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Fuel consumption evaluation of a hybrid electric car over aggressive cycles for thermal engine optimization

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A B S T R A C T

This paper investigates fuel consumption of a thermal engine in a hybrid electric vehicle system over aggressive cycles in order to optimize its energy consumption. The model of the system is first developed using data obtained from experiments over two aggressive driving cycles and then used to validate the model and further used as a platform to test other control strategies. The car's actual control strategy operates on high torque region of the engine to sustain battery charge and caused high fuel consumption. Based on previous researches, there are two optimal control strategies that can be implemented for a series hybrid electric vehicle system; the dynamic programming control method and the optimal torque control method. Result analysis shows that the operations of the engine are different between the two control methods; it is concentrated on high speed region for the dynamic programming control method and at the middle of the engine map for the optimal torque control method.

1. Introduction

According to report, transportation is the main user of fuels and account as the second largest source of greenhouse gas emissions in the world (Saxena et al., 2014). With problems like global warming, harmful emissions from thermal engines, less fossil fuel resources, and the fuel price hike, we are searching for ways to consume effectively our resources (Taymaz and Benli, 2014; Zhou et al., 2017). But, these resources will not last for a long time if no efforts are made to slow down the present trend. With all effort are given in all sectors to reduce pollutant emissions and new legislation on emissions of vehicle; hybrid electric vehicle (HEV) is regarded as one of the best alternative to respond well to this expectation with realistic economical, infrastructural, and customer acceptance constraints (Silva et al., 2014; Wu et al., 2016; Li et al., 2017).

Hybrid electric vehicle (HEV) is a system which has two or more propulsion power, two or more kinds or types of energy storages, sources or converters, and at least one of them can deliver electric energy (Taymaz and Benli, 2014; Torres et al., 2014). HEV has the advantages of an electric powertrain with a kinetic recovery system and possible zero tank-to-wheel emissions till certain vehicle speeds in urban drive and combines the advantages of the ICE based vehicles, represented by high power and energy density, rapid recharging of the fuel tank, and high range in extra-urban drives (Hu et al., 2013; Dimitrova and Maréchal, 2015a; Enang and Bannister, 2017).

Presence of reversible energy storage system (ESS) and electric machines (EM) offer capability of idle off, regenerative braking, power assist, and engine downsizing making HEV appears as a viable technologies with significant potential to reduce fuel consumption (Serrao et al., 2011; Taymaz and Benli, 2014; Dimitrova and Maréchal, 2015a; 2015b).

Compared to conventional ICE system, HEV integrates more electrical apparatus in its system making the energy management complicated and needs a high degree of control flexibility due to more degrees of freedom. So far, there are two concepts of energy management; the heuristic based and the optimal theory based (Hou et al., 2014; Zhang et al., 2014; Wang et al., 2016). At depth, control strategies for energy management are reviewed on two main tiers; offline control strategy and online control strategy (Enang and Bannister, 2017). The control strategy in general is a law regulating operation of vehicle's drive train which inputs measurements of vehicle operating conditions such as speed or

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acceleration, driver's torque request, current roadway type or traffic information, in-advance solutions, and even the information provided by the Global Positioning System (GPS) to achieve improved fuel economy and reduced emissions.

A control strategy is usually tested on some specific driving cycles to evaluate its performance like NEDC and ARTEMIS standard cycles (Trovão and Antunes, 2015). The fuel savings are influenced by the driving patterns that the vehicles are exposed to (Saxena et al., 2014). Some cycles are predicted beforehand for different application (Wang et al., 2016) or used in a model predictive control to get a better overall efficiency of HEV system (Gökce and Ozdemir, 2014; Li et al., 2017).

Regardless of the driving cycles, most of the time for a HEV system, the internal combustion engine (ICE) operating points are controlled as close as possible to the optimal operating points (OOP) or emissions at a particular engine speed known as the optimal torque region (Wirasingha and Emadi, 2011; Hu et al., 2013; Gökce and Ozdemir, 2014; Hou et al., 2014; Wu et al., 2016). In ICE, the fuel efficiency is not more than 30% where 60-70% of the energy is wasted in form of heat making development of waste heat energy recovery technologies like thermoelectric generators, six-stroke cycle ICE, turbochargers, and Rankine Cycle attractive and promising (Horrein et al., 2015; Zhou et al., 2017). And, it requires air fuel ratio (AFR) in the injection system to be at the optimum stoichiometric value to maximize efficiency of an ICE (Carbot-Rojas et al., 2017). But, AFR is very sensitive to small perturbations and needs precise control. Researches on model based controllers using observers or intelligent control show reduction in fuel consumption and pollutant emissions. The use of a right dose of hydrogen as an additive in the ICE can also guarantee optimal operation of the engine (Carbot-Rojas et al., 2017).

