 10: Parallel hybrid - City 1a

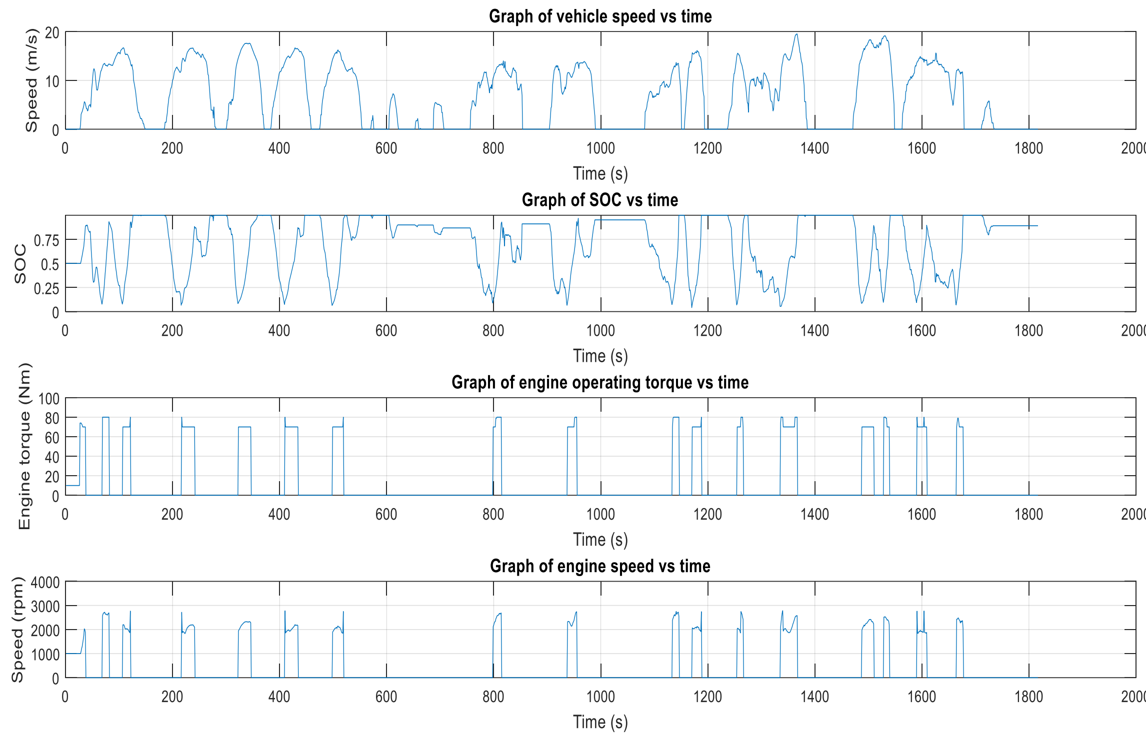

Figure 11: Parallel hybrid - City 2

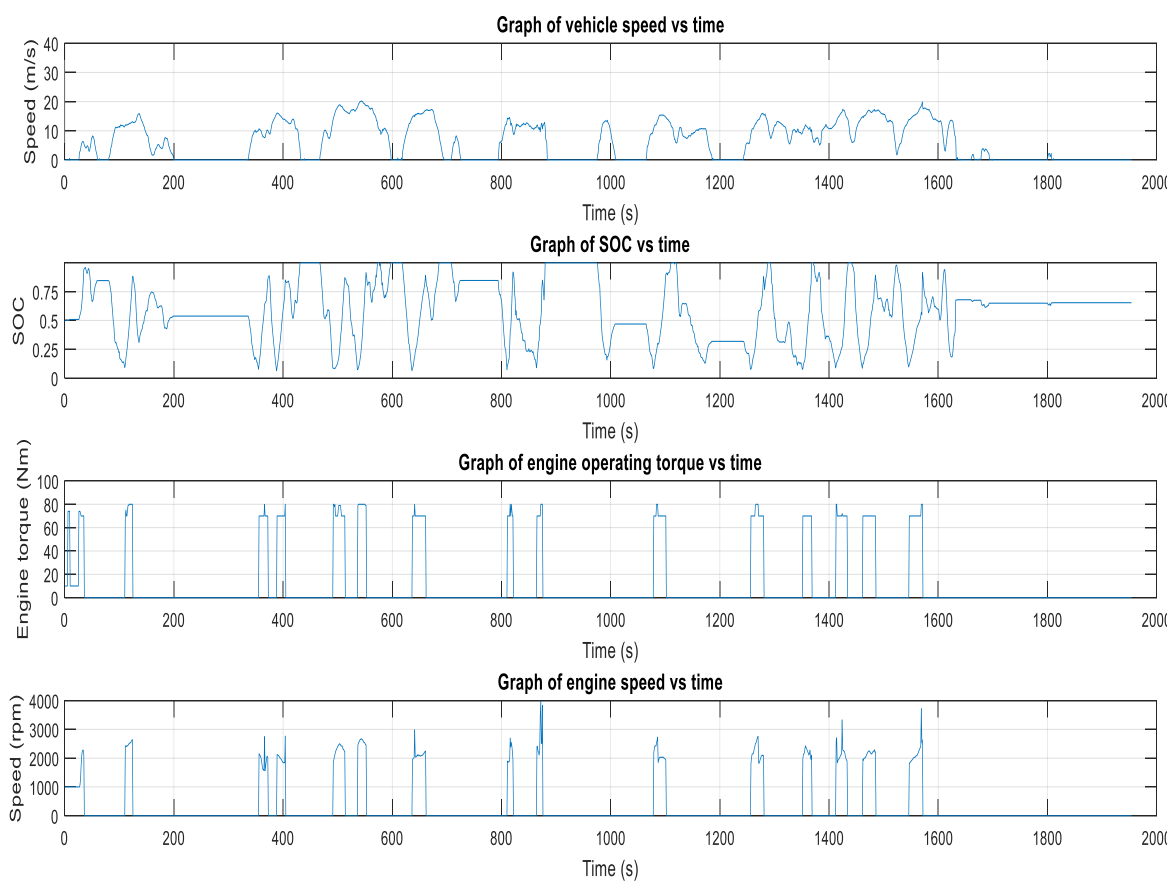

