
Fuel economy regression analyses for hybrid electric vehicle

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ABSTRACT. This study analyses the modelling and simulation of different hybrid electric vehicles (HEV) from battery, DC to DC converter, electric motor and generator, operational modes, planetary gear, internal combustion engine, vehicle body, vehicle dynamics, and control system. Several HEVs are simulated based on different size on specific drive cycle, and fuel consumption is recorded for each. The optimized HEV is extracted from regression model calculated by MATLAB with different polynomial order.

RÉSUMÉ. Cette étude analyse la modélisation et la simulation de différents véhicules électriques hybrides (VÉH), y compris les batteries, les convertisseurs CC / CC, les moteurs et générateurs électriques, les modes de fonctionnement, les engrenages planétaires, les moteurs à combustion interne, les carrosseries, la dynamique du véhicule et le système de contrôle. Plusieurs VÉHs ont été simulés en fonction de la taille d'un cycle de conduite spécifique et la consommation de chaque VÉH a été enregistrée. Le VÉH optimisé est extrait du modèle de régression calculé par MATLAB avec un ordre polynomial différent.

KEYWORDS: regression analyses, fuel consumption, optimal model, hybrid electric vehicle, drive cycle.

MOTS-CLÉS: Analyses de régression, consommation de carburant, modèle optimal, véhicule électrique hybride, cycle de conduite.

DOI:10.3166/EJEE.20.363-377 © 2018 Lavoisier

1. Introduction

This article investigates the modelling and simulation of different hybrid electric vehicles (HEV). All HEVs components are included to design a holistic scheme of real vehicle. This model is included, battery, DC to DC converter, electric motor and generator, operational modes, planetary gear, internal combustion engine, vehicle body, vehicle dynamics, and control system. Eight different hybrid electric vehicles on ten different standardized tire sizes are simulated for their fuel consumption on an urban dynamometer driving schedule UDDS FTP75. Fuel consumption data from those eighty simulations are recorded and processed in different regression analyses to find out the best fit model to estimate the fuel consumption and to determine the optimal vehicle size and tire for the best fuel economy. Finally fuel consumptions are simulated on several other drive cycles of FTP75, NYCC, HWFET, and EUDC for comparison of the optimized model and the nearby model.

Hybrid vehicle is a vehicle with at least two power sources, typically one of the power sources is provided by an electrical motor. Hybrid electrical vehicles (HEVs) are the type of hybrid vehicle that combines the best merits of internal combustion engine (ICE) and electric motor (EM). Hybrid Vehicles can save up to 45% less fuel when compared to conventional vehicle in the same class.

These are three main types of HEVs: series, parallel, and the series-parallel. In series type the internal combustion engine is not connected to the vehicle powertrain and it only is used to rotate the generator to provide electrical power to battery. The electrical power from the battery is used to propel the wheels. In the parallel type mechanical and electrical power are both connected to the powertrain of the vehicle and different control strategies are used during motion to determine if only the EM is used (at low speed) or if only the ICE is used (at high speed) or if both the ICE and EM are used to run the wheels in very high speed or extreme load. In the series-parallel type, it is like the parallel type but has an additional electric motor and a planetary gear unit, this makes the control complex but more efficient as one of the electric motor runs as a generator for charging the battery while the other is used for the running the wheel.

Reviewing some recent researches on HEVs fuel economy modeling and simulations: Simulations and design of HEV dual clutch transmission is referred in (Minh *et al.*, 2017; Afzulpurkar, 2018), where three HEV models are designed and simulated in different driving cycles for achieving the optimal fuel saving; A research of optimization with multi objective for HEV emissions and fuel economy with the self-adaptive differential evolution algorithm is found in (Wu *et al.*, 2011); Optimization of HEV management energy strategy based on some driving cycle modeling is presented in (Naxin & Shim, 2015; Cui *et al.*, 2015) to increase the fuel economy and management for HEVs. Advanced control technologies are applied into the fuel saving control. A control strategy based on fuzzy controller optimized by Sugeno and Mamdani optimization is presented in (Minh *et al.*, 2016; Reza & Minh, 2016); Fuel management economy for HEV and battery modeling can be controlled is introduced in (Liu, 2013). Fuzzy logic control of clutch vibration of HEV is designed in (Minh & Pumwa, 2013), and model predictive controller for real-time

power strategy transmission for HEV is found in (Minh & Hashim, 2012). Effective torque of brake allocation in braking regenerative system for vibration in shaft with model predictive control is presented in (Naik & Shim, 2015). In a comprehensive scheme, operations of electric vehicle traction system has been reviewed by Youssef in (Youssef, 2018).