Up to now, optimizations are made to the HEV control method but not yet for the engine to be used in the system. In this paper, an analysis of the fuel consumption considering the actual heuristic control of the car, dynamic programming control method, and the optimal torque control method is studied. As a starter, the analysis will only consider consumption over the car's real driving profiles which are two racing circuits. The objective of the analysis is to identify the most recurrent points in ICE operation and estimate fuel consumption at certain points of the efficiency map so that the engine can be optimized efficiently without having to take into account all operating points. A simulation model and its control scheme is developed based on Energetic Macroscopic Representation (EMR) method in Matlab/Simulink and validated using the car experiment data. The results of the fuel consumption are illustrated on the engine efficiency map to better understand and plan optimization of the engine. The organization of this paper is as follow: first it will be the introduction, and then the methodology will explain about the simulation, control methods are described before results interpretation, and lastly the conclusion is in the last section.

2. Simulation methods

Simulation is a key factor in the design state because it allows us to evaluate different vehicle concepts and control configurations (Silva et al., 2014). In this paper, the model is developed based on EMR method. This method is first introduced by Bouscayrol et al. (2006) and since then has been used as a representation method to develop vehicles model for simulation like in Chen et al. (2008, 2009), Cheng et al. (2009), and Horrein et al. (2016). Due to its intrinsic feature, this method has been applied to other complex electromechanical system such as hybrid electric vehicle system (Gauchia et al., 2011), electric vehicle (Silva et al., 2014), and railcar prototype (Serge et al., 2016). Through EMR, we can design a new system, develop a new control strategy, and perform evaluation of energy consumption.

In this paper, a hybrid electric vehicle with series architecture was built to study renewable energy application in a circuit car which parameters are listed in Table 1. The car powertrain uses electric motor to drive wheels through simple gears transmission. Its energy sources come from combustion of fuel and potential chemical energy stored in battery. As it is a series arrangement, the battery will first accumulate energy from the engine before transferring them to the electric motor according to the power demand. The EMR configuration of this system to develop Matlab Simulink blocks representing the model is shown in Fig. 1.

After developing the model, comparison between experimental data and the simulation results were made to validate the model. The experiments have been conducted on two circuits creating two driving cycles in Fig. 2 in order to extract data from the physical HEV system. As can be seen in the figure, these driving cycles maximum speed can reach up to 150 kmh^{-1} with 108 kmh^{-1} average speed for circuit 1 and 90 kmh^{-1} for circuit 2. Compared to standard NEDC cycle, these cycles are considered aggressive and are expected to consume more energy. Details of the cycles for circuit 1 and circuit 2 are depicted in Table 2.

For validation, all available parameters for each subsystem were checked before we can proceed to the next subsystem. So, parameters starting from vehicle resistance to the electric motor, battery, all the components in between, and lastly engine were verified to ensure the fidelity of the model in generating results as same as its physical experiment. Only three parameters verification are shown for this paper as comprised in Fig. 3; the power demand at electric motor, the state of charge of the battery, and the torque of engine. Referring to the graphs, we can say that the model is reliable because the results from the model are close to those results from the experiments.

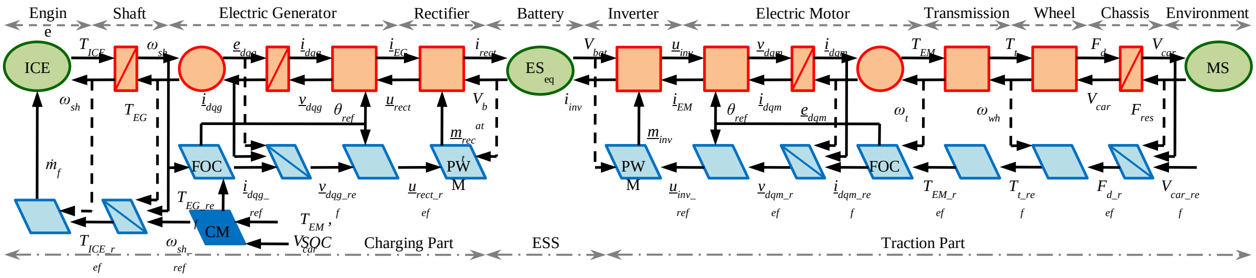

Fig. 1: EMR description of the series HEV system

Table 1: Vehicle parameters

Curb weight (kg)	1200
Wheel radius (m)	0.31
Drag coefficient	0.35
Front area (m^2)	2.0
Maximum power (kW)	100
Engine capacity (L)	0.996
Battery capacity (Ah)	42

