

# DESIGN OF A HYBRID ELECTRIC MOTORCYCLE FOR OPTIMUM FUEL CONSUMPTION AND PERFORMANCE

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**Abstract**— In this paper, design and conversion of a conventional motorcycle to a Hybrid Electric Motorcycle is performed. Firstly, for a reference motorcycle with 125 cc internal combustion engine, the sizing of the main components based on performance is described. Furthermore, ADVISOR is used to simulate the proposed motorcycle and calculate the fuel consumption in different cycles. The configuration of hybrid design is a separated parallel or through the road type, in which a brushless DC motor is assumed to be fitted in the front wheel. An optimization process is carried out to size the components for both the performance and fuel economy of the motorcycle. The results show that a 1.5 kW electric motor in front can improve the performance and grading of the motorcycle as well as to decrease the fuel consumption of the motorcycle on several driving patterns.

**Keywords**— Motorcycle; hybrid; fuel economy; performance

## I. INTRODUCTION

The large number of automobiles in use around the world has caused serious problems for the environment and human life. Air pollution, global warming, and the rapid depletion of the Earth's petroleum resources are now problems of paramount concern (Ehsani *et al.*, 2009). One of the major sectors of the automotive industry include motorcycles. Due to extensive usage of this kind of vehicle, it is quite logical to survey a way to reduce the harmful effects of motorcycle for the environment and human life.

The future prospect of hybrid technology is expected to become more expandable and popular. Many scientists show interest in finding simple, economical and efficient ways to make existing vehicles to become more environmental-friendly. Hybrid electric vehicles (HEV) are one of the best solutions so far for this purpose. Ribau *et al.* (2012) reviewed different engines application in series configuration of hybrid vehicle with comparison in various driving cycles. Cipek *et al.* (2013) introduced a simulation model for control unit of a hybrid electric vehicle with two electric machines and two planetary gearboxes.

The fuel consumption of motorcycles is less than the passenger cars. This fuel economy is due to the motorcycles lighter weight. However, the fuel consumption per weight of the motorcycles is much worse than the passenger cars (Chen *et al.*, 2014). Because of large usage of motorcycle is in urban area which provides lower demand of ICE's power, working in inefficient areas of ICE is inevitable. Accelerating and decelerating during driving, changing speed and braking too much cause ICE

have an incomplete combustion, emitted more pollutant, and increased fuel consumption. For this reason, researchers have been trying to resolve this problem by offering hybrid propelled vehicles such as fuel cell, electric and solar concepts during years.

Although HEVs are widely offered in the market, hybrid motorcycles are rare and very little work is carried out in this field. Until now, a vast majority of companies produced electric motorcycle but only a few of them tend to produce hybrid motorcycle in large commercial scale. For instance, Piaggio has introduced hybrid bike that combines plug-in electric with lithium ion battery. Japanese manufacturer, Yamaha, is building a prototype Gen-Ryu as a motorcycle bearing the hybrid technology but still a concept that has not been produced in industrial scale. Hannan *et al.* (2012) presented the multi-source energy models and rule-based feedback control algorithm of an energy management system for light electric vehicle, i.e., scooters. They proposed a control algorithm which they believed it was efficient and feasible for any light electric vehicle. Sheu and Hsu (2006) studied on hybrid power system incorporated a mechanical type rubber V-belt, continuously-variable transmission and chain drives to combine power of the two power sources, a gasoline engine and an electric motor. Four modes of operation are defined to reduce emissions and maximize the performance of motorcycle. They use the mechanical-type clutches for easy control and low cost to put the electric motor in work. Morandin *et al.* (2014) worked on the design of power-train for HEM. Synchronous electric machine is used to couple with ICE. Besides, a low weight and volume battery pack is selected to optimize the performance of motorcycle and experimental test of HEM prototype on test bench is presented. Hsu and Lu (2010) also designed a HEM by coupling a 1 kW DC motor via a one-way clutch to the transmission and a generator coupled to the 125 cc ICE. In addition, design of HEM management system which utilizes an electronic control unit is implemented to combine two power flow together.

Chen *et al.* (2018a) worked on recognition of driver braking intensity in order to control and energy management of electric vehicles. They proposed a method based on Artificial Neural Networks (ANN) to recognize and analyze the brake intensity by using the prior determined features of vehicle states. The testing results show that their methods are able to accurately classify the braking intensity levels and predict the braking pressure correspondingly. In the another study, (Chen *et al.*, 2017) used novel estimation algorithm for notifying backlash position and half-shaft torque of an electric powertrain. The

powertrain modeling is implemented by hybrid automata. Then the hybrid observer state was designed to simultaneously identify backlash position and half-shaft torque. The proposed observer is validated under highly dynamical transitions scenario of vehicle states. They also used vehicle road testing data to validate the parameters. Chen *et al.* (2018b) established a dynamic model of driver neuromuscular interaction that can be used in highly automated vehicles. Bunch of experiments of driver-in-the-loop are held to identify the key parameters of driver steering wheel. At the end, the values of the stiffness coefficient of the subjects are mainly within the range of 2.5Hz-3.5Hz, and the values under the active steering tasks are mostly below 1 Hz.