Figure 12: Parallel hybrid - City 2a

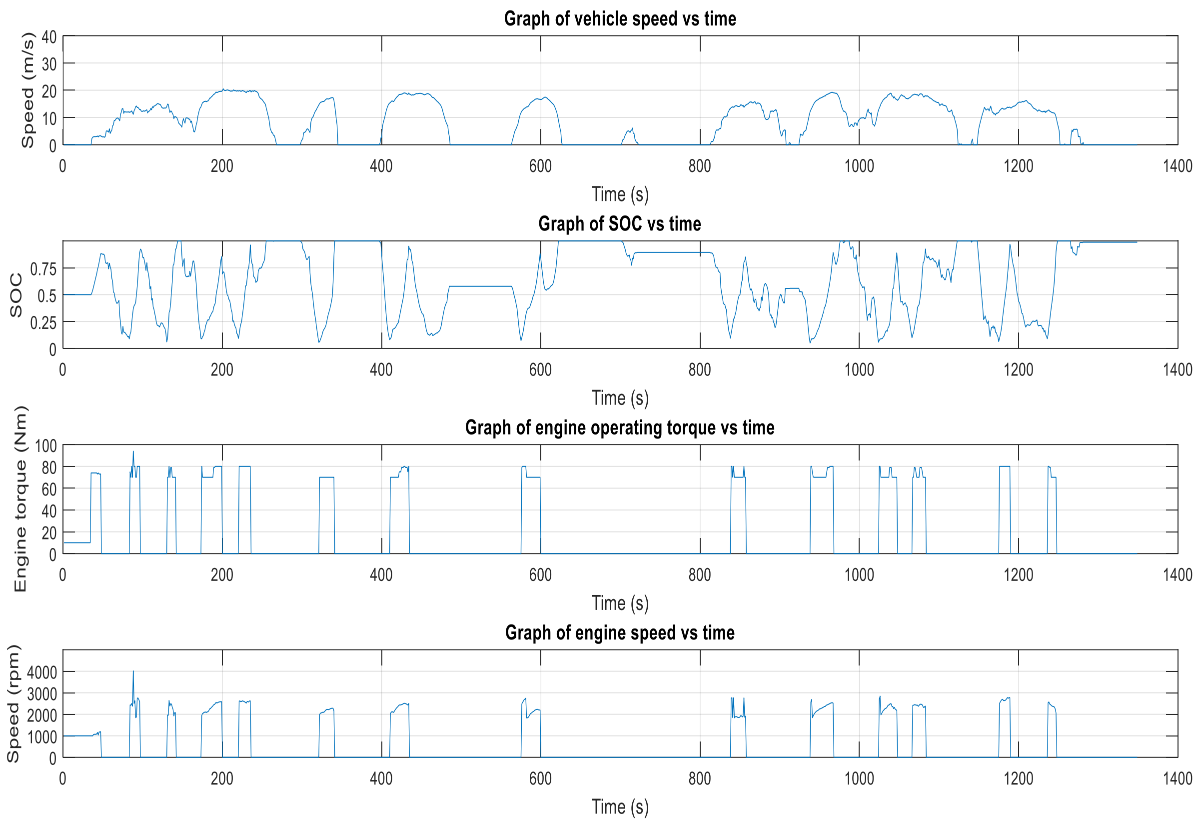

Figure 13: Parallel hybrid - City 3