Table 2: Characteristic of driving cycles

	Circuit 1	Circuit 2
Total time (s)	611	502
Maximum velocity (ms^{-1})	41.6	42.6
Average velocity (ms^{-1})	29.6	24.8
Distance (km)	18.05	12.39

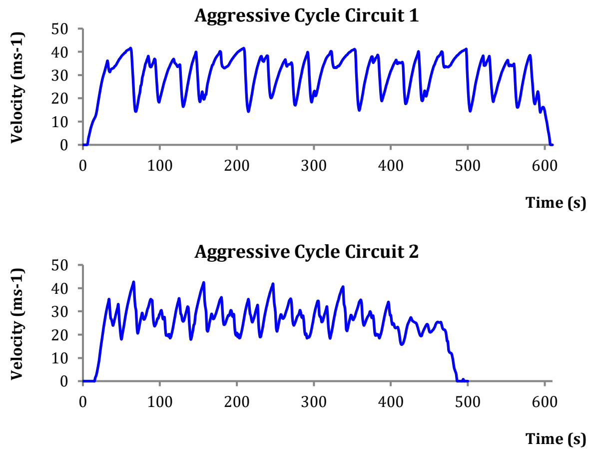

Fig. 2: The two aggressive driving cycles obtained from experiments; Circuit 1 and Circuit 2

3. HEV control methods

Since this car is specially designed to be used in a circuit, the energy management will tend to prioritize power demand delivery rather than to sustain SoC like other controls developed for HEVs. In order to optimize thermal engine for further development of this HEV, first we have to take a look at the fuel consumption distribution of the engine under operation using the actual control method, the dynamic programming method, and the optimal torque control method. Only after that, we can plan optimization on specific region of the engine shown in Fig. 4. As we can observe, the ICE has best efficiency of 0.3 approximately at 60 Nm torque and 450 rads^{-1} of its rotational speed.

The actual control defined for this car imposes a constant rotational speed of engine and varied torque according to torque request weighted by SoC value to compensate the battery voltage decrease. This control method is easy to implement and is based on engineering experiences. It is not optimal because it operates at high speed high torque region where the friction loss is high. But, this will avoid the SoC to deplete rapidly and offer more autonomy to the car. Known as a benchmark to other control strategies, dynamic programming (DP) is usually used as a tool to design and to determine optimal energy distribution. With development in telecommunication technology, DP can be used in real time over a predefined driving cycle and choose an engine operation around the optimal operating points (OOP) with minimum BSFC and maximize overall efficiency. Using historical or telecommunication data, DP can output the engine's power that should be generated during the intended drive cycle, but if the velocity change, the whole system operation will become less optimal (Sorrentino et al., 2011; Stockar et al., 2011).

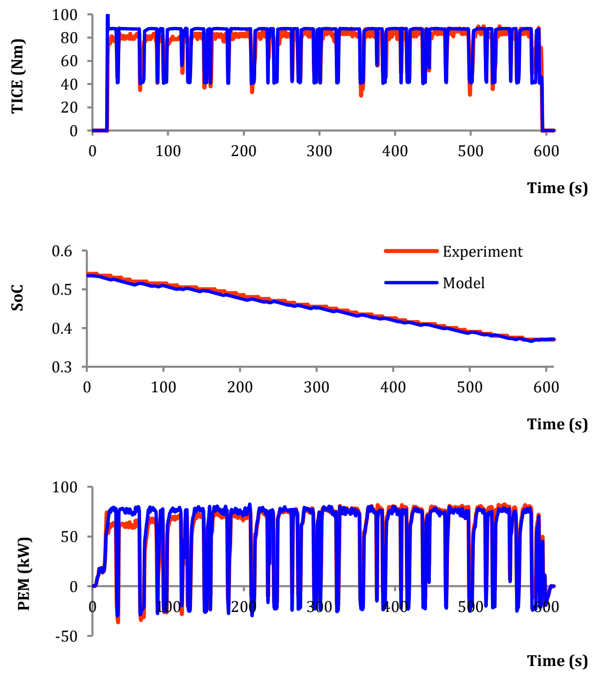

Fig. 3: Parameter verification between the experiment and the simulation model for Circuit 1

The optimal torque control strategy will impose the engine's speed to follow the electric motor's speed fluctuation while at the same time operating at optimal torque for that rotating speed to ensure good efficiency. It has a good transient operation than other control strategies, but the battery charge will deplete faster and shorten the car's autonomy (Opila et al., 2012; Moura et al., 2011).