According to Kejha and Venkateswaran (2008), through the road configuration is the easiest way to convert a vehicle to electric hybrid one. Fallahi and Niasar (2013) designed and implemented separated parallel configuration to a vehicle and used suitable energy optimization strategies to meet desired efficiency, low pollution, and less fuel consumption. Amjad *et al.* (2011) studied on battery pack sizing and cost which is played a significant role in range of plug-in hybrid electric two-wheelers. Also, they focused on effect of cycle life on cost of battery pack during a year. A hybrid fuel-cell motorcycle was designed by some researchers in Iran, but the converted HEM is the first prototype in Iran (Asaei and Habibidoost, 2013).

In Iran, there are around 8 million motorcycles. Almost one third of that is in the capital Tehran. Therefore, there is a real need to reduce the motorcycle emissions. Electric motorcycles are not popular due to their high cost and low range. One practical shortcoming of these vehicles is their reduced performance in mountainous areas like Tehran. A hybrid motorcycle that keeps the performance of the conventional type, is a good solution and will be the focus of this paper.

In this paper, based on two performance indexes, a simple mathematical calculation of size of the motor and battery has been presented. Simulation of conventional motorcycle and hybrid electric motorcycle based on the calculated size of hybrid component has been implemented in ADVISOR. The preliminary improvement of HEM compared with conventional motorcycle is shown by ADVISOR in two standard driving cycle (included ECE and UDDS). Fuel consumption, maximum speed and acceleration time of two proposed motorcycle is demonstrated. In the next level of this study, an optimization of three component's size has been studied. In this regard, the objective function is fuel consumption which should be minimized and two constraints are defined include maximum speed and acceleration time. Three vectors for optimization are battery capacity, engine power and motor power which have got their own lower bound and upper bound to limit the search area of optimization problem. At the end the optimum size of hybrid components and engine is shown in many standard driving cycle. The improvement of the optimum size and previous calculated size is compared.

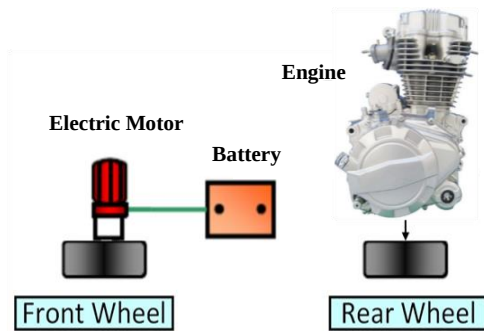


Figure 1. Proposed separated parallel hybrid configuration for motorcycle.

The main novelty of this work is sizing hybrid electric components based on fuel consumption. Although some performance constraints have been considered, but the main objective function of optimization problem is fuel consumption. The results are gained by coupling MATLAB (for running NSGA II) and ADVISOR (for simulating motorcycle and calculate fuel consumption).

## II. METHODS

### A. Powertrain Layout

Separated parallel architecture is preferred here mainly for three reasons; simplicity in control circuit, higher benefit in economical, and perfectly matched to conventional system with minimum manipulations. Separated parallel hybrid configuration, shown in Fig. 1, have ICE and electric motor acting on different driving axes. The road acts as a torque coupling for this configuration and as a result this configuration is sometimes called the through the road configuration (TTR). This special form of parallel architecture avoids mechanical complexity and would be implemented on vehicles without any fundamental modification in conventional propulsion system.

Honda wave 125 is selected for hybridization for two main reasons. First, its automatic transmission, by which the rider experiences a smooth motion of the hybrid motorcycle. Secondly, Honda wave 125 has an adequate space under seat of driver and upper space of fuel tank between two knees of driver for packaging additional components such as battery pack and controller.

### B. Preliminary Sizing

The propulsion unit of hybrid motorcycle consists of two prime movers, the internal combustion engine and electric motor. Due to the TTR hybrid architecture of motorcycle, there is no need to change anything for ICE. The powertrain sizing, therefore, is carried out for the traction motor and battery. To this end, it is necessary to define longitudinal dynamic requirements or performance criteria to determine proper sizes for the electric motor and battery. The performance requirements to make a logical decision of selecting components are described as follows:

- Achieving top speed of 60 km/h in electric-only mode.
- All electric range of 25 km at a constant speed of 40 km/h.

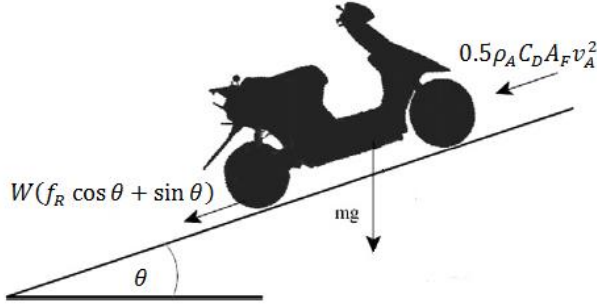


Figure 2. Free body diagram of a motorcycle.

First performance index specifies the amount of power for the electric motor and the second index defines the capacity of battery pack.

### C. Electric motor

One simple approach in modeling the longitudinal performance is to assume that the vehicle uses a constant power to accelerate up to its maximum speed. This corresponds in practice to a full throttle acceleration (Crolla and Mashadi, 2011). The free-body diagram of a motorcycle is demonstrated to clarify tractive and resistant forces, as shown in Fig. 2.