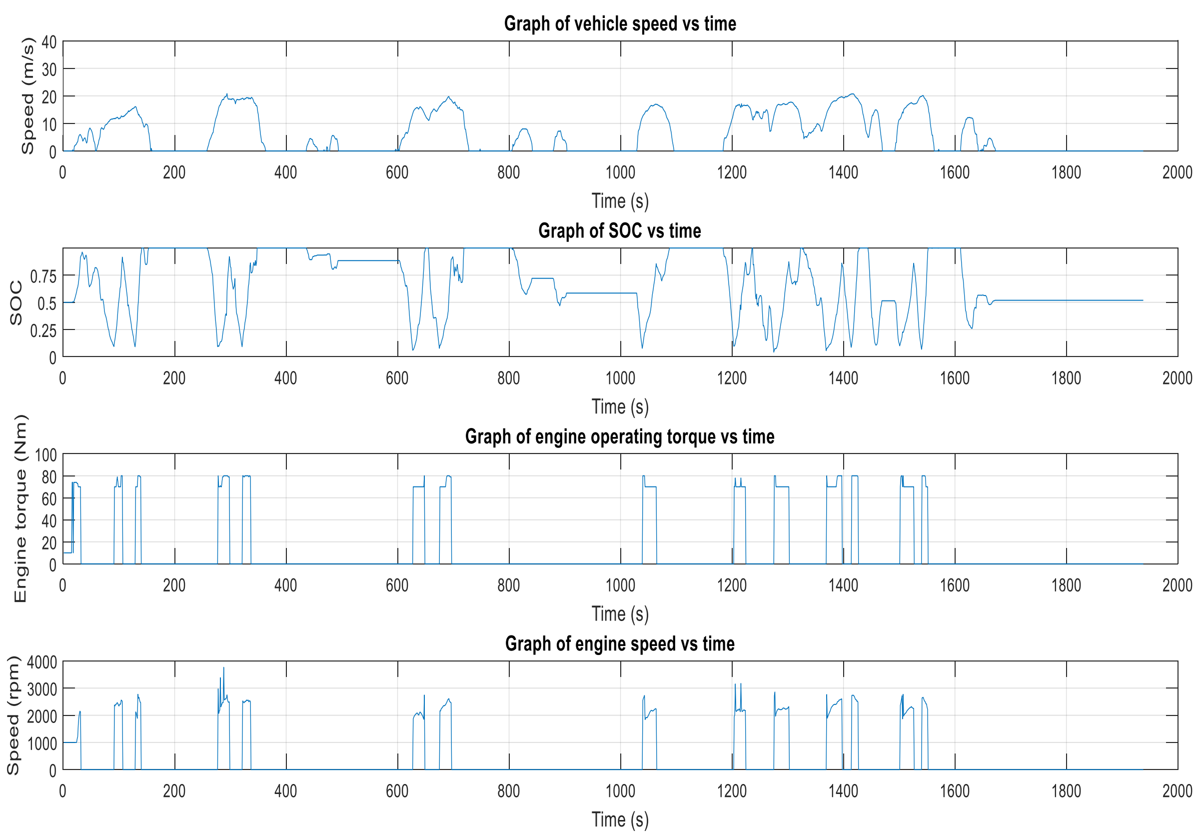

Figure 14: Parallel hybrid - City 3a

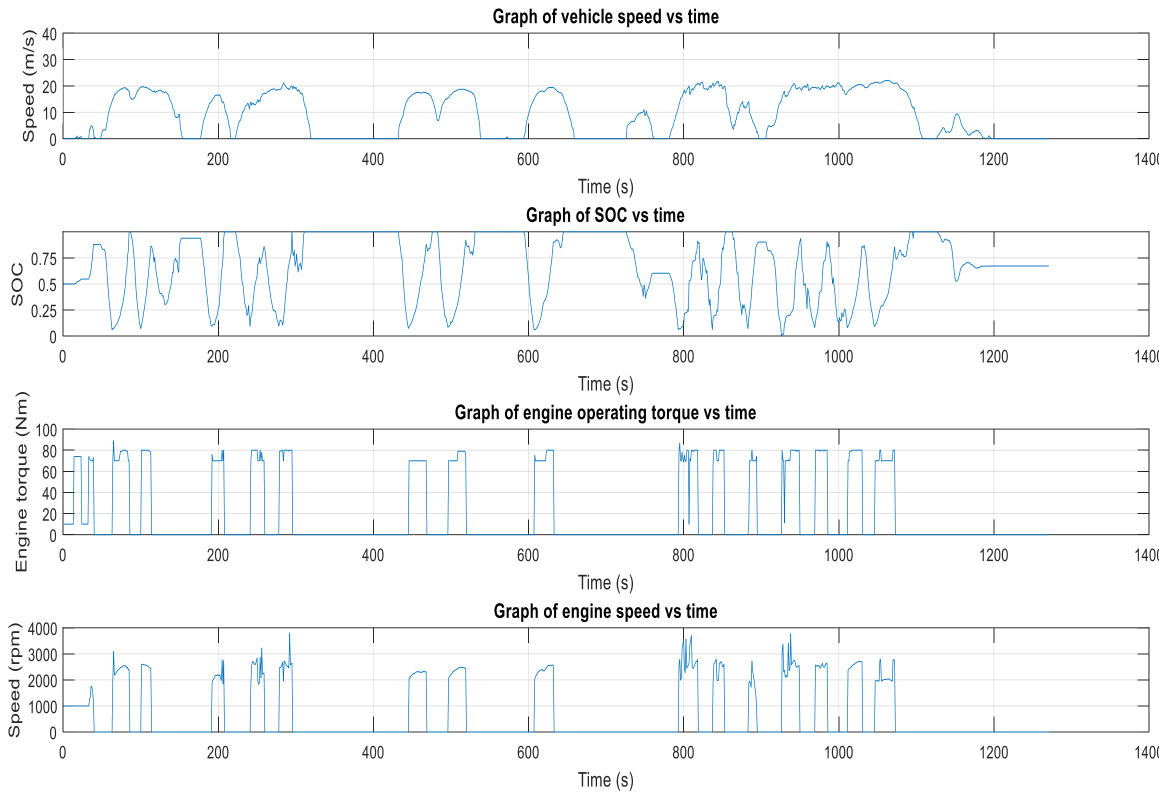

Figure 15: Parallel hybrid - City 4