4. Results and discussion

After simulation, the obtained results are treated so that we can distinguish consumption of each ICE's point. As presented in Fig. 5, Fig. 6, and Fig. 7, the ICE efficiency map is separated into 48 points which signify increment of 100 rads^{-1} and 10 Nm each step. However, some of the steps are group together due to insignificant value.

Table 3 presented the results of the total fuel consumption, the initial and final SoC, and where is the ICE region with most consumption for the three control methods. As we can observe, the consumption for circuit 1 is higher than for circuit 2 except for the optimal torque control. If we can notice, the SoC depletion trend are not the same for all cases even if the initial SoC is set to be 0.540. Depletion is high for the optimal torque, but is slightly sustained in dynamic programming control resulting in less depletion compared to the actual control. As expected, the fuel consumptions are concentrated at high torque region of 60-90 Nm with speed ranging from 200-400 rads^{-1} for these driving cycles.

Table 3: Results comparison between control methods for Circuit 1 and Circuit 2 driving cycles

		Actual control	Dynamic programming	Optimal torque
Total fuel consumption (kg)	C 1	1.71	1.78	0.80
	C 2	1.31	1.26	1.07
Initial SoC		0.540	0.540	0.540
Final SoC	C 1	0.387	0.418	0.291
	C 2	0.457	0.475	0.396
Concentrated ω_{ICE} (rads^{-1})		400>500	500>600	200>400
Concentrated T_{ICE} (Nm)		80>90	70>80	60>70

Referring to Fig. 5, the actual control chooses region of 80-90 Nm torque and engine speed at 400-500 rads^{-1} to consume 1.43 kg fuel out of 1.71 kg for circuit 1 and 0.96 kg from 1.31 kg of fuel for circuit 2 which represent 84% and 73% of the total consumption respectively. Using this actual control, the engine speed is limited to operate between 50-90 Nm and at 400-500 rads^{-1} most of the time. The speed is controlled to not exceed 500 rads^{-1} because according to experience and driving profiles for circuit car, the engine will operate continuously due to high vehicle speed and this will cause nonstop heavy load to the engine with high friction loss most of the time.

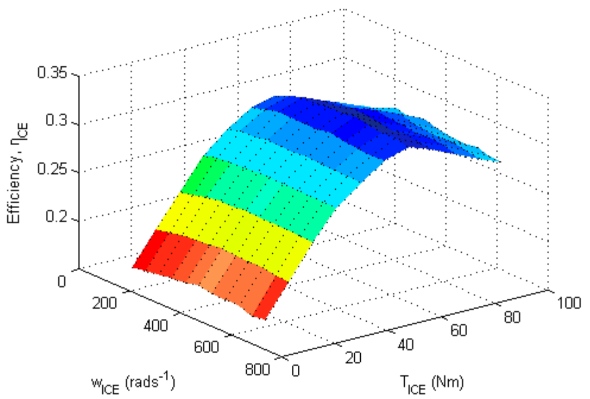

Fig. 4: Internal combustion engine efficiency map

In Fig. 6, the fuel consumptions are concentrated at torque 70-80 Nm and engine speed of 500-600 rads^{-1} for both circuits with 1.62 kg over 1.78 kg for circuit 1 and 1.00 kg over 1.26 kg for circuit 2 consumed at this point. This shows that the dynamic programming control method will always choose the best consumption point over any given driving cycles in order to optimize the overall efficiency. Since the drive cycles are aggressive, this control method tends to use as much as fuel it can in order to sustain SoC from 0.54 to 0.418 for circuit 1 and to 0.475 for circuit 2. Even if its fuel consumption is not the best, this control method can keep energy in battery for longer range than the other two control methods.