According to Newton's second law of motion the electric motor must supply the tractive force  $F_T$ , to overcome aerodynamic resistance force  $F_A$ , rolling resistance force  $F_{RR}$ , and gradient resistance force  $F_G$ .

$$F_T - (F_{RR} + F_A + F_G) = m \frac{dv}{dt} \quad (1)$$

$m$  and  $v$  are the motorcycle mass and speed respectively. In addition, tractive power requirement of motor related to speed of motorcycle with aforementioned assumption of a constant power  $P$  is,

$$\eta_d P = F_T v \quad (2)$$

in which  $\eta_d$  is driveline efficiency. Combining the two equations leads to,

$$m \frac{dv}{dt} = \eta_d \frac{P}{v} - F_0 - cv^2 \quad (3)$$

where  $F_0$  and  $c$  are defined below:

$$F_0 = W(f_R \cos \theta + \sin \theta) \quad (4)$$

$$c = 0.5 \rho_A C_D A_F \quad (5)$$

$W$ ,  $f_R$ ,  $C_D$  and  $A_F$  are the motorcycle weight, rolling resistance coefficient, aerodynamic drag coefficient and frontal area respectively.  $\theta$  and  $\rho_A$  are the slope angle and air density. The maximum speed of the vehicle will take place when the resistive force of vehicle equals to the tractive force available. In mathematical terms this means:

$$\frac{dv}{dt} = 0 \quad (6)$$

By putting the right hand side of Eq. (4) to zero, the required power for the motor can be estimated. Fig. 3 shows the solution of this equation. The power of electric motor to propel the motorcycle up to the maximum speed of 60 km/h is 1.43 kW.

Kelly Controls Company offers a 1.5 kW hub motor with a maximum 87 N.m torque. At the final speed of 60 km/h, the motor speed is 530 rpm at which the available traction is larger than 80 N (Fig. 3). Initial traction force, however, is around 300 N and this will increase the acceleration time.

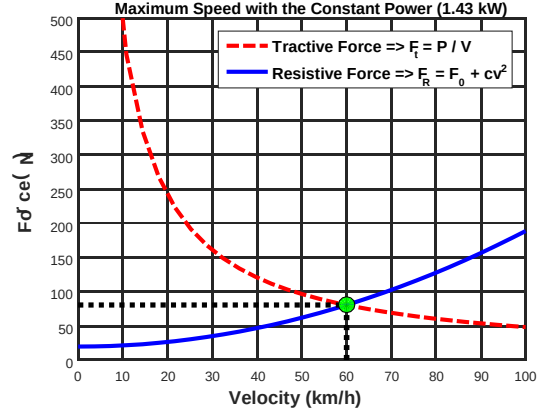


Figure 3. The variation of tractive and resistive forces with motorcycle speed.

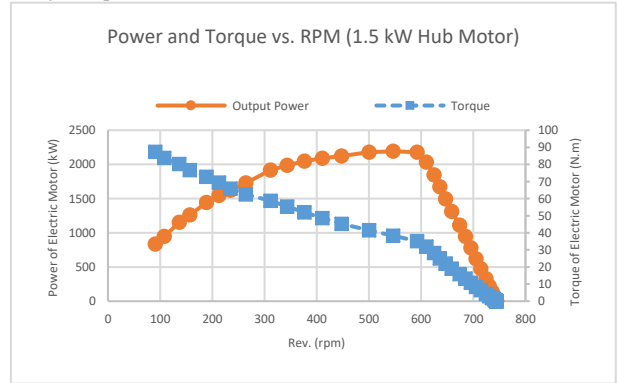


Figure 4. Power and torque characteristics of 1.5 kW of electric motor.

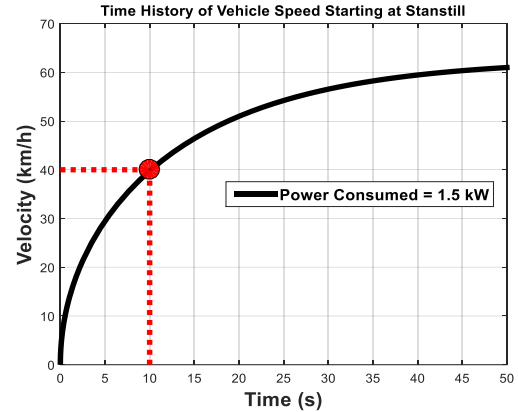


Figure 5. Time history of motorcycle speed with a 1.5 kW electric motor.

Acceleration time can be calculated by using Eq. (3). For a 1.5 kW constant power, the time history of motorcycle velocity is shown in Fig 5. Estimates for the times to reach speeds of 40 and 60 km/h are 10 and 45 seconds respectively. The actual times must be calculated by making use of the motor torque curve.

For a given grade  $\theta$  in electric mode, the motor torque must satisfy:

$$T_m > \frac{r_w * W * (f_r \cos \theta + \sin \theta)}{n * \eta_d} \quad (8)$$

For a maximum torque of 87 Nm, a 14 percent grade for the motorcycle is obtained. Electric motors in general can tolerate overload force (usually with impact factor of

2) in few seconds (Asaei and Habibidoost, 2013). So if electric motor produces 174 Nm of torque in overload condition for a short duration, the grade-ability is 29 per cent.