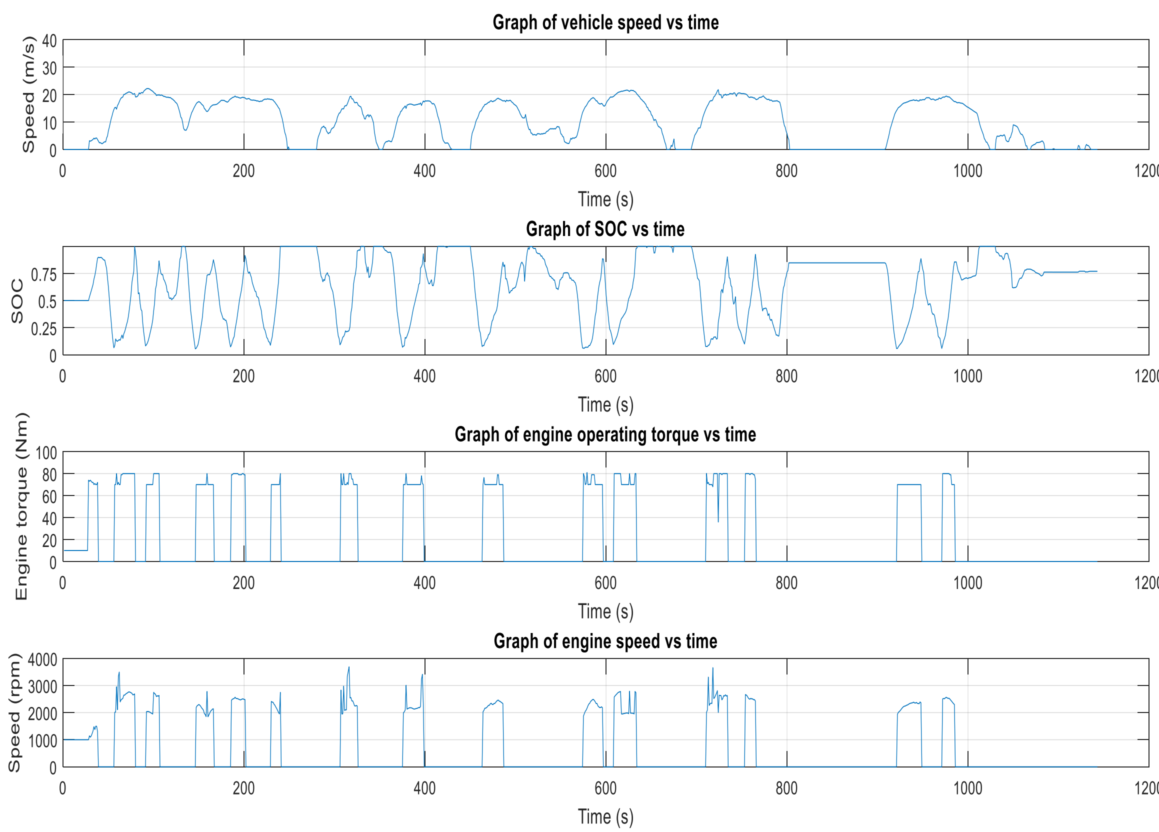

Figure 16: Parallel hybrid - City 4a

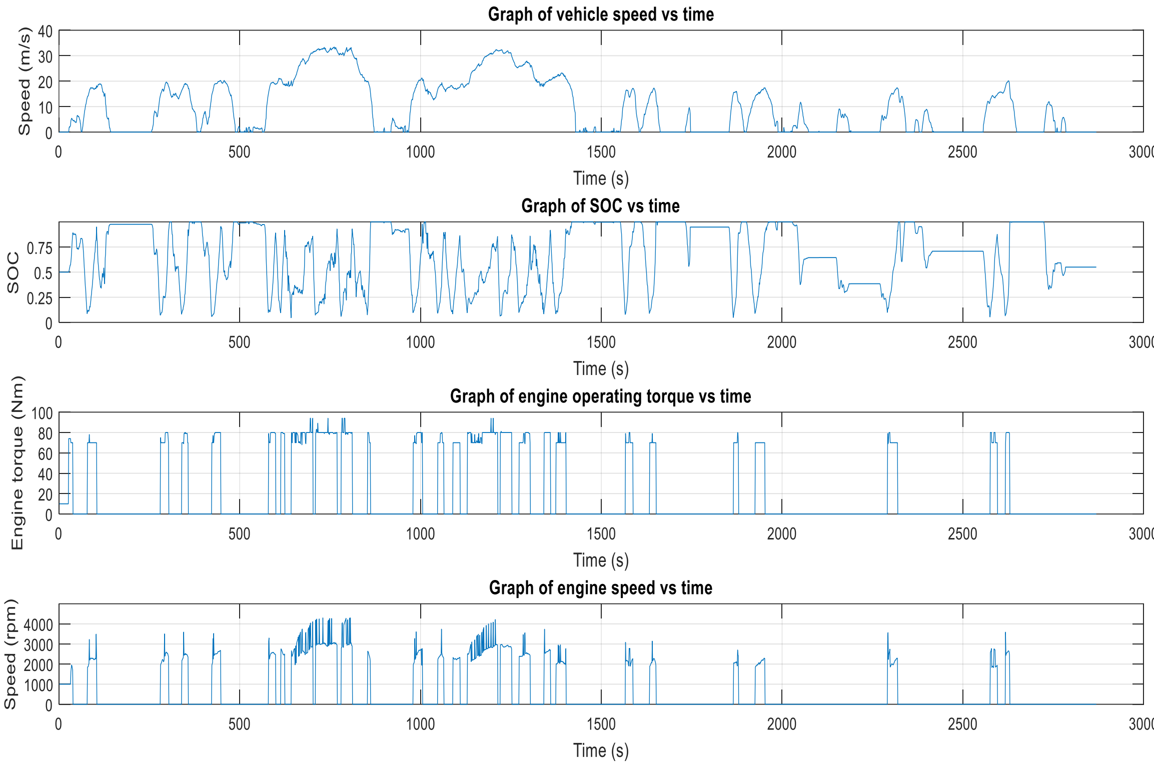