The fuel consumption distribution if using optimal torque control is presented in Fig. 7, where we can see the speed range will be not more than 400 rads^{-1} and the torque is controlled to be in range from 50 Nm to 70 Nm only. The significant consumption is at the middle of the ICE map where for circuit 1, 0.555 kg from 0.8 kg of the fuel consumed is located at 300-400 rads^{-1} and 60-70 Nm. However, for circuit 2 the consumption at the same region is only 0.1586 kg out of the 1.07 kg total consumption and recurrent consumption of 0.3074 kg is shifted a bit lower at speed of 200-300 rads^{-1}. As the power produced at this region is lower, the battery will compensate the remaining power needed and has caused SoC to decrease from 0.54 to 0.291 for circuit 1 and to 0.396 for circuit 2. This control method is sensitive to power demand fluctuations making different distribution of the fuel consumption between the two cycles.

As can we observed from the fuel consumption distribution on the ICE efficiency map, we can see that for HEV system, the consumption can be controlled on the most efficient operating region of ICE. But because of the power demand, for particular aggressive cycles, the high torque and high speed region is preferred rather than operating only on the most efficient point at 400 rads^{-1} and 60 Nm.

As overall observation in Fig. 5, Fig. 6, and Fig. 7, the areas that should be given more attention for ICE optimization are between 300 rads^{-1} to 600 rads^{-1} speed, and between 60 Nm to 90 Nm torque for the studied aggressive driving cycles. This study can be extended to analyze ICE operating areas for standard cycles like NEDC and ARTEMIS and optimizing ICE accordingly for more efficient operation of hybrid electric vehicle system.

5. Conclusion

This paper analyses operation of an ICE in a series HEV system under three most utilized control methods which are the heuristic method used as the actual control of the car, the dynamic programming control method used as benchmark of a control method in development, and the optimal torque control method which mostly uses OOP line for real-time optimization of a control method. The simulation model of the system is developed using EMR method and validated with experiment data of the car.

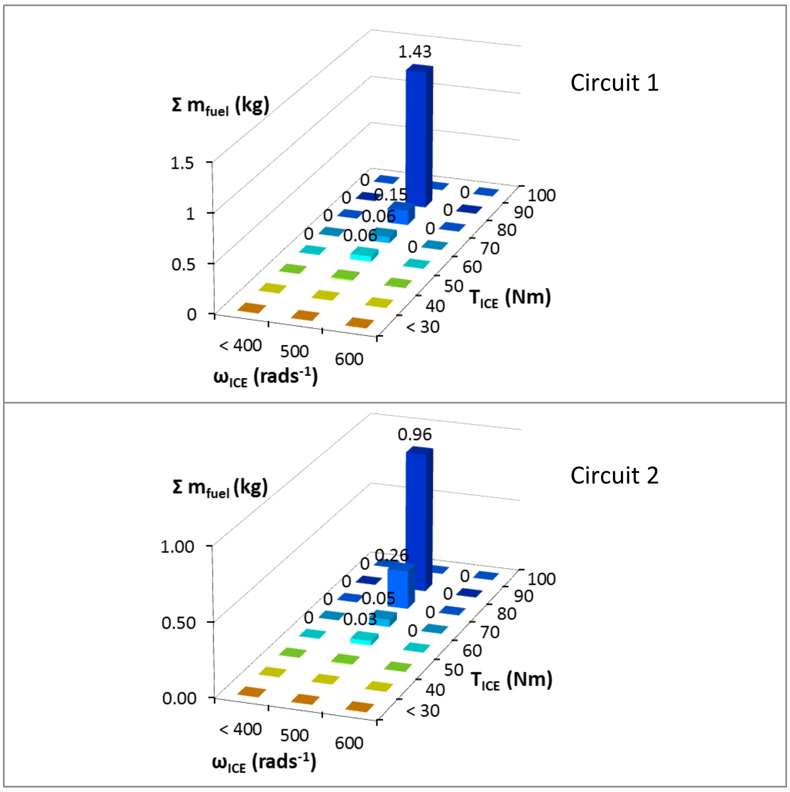

Fig. 5: Fuel consumption distribution of the actual control method on the ICE map