#### D. Battery

The state of charge (SOC) of a battery demonstrate a measure of the present charge capacity of the battery. The instantaneous SOC can be expressed as below:

$$SOC(t) = 1 - \frac{1}{E_0} \int_0^t P(t) dt \quad (9)$$

in which  $I(t)$  is the instantaneous discharge current of the battery and  $E_0$  is the battery capacity in Wh. The difference between any two states of charge at two different times is  $\Delta SOC = SOC(t_2) - SOC(t_1)$ , and can be expressed as:

$$\Delta SOC = -\frac{1}{E_0} \int_{t_1}^{t_2} P(t) dt \quad (10)$$

The integral part of equation is the net energy during time span of  $t_1$  to  $t_2$ , which is . During the all-electric range, the motorcycle begins with a high state of charge of battery  $SOC_H$  and it ends with a low level  $SOC_L$  at the end of driving cycle. Thus the net energy is consumed by average power consumption and cycle time ( $\Delta t$ ). The required capacity of battery can be expressed as:

$$E_0 = \frac{P_{av} \Delta t}{SOC_H - SOC_L} \quad (11)$$

According to the requirement, motorcycle must be able to travel 25 km at the speed of 40 km/h in all electric mode. With high and low SOC levels of 80 % and 20 %, the capacity of required battery is 0.733 kWh.

### III. SIMULATION AND RESULTS

ADVISOR developed by the National Renewable Energy Laboratory for the US DOE is written in the MATLAB/Simulink environment and is suitable for the simulation of conventional and hybrid vehicles. Different variables of the motorcycle are defined in the software and results are presented.

#### A. Conventional motorcycle

For the simulation of conventional motorcycle, the vehicle parameter values presented in Table 1 are entered in the software. In addition, engine performance curve also must be defined. A scaling method is used to generate the engine performance curves (Kejha and Venkateswaran, 2008).

Table 1. Motorcycle parameters (Bosch, 1996).

| Parameter                      | value | unit |
|--------------------------------|-------|------|
| Engine power                   | 7.2   | kW   |
| Mass without driver            | 90    | kg   |
| Mass with driver               | 170   | kg   |
| Primary gear ratio             | 4.05  |      |
| First gear ratio               | 2.615 |      |
| Second gear ratio              | 1.555 |      |
| Third gear ratio               | 1.136 |      |
| Fourth gear ratio              | 0.916 |      |
| Final drive ratio              | 2.64  |      |
| Aerodynamic Drag coefficient   | 0.27  |      |
| Rolling resistance coefficient | 0.013 |      |
| Wheel diameter                 | 0.3   | m    |

Table 2. Motorcycle performance results.

| Performance measure   | Simulation | Manufacturer |
|-----------------------|------------|--------------|
| 0 to 60 km/h time (s) | 10.1       | 10           |
| Maximum speed (km/h)  | 107.5      | 110          |

Table 3- Fuel consumption of conventional motorcycle (lit/100km)

| Drive cycle | ECE  | UDDS | Constant50 |
|-------------|------|------|------------|
| value       | 2.80 | 2.23 | 1.47       |

Table 4. HEM performance results.

| Performance measure   | Simulation |
|-----------------------|------------|
| 0 to 60 km/h time (s) | 4.9        |
| Maximum speed (km/h)  | 105.5      |

Table 5- Fuel consumption of HEM (lit/100km)

| Drive cycle | ECE  | UDDS | Constant50 |
|-------------|------|------|------------|
| value       | 1.35 | 1.21 | 0.87       |

Results of acceleration test from 0 to 60 km/h and maximum speed test, are provided in Table 2. The results are compared with data given by the manufacturer Honda. A good agreement can be seen between the actual and simulated results. This is an indication of the model accuracy.

ECE and UDDS driving cycles are well known standard cycles. Another driving cycle, named CONSTANT50, is a simple cycle at a constant speed of 50 km/h. The fuel consumption of motorcycle under Constant50 is close to the fuel consumption that manufacturer states. The minimum use of fuel is occurred during constant speed cycle since the losses in during changing gear are absent and engine works at its best operating point. Results of simulation of conventional motorcycle for fuel consumption under ECE, UDDS and Constant50 driving cycles are given in Table 3. Simulation results of conventional motorcycle in the UDDS and ECE cycle are shown in Fig 6.

#### B. Hybrid motorcycle

For the simulation of hybrid motorcycle, all of the settings applied to the conventional motorcycle are identical to those of the hybrid motorcycle. Some other components, however, are added to the base motorcycle, for instance, battery and electric motor. The motor and battery properties are scaled by making use of Advisor scaling method. Another important feature of hybrid motorcycle is its TTR configuration. ADVISOR doesn't have such configuration in its default hybrid systems.

By omitting torque coupling component, connecting electric motor to the front wheel and transferring torque of ICE to the rear wheel, TTR hybrid configuration is constructed in Advisor environment. The result is illustrated in Fig. 7. First direction in Fig. 7 represents electrical path from battery pack to the front wheel and second direction shows the power flow of ICE from fuel tank to the rear wheel. The acceleration and max speed test results are presented in Table 4. The 0-60 km/h time in this case is halved compared to the conventional motorcycle.

The fuel consumption results of the hybrid electric motorcycle for ECE, UDDS and Constant50 driving cycles are given in Table 5.