Figure 17: Parallel hybrid - Highway

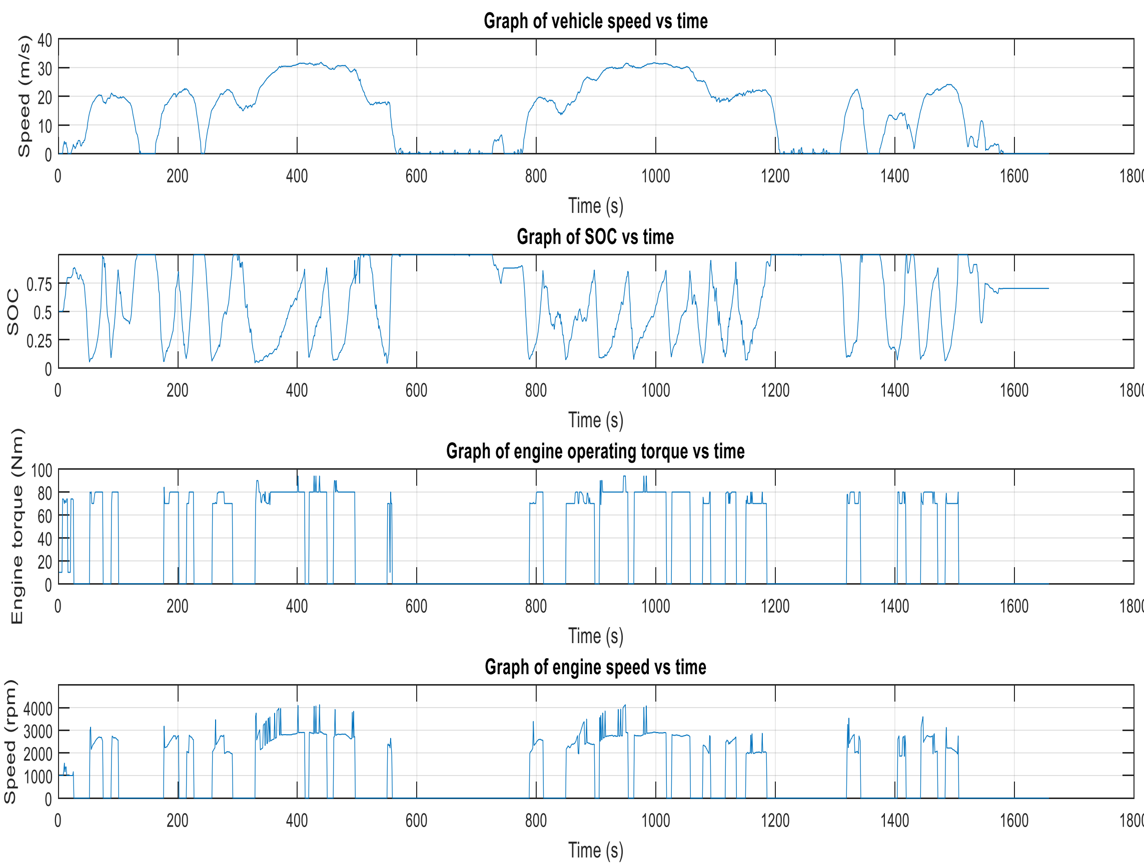

Figure 18: Parallel hybrid - Highway a

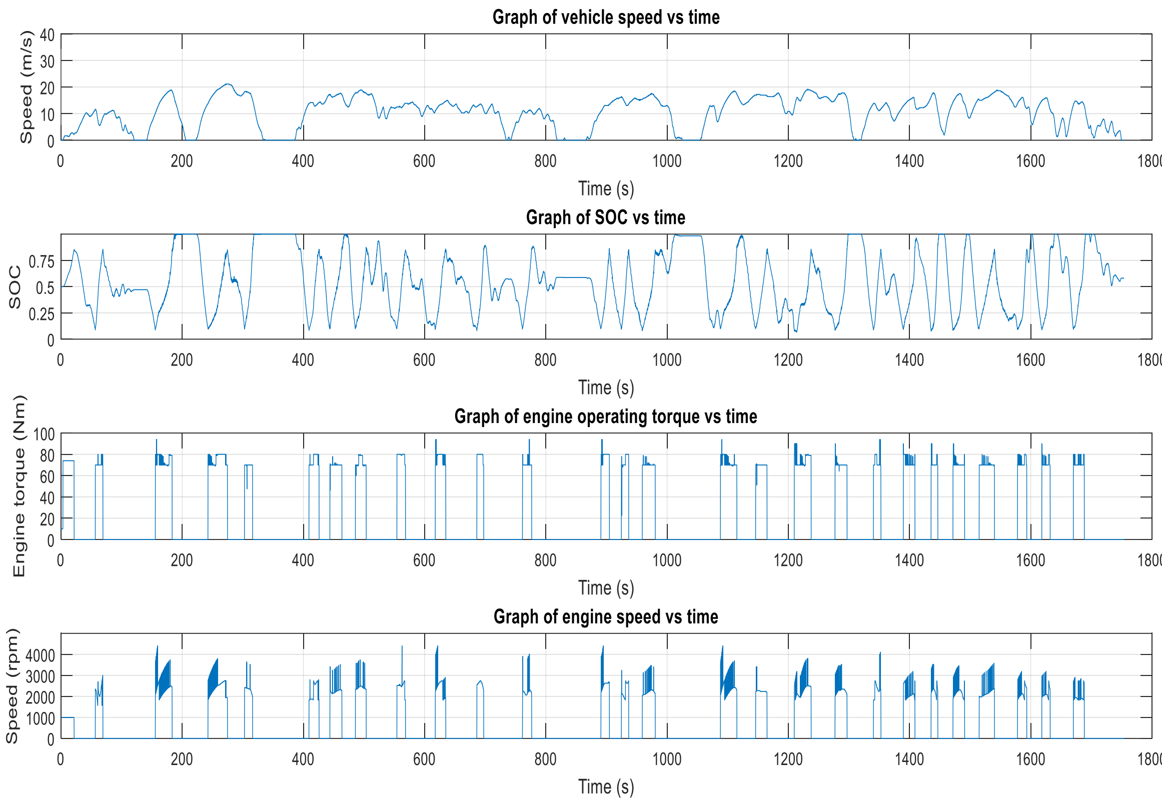