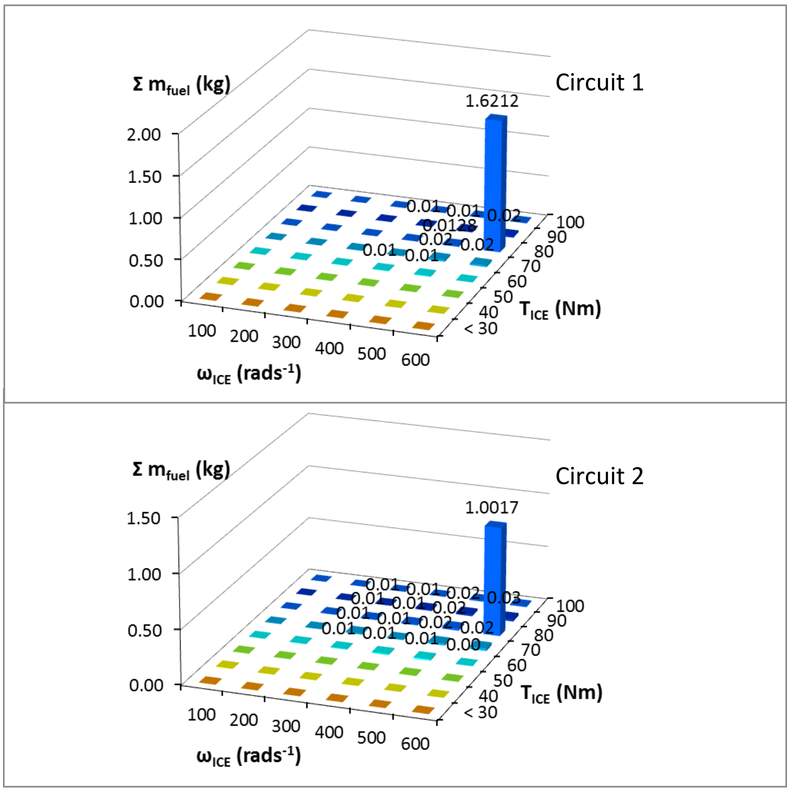

Fig. 6: Fuel consumption distribution of the dynamic programming control method on the ICE map

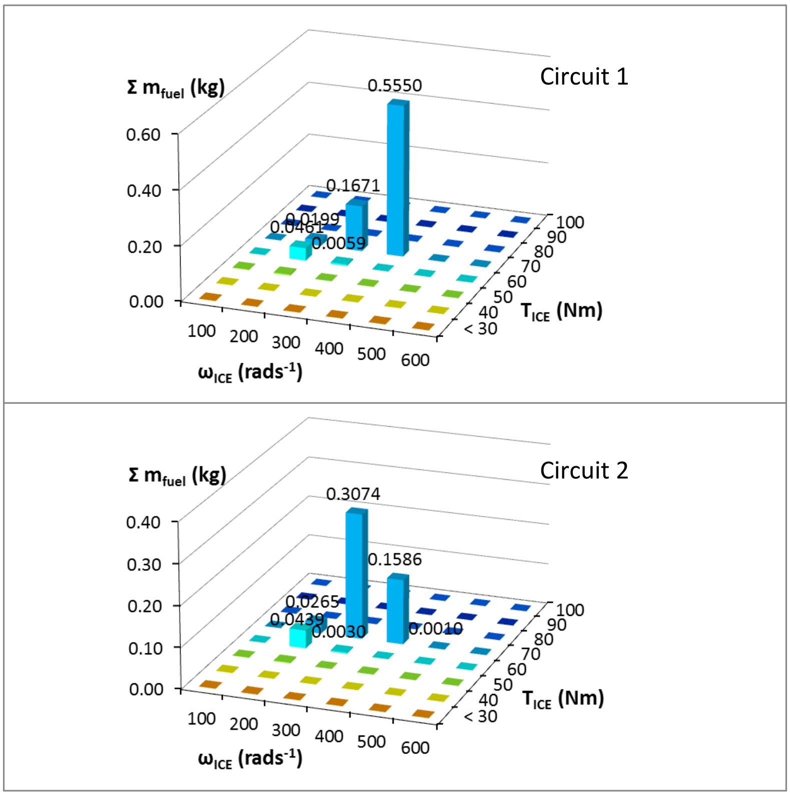

Fig. 7: Fuel consumption distribution of the optimal torque control method on ICE map

Analysis on two aggressive driving cycles of Circuit 1 and Circuit 2 reveals that the ICE operating areas are mostly concentrated on 300 rads^{-1} to 600 rads^{-1} engine speed and between 60 Nm to 90 Nm torque for up to 90% of the fuel consumption. So, for an ICE to be used in HEV series car system and circuit application, these areas with the most consumption should be further studied for better optimization of the system.

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