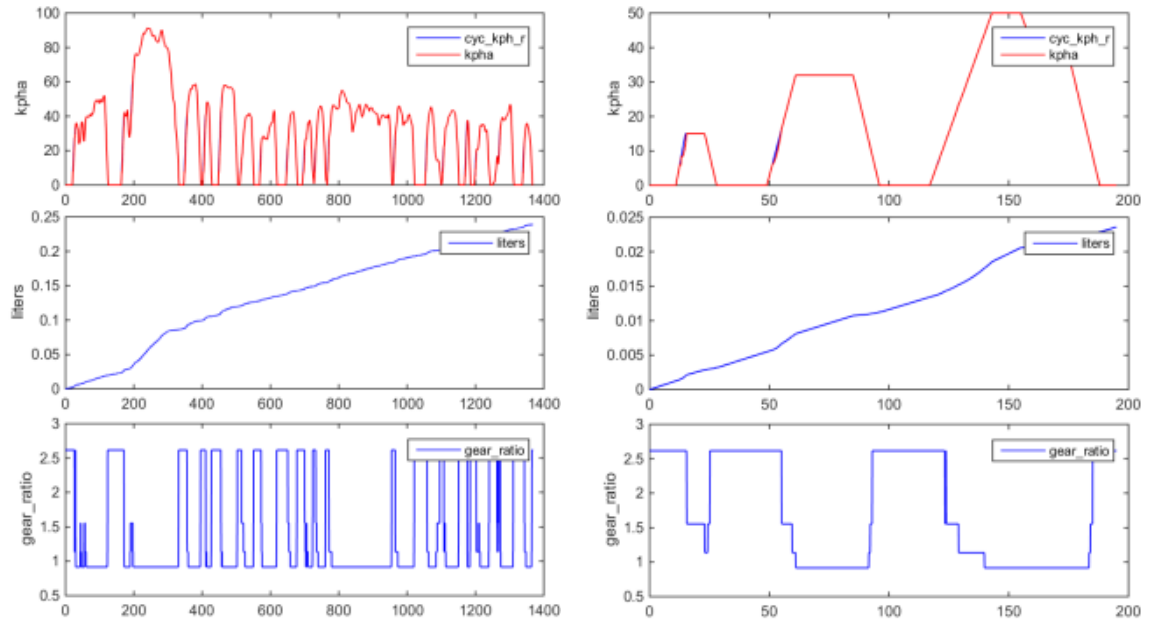


Figure 6- Simulation results of conventional motorcycle in ADVISOR

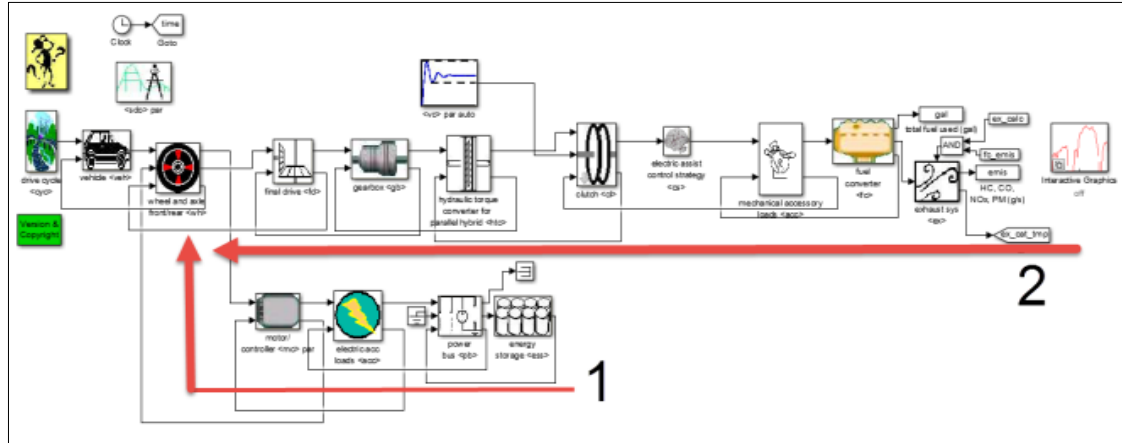


Figure 7. Separated parallel hybrid configuration constructed in ADVISOR.

Typical simulation results of hybrid motorcycle for the UDDS cycle are shown in Fig. 8.

### C. Simulation comparison

The outcomes of simulation for the hybrid and conventional motorcycles are presented in Table 6 and depicted in Fig. 9. The performances of the motorcycle based on the simulations carried out by making use of ADVISOR for the conventional and hybrid electric motorcycles are compared in Table 6. It can be seen that the acceleration time is improved considerably due to adding another power source to assist ICE. The maximum speed of the motorcycle, however, is not improved. The reason is that the electric motor has restrictions for high speeds and cannot assist at high speeds.

Table 6. ADVISOR simulation results comparison.

|                               | ADVISOR |        |
|-------------------------------|---------|--------|
|                               | Conv.   | Hybrid |
| 0 to 60 acceleration time (s) | 10.1    | 4.9    |
| Max speed (km/h)              | 107.5   | 105.5  |

The reduction of maximum speed is happened due to increase in the vehicle weight and in turn the rolling resistance force. Figure 9 illustrates that the fuel consumption of the hybrid electric motorcycle has been improved in comparison to the conventional motorcycle around 48, 35 and 14 percent over ECE, UDDS and Constant50 cycles respectively. Fuel economy in UDDS is much better than ECE due to the advantage of regenerating braking in hybrid electric motorcycle. The least amount of reduction of the fuel consumption is observed in Constant50 cycle. The electric motor does not have much influence on the fuel consumption in Constant50 cycle, due to constant speed of motorcycle in this driving pattern. Since the speed profile of ECE cycle is smooth and linear in comparison with UDDS driving cycle, the engine tends to work in optimum region which results better improvement in fuel consumption. Furthermore, the speed of motorcycle during UDDS cycle is more than ECE cycle. Therefore, the fuel consumption reduction is not noticeably high in comparison with the ECE driving cycle