Figure 19: Parallel hybrid - City 5

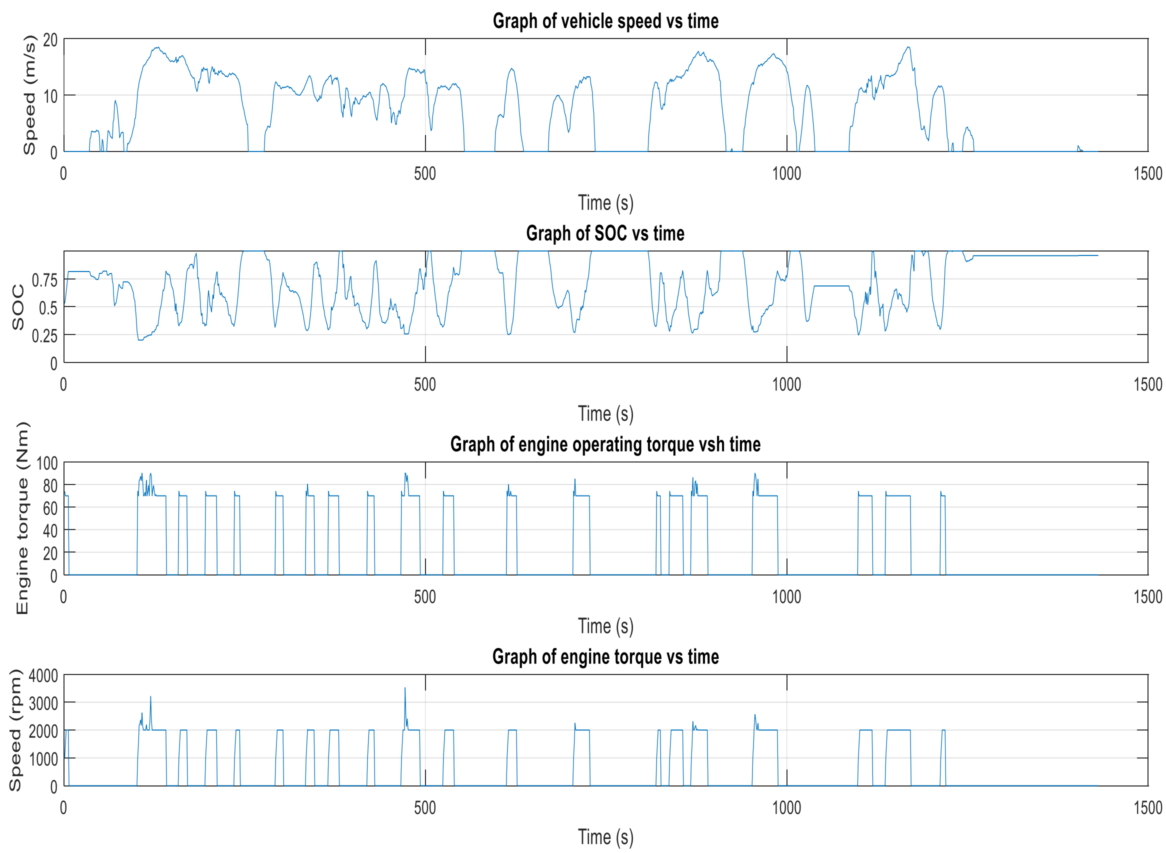

Figure 20: Series hybrid - City 1

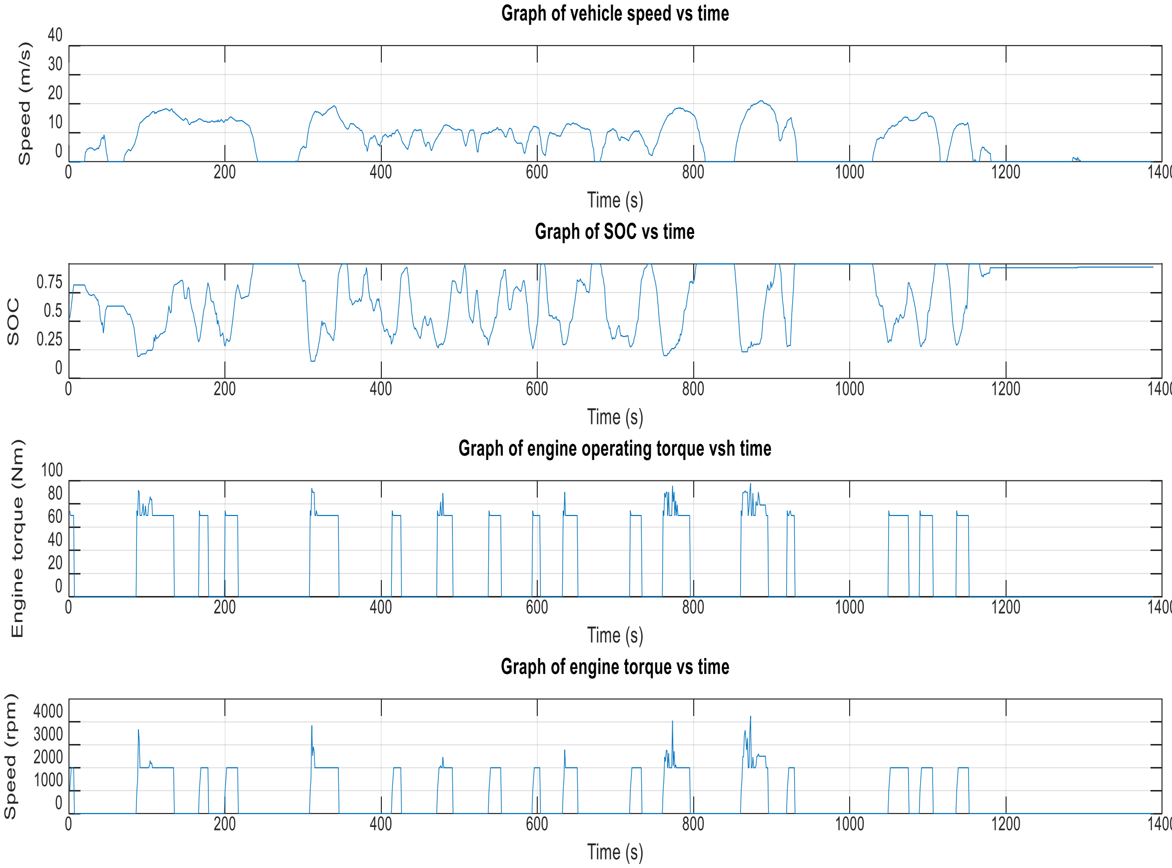

Figure 21: Series hybrid - City 1a

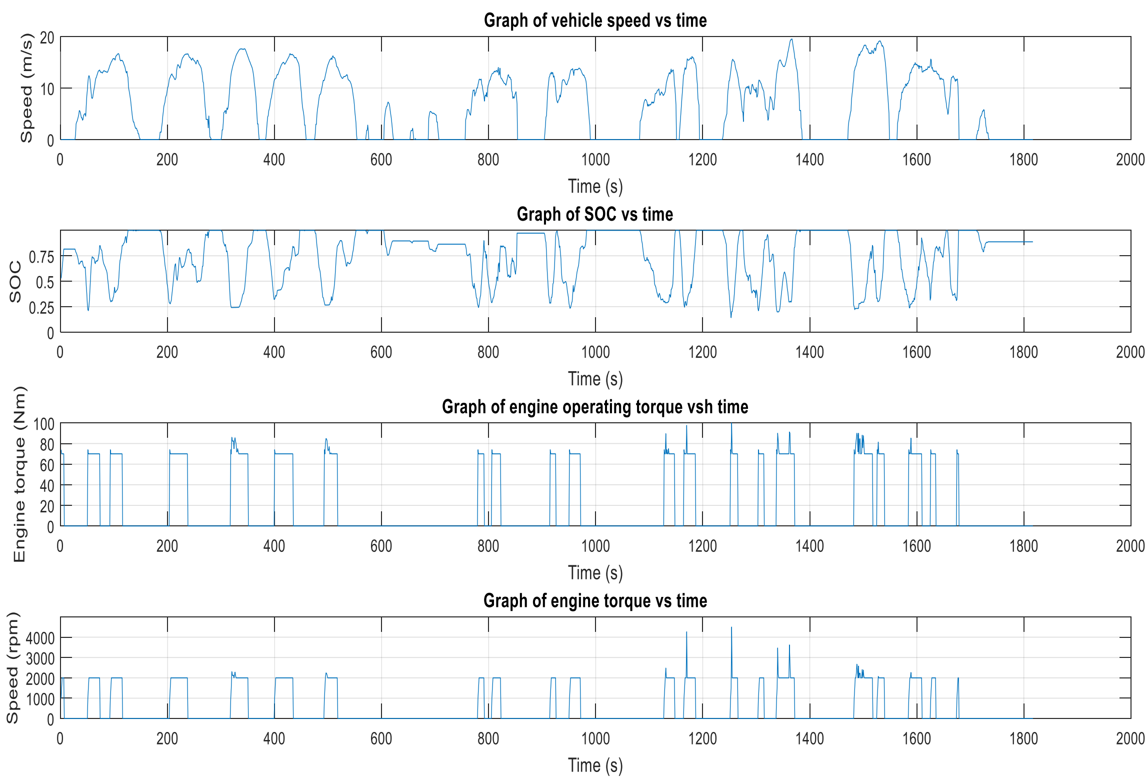

Figure 22: Series hybrid - City 2