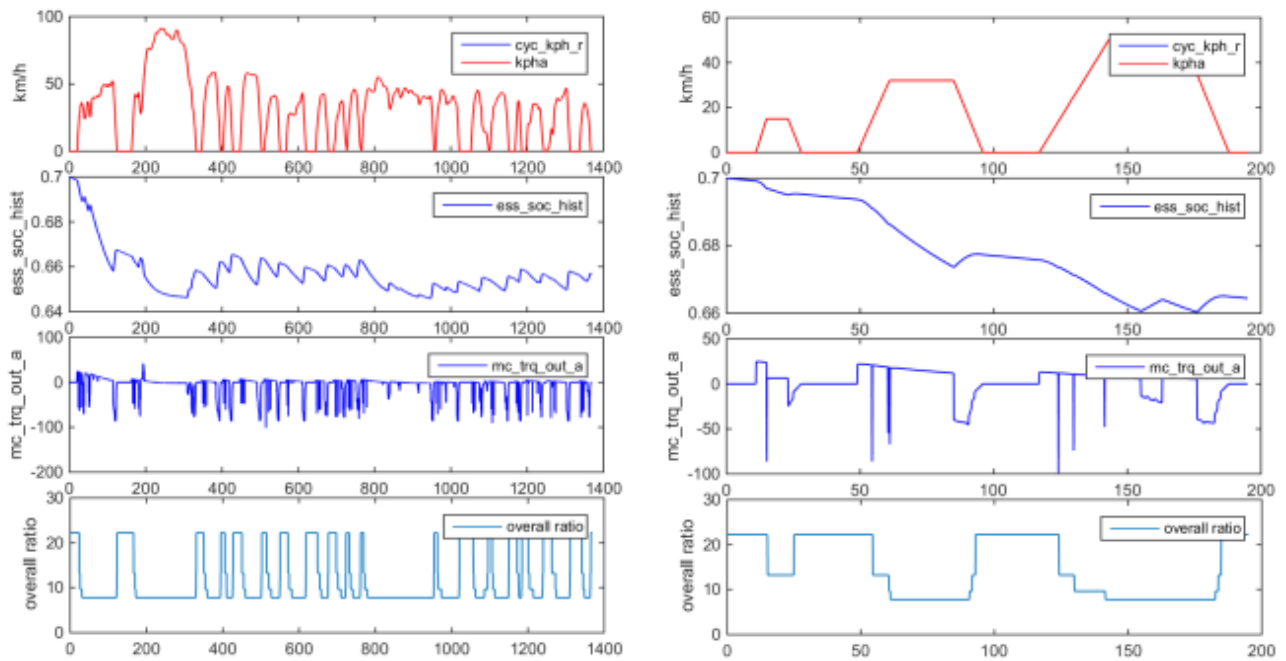


Figure 8. ADVISOR simulation results of hybrid motorcycle for UDDS.

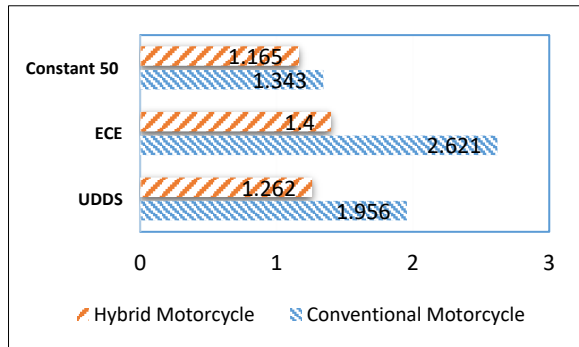


Figure 9. Comparison of fuel consumption in conventional and hybrid motorcycle.

while the motorcycle is under UDDS driving cycle. UDDS cycle is more like real-world driving cycle rather than ECE cycle, however, the amount of reduction of the used fuel over UDDS cycle is less than that over ECE cycle. Vast numbers of stop and go situation in UDDS driving cycle represent urban driving pattern which many motorcycles are confronted. So the advantage of hybrid electric motorcycle is noticed in this condition rather than constant speed cruising.

#### D. Optimum Sizing

The sizing based on performance, which is discussed in previous section, deals with components design to reach desirable performance and does not necessarily improve the fuel consumption. Although the desired performance is a main goal in sizing the motorcycle fuel consumption is another important issue. In fact, the main aim of hybridization in general is to improve fuel economy and thus this factor must be included in the sizing process. The sizing of hybrid electric motorcycle is aimed at many simultaneous targets such as minimizing the fuel co-

Table 7. Driving performance constraints.

| Constrains            | Description | Value |
|-----------------------|-------------|-------|
| Acceleration time (s) | 0-60 km/h   | <7    |
| Max Speed (km/h)      | -           | >105  |

Table 8- Upper and lower bound of design variables

| Variable           | Lower bound | Upper Bound | Step |
|--------------------|-------------|-------------|------|
| ICE power (kW)     | 5           | 10          | 1    |
| Motor power (kW)   | 0.5         | 3           | 0.5  |
| Battery Module (#) | 5           | 20          | 1    |

sumption whereas maximizing max speed and minimizing acceleration time or satisfying driving performance requirements.

In this section, the sizes of main components of hybrid powertrain namely engine, motor and battery pack are determined by using an optimization algorithm. Optimization algorithm helps to search area of three design parameters extensively which fulfill objective function and does not violate constrains. Engine power, motor power and battery capacity are the design parameters and the fuel consumption is the main objective. There are some constrains in this optimization problem which are maximum speed and acceleration time. Hence, the optimization problem of hybrid electric motorcycle components is single objective problem with nonlinear constraints. In mathematical form, the process is:

$$\text{Minimize } J(x) \quad (12)$$

Subject to:

$$g_i(x) \leq 0 \quad i = 1, 2 \quad (13)$$

where  $J(x)$  is the objective function for minimization of fuel consumption,  $g_i(x)$  is the  $i$ th driving performance constrain listed in Table , and  $x$  is the vector of the optimization variables including engine power, motor power and battery capacity. The range of optimization variables are shown in Table 8.



Two different approaches may be considered for the optimization problem. First approach considers a single target optimization, satisfying constraints by using penalty functions and the second one reforms the problem from single objective constrained optimization to multi objective optimization with Pareto optimal solution.

In this work, the multi objective optimization procedure is utilized. For implementing optimization problem, there should be a link between ADVISOR, which plays a role of function for cost functions and constraints function, and optimization algorithm which offers best solution for the problem. Figure 10 demonstrates this link. Since there is no explicit or analytical function for calculating fuel consumption in each step when changing the power of ICE or electric motor, a vehicle simulation model should be utilized for function evaluation like ADVISOR. In an engineering optimization problem, cost functions are calculated by specific mathematical functions. When such functions are complicated, a code or software must be used for the cost function calculation. In this paper, ADVISOR plays such a role. The optimization algorithm produces various inputs during each iteration and these are used by ADVISOR to calculate the outputs. Afterwards, optimization algorithm evaluates the outputs and determines whether the process must be stopped or continued. By means of inputs and outputs, design variables and design objectives are represented respectively. The inputs are updated by optimization algorithm and the outputs which are determined by ADVISOR, are then evaluated using the optimization algorithm. Non-dominated sorting genetic algorithm (NSGA II) is used for optimization algorithm. Derivative-free methods such as genetic algorithm are often the best global algorithms because they must often sample a large portion of the design space to be successful (Mi *et al.*, 2011).

Genetic algorithm is a stochastic global search process which is an impressive technique to solve complicated engineering optimization problems characterized by non-convex, multi-model and non-linear objective functions. Unlike mathematical problems, engineering problems involve multi objectives that must be satisfied. Thus, NSGA II is implemented to locate multiple pareto-optimal solutions at one simulation run.

By running multi-objective optimization algorithm which is coupled with ADVISOR, the results of two objectives, which are the acceleration time and fuel consumption, are shown in Fig. 10. Results of optimization problem could be depicted in three dimensional diagrams due to existence of three objectives. Figure 11 shows two objectives out of three under ECE driving cycle in the form of Pareto solution.

Among optimum solutions of Pareto front, there is a need to specify unique answer which represents the output of optimization problem. So a multi-criteria decision analysis method should be implemented to determine final solution. The Technique for Order of Preference by Similarity to Ideal Solution (**TOPSIS**) is utilized.

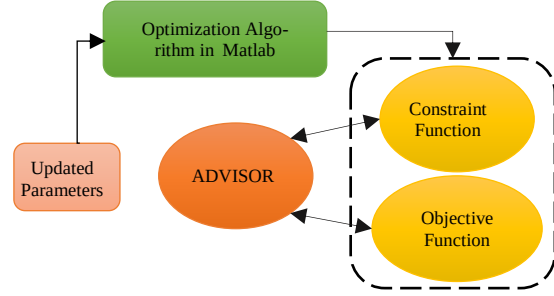


Figure 10. Link between ADVISOR and optimization algorithm.

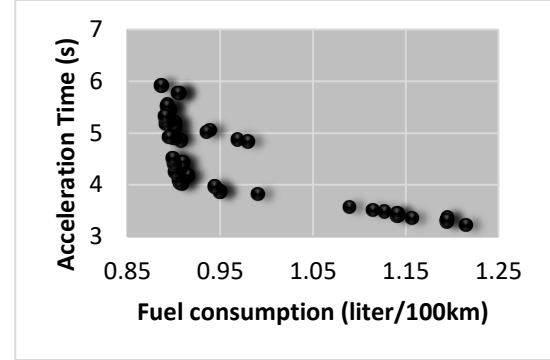


Figure 11- Pareto solution of fuel consumption vs. acceleration time in ECE cycle.

Table 9. Values of objective variables of hybrid motorcycle in optimum sizing in ECE cycle.

| Design objective                | value |
|---------------------------------|-------|
| Fuel consumption (liter/100 km) | 1.18  |
| Acceleration time (sec)         | 5.9   |
| Max Speed (km/h)                | 103   |

Table 10. Values of optimization variables of hybrid motorcycle in optimum sizing in ECE cycle.

| Optimization variables | value |
|------------------------|-------|
| ICE power (kW)         | 5     |
| Motor power (kW)       | 1.5   |
| Battery capacity (kWh) | 1.4   |

TOPSIS introduced by Hwang and Yoon (1981) is used to rank the given alternatives of the Pareto solutions obtained by NSGAII.

The basic concept of TOPSIS determines the positive ideal solution ( $S^+$ ) as well as the negative ideal solution ( $S^-$ ) and then finds the best compromise solution which is the closest to  $S^+$  and the farthest from  $S^-$  from the Pareto set according to the decision maker's objective weights. The positive ideal solution has the largest network reliability and the smallest cost in the Pareto solutions (Lin and Yeh, 2012).