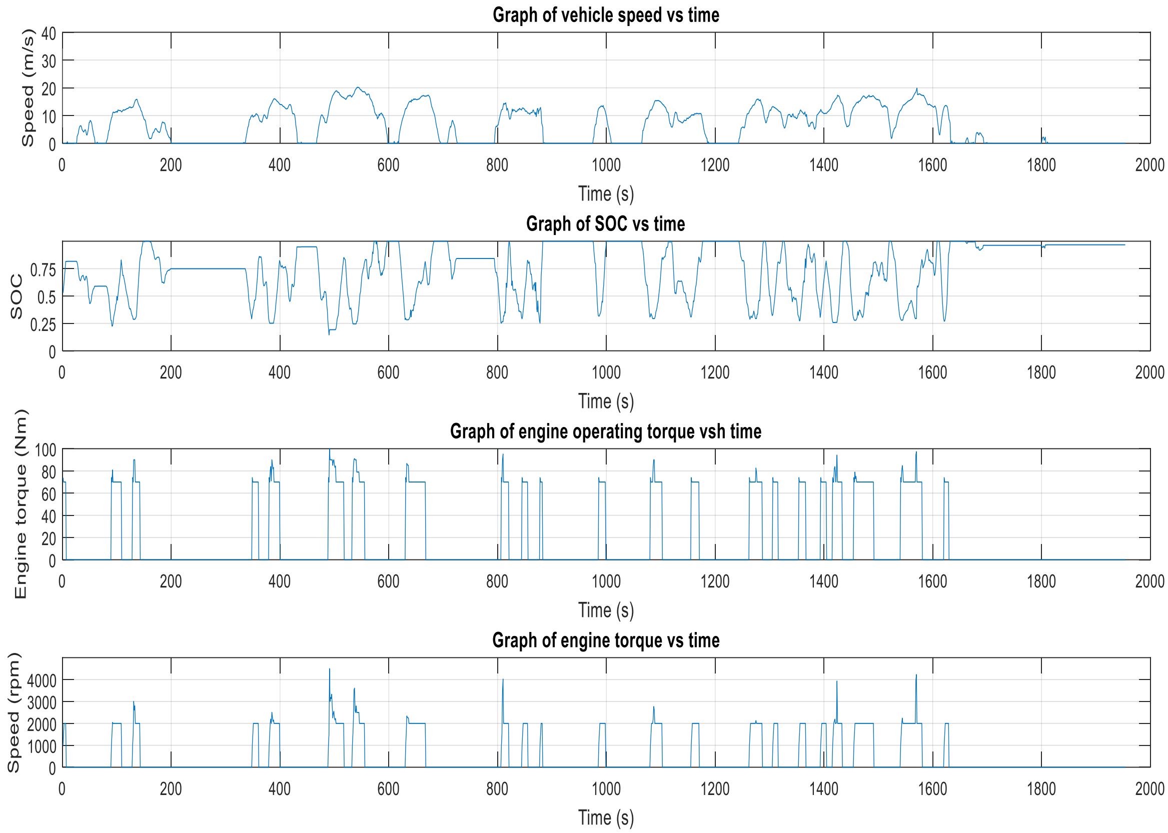

Figure 23: Series hybrid - City 2a

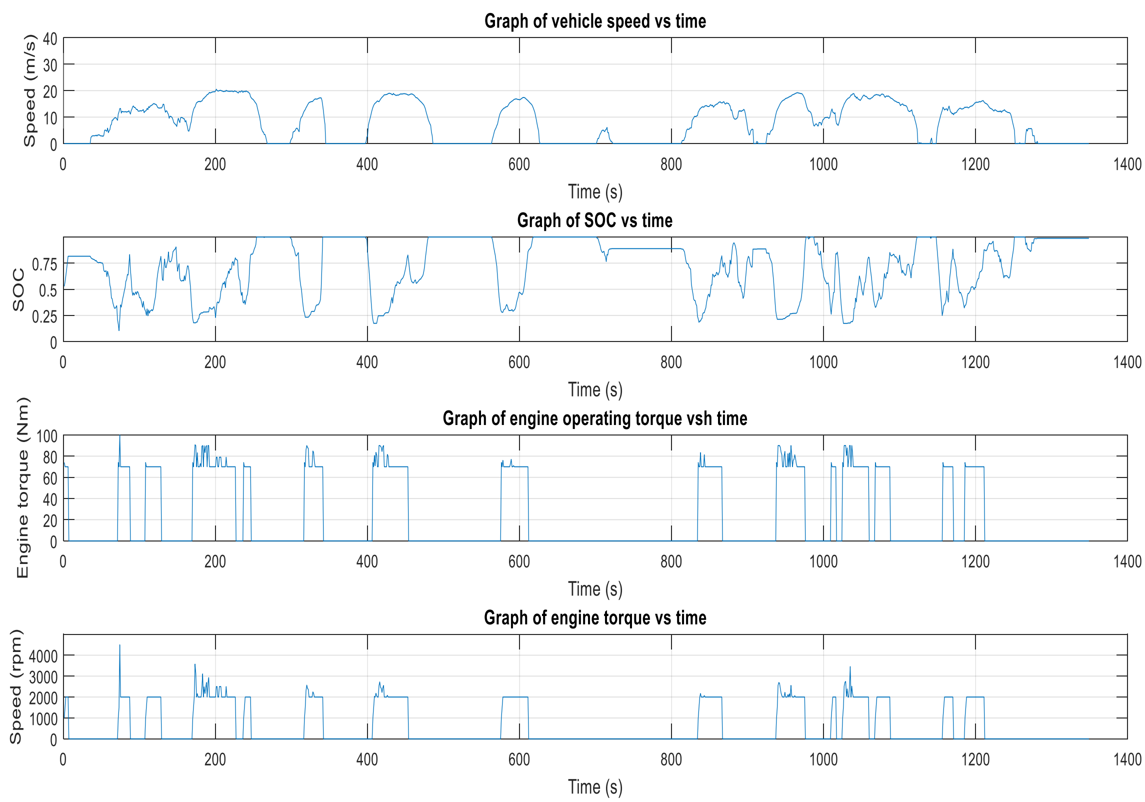

Figure 24: Series hybrid - City 3