By selecting the most appropriate amount of weight (W) for each of the objectives, best point can be chosen. These weighting factors represent the influence of each objective among Pareto solutions. Due to emphasizing more on fuel consumption in this work, 90 % is designated to fuel consumption and 5 % to each of other two objectives. Optimization variables and objectives with respects to the following weighting factors are presented in Table 9 and Table 10.

The engine power has been downsized to 5 kW to reach minimum fuel consumption whereas other objectives like acceleration time and max speed have been improved reasonably. The procedure of finding optimum solution was implemented in ECE driving cycle so far. Now this process should be considered in different driving cycles in order that the results can be generalized. UDDS, ARTERIAL, WMTC and EUDC are other driving cycles considered for this purpose. In Table 11, the results of the optimization problem under different driving cycles are presented. Running NSGAI and applying TOPSIS on the output of optimization problem are the process of finding final solution for hybrid motorcycle.

The fuel consumption of the conventional motorcycle is compared with the two hybrid electric motorcycle designs (preliminary and optimum design) at different driving cycles and the results are demonstrated in Fig. 12.

Fuel consumption of the hybrid motorcycle which is determined according to the optimum sizing in comparison with conventional motorcycle is improved up to 40.1, 17.2, 54.9, 29.5 and 34.3 percent in UDDS, EUDC, ECE, WMTC and ARTERIAL driving cycles respectively. This comparison also shows that the fuel consumption that was reduced for preliminary sizing, is further

Table 11. Final results of optimization problem in different driving cycles.

|                       |                                  | ECE<br>cycle | S-<br>cy- | UDD<br>C-<br>cy- | EUD<br>C-<br>cy- | WMTC<br>C-<br>cy- | ARTE<br>RAL |
|-----------------------|----------------------------------|--------------|-----------|------------------|------------------|-------------------|-------------|
| Design<br>param-      | ICE power (kW)                   | 5            | 5         | 5                | 5                | 5                 |             |
|                       | Motor power (kW)                 | 1.5          | 1.6       | 1.3              | 1.9              | 1.3               |             |
|                       | Battery capacity (kWh)           | 1.4          | 1.4       | 1.3              | 1.6              | 1.2               |             |
| Design ob-<br>jective | Fuel consumption (liter/ 100 km) | 1.18         | 1.17      | 1.67             | 1.62             | 1.17              |             |
|                       | Acceleration time (s)            | 5.9          | 5.48      | 6.2              | 5.06             | 5.9               |             |
|                       | Max speed (km/h)                 | 103          | 105       | 104              | 105              | 103               |             |

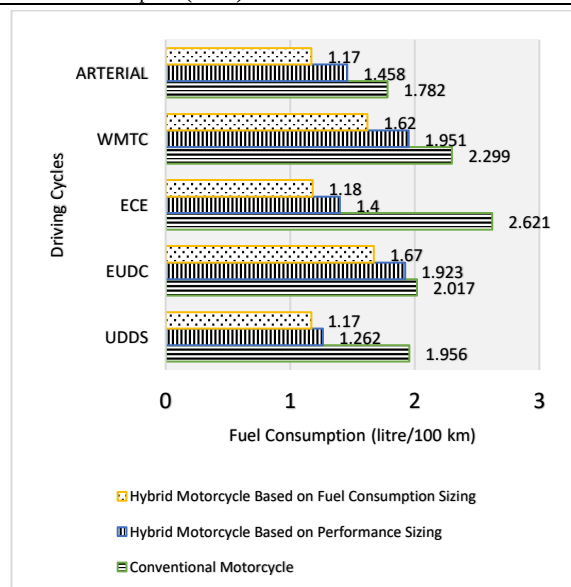


Figure 12. The comparison between the fuel consumption of the conventional motorcycle with those of hybrid electric motorcycle with two sizing methods.

reduced during the optimum sizing. This improvement is about 5, 13, 8, 14 and 16 percent in fuel consumption for UDDS, EUDC, ECE, WMTC and ARTERIAL driving cycles respectively. It simply indicates that downsizing of engine could have much more impact on fuel consumption.

#### IV. CONCLUSIONS

In this paper, the sizing of a hybrid electric motorcycle with two approaches were carried out. Through the road hybrid configuration is selected in which the electric motor is mounted on the front wheel and internal combustion engine propels the rear wheel as in the conventional motorcycle. The simulation of conventional and hybrid motorcycles are performed in ADVISOR software environment.

The results are validated by those presented by the manufacturer for the performance and fuel consumption. A preliminary sizing of the components is carried out based on the performance of hybrid motorcycle in electric mode. In this approach a 1.5 kW motor and 0.8 kWh battery pack are calculated for the hybrid motorcycle. This simple hybridization has reduced the fuel consumption by 35% in ECE driving cycle compared to the conventional motorcycle. In addition, the acceleration time is enhanced 51 percent with respect to the conventional motorcycle. An optimum sizing method is also carried out with the aim of optimizing the fuel consumption. By considering NSGAI as an optimization algorithm, a multi criteria decision analysis method is applied to the output results of optimization problem. In this approach a 5 kW ICE, a 1.5 kW motor and a 1.3 kWh battery pack are resulted. Reduction of fuel consumption in this approach is clear. Hybrid motorcycle with downsized engine has 46 percent less consumption of fuel in average with respect to the conventional motorcycle.

Further work could be carried out as using another optimization algorithm like PSO (Particle Swarm Optimization) or SA (Simulated Annealing). Another approach can be considered for solving optimization problem which is single objective function with couples of constraints. Utilizing another vehicle simulation line GT Suit or AVL Cruise would be a huge beneficial for future work.

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