In our paper, a high-level model of HEV is built and simulated for eight (8) different HEVs using ten (10) different tire sizes in a typical city driving cycle FTP75. Eighty (80) data of fuel consumptions are recorded and processed in different regression models to find out the best fit model to predict the HEV fuel consumption and to generate the optimal HEV size for best fuel economy performance. Lastly, several simulations of fuel consumption between the optimal HEV and the nearby HEV are conducted on several drive cycles to compare their fuel consumption performances. The layout of this paper is as follows: Section 2 briefs HEV modelling; Section 3 presents fuel economy regression model analyses, HEVs simulations and comparison; and finally, Section 4 draws conclusions and recommendations.

2. HEV modeling

2.1. Battery

The battery is modeled as resistance and voltage which changes the load and power flow. A sub-block was modeled for the state of charge (SOC) taking voltage and current as input and the output of the battery voltage is just over 200V is connected to the input of the DC to DC converter. The modeling criteria used for the battery model can be found in (Liu, 2013) and shown in Figure 1.

The differential equation for electrical scheme is

$$\frac{dV_{terminal}}{dt} + \frac{V_{terminal}}{R_{dy}C_{dy}} = R_{ohm} \frac{dI}{dt} + \frac{R_{dyn}+R_{ohm}}{R_{dyn}C_{dyn}} I + \frac{V_{oc}}{R_{dyn}C_{dyn}} \quad (1)$$

where I is the terminal current of the battery (A), $V_{terminal}$ is the battery system terminal voltage (V), T is the battery temperature, and V_{oc} , R_{ohm} , R_{dyn} and C_{dyn} are the scheme parameters which depend on T and SOC.

Battery calculation of SOC can be applied from the integration of current:

$$SOC(t) = SOC(t_i) + \frac{1}{Cap_{Ahr}3600} \int_{t_i}^t I(t)\eta_{bat}(SOC, T, sign[I(t)])dt, \quad (2)$$

$$SOC(t_i) = SOC_i(initial\ SOC)$$

where η_{bat} is the efficiency battery Coulombic and Cap_{Ahr} is the ampere-hours capacity.

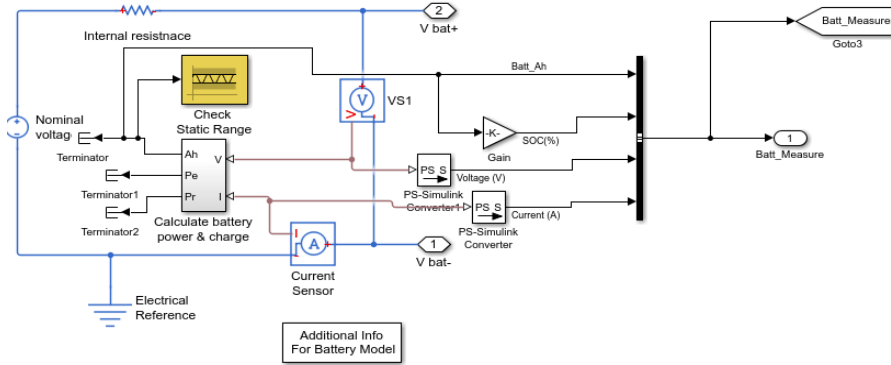


Figure 1. Battery in simulink model

2.2. DC-DC converter

The DC - DC converter is seen as DC equivalent to a transformer AC with a continuously turning ratio. Like a transformer, it is used to step up or step-down DC voltage source. The criteria used for the modelling of the DC-DC converter can be found in (Minh & Pumwa, 2013) and (Minh & Hashim, 2012). For this study the DC to DC converter is used to boost the input voltage from 200V to the output voltage of 500V to drive the motor. The Simulink model of DC-DC converter is drawn in Figure 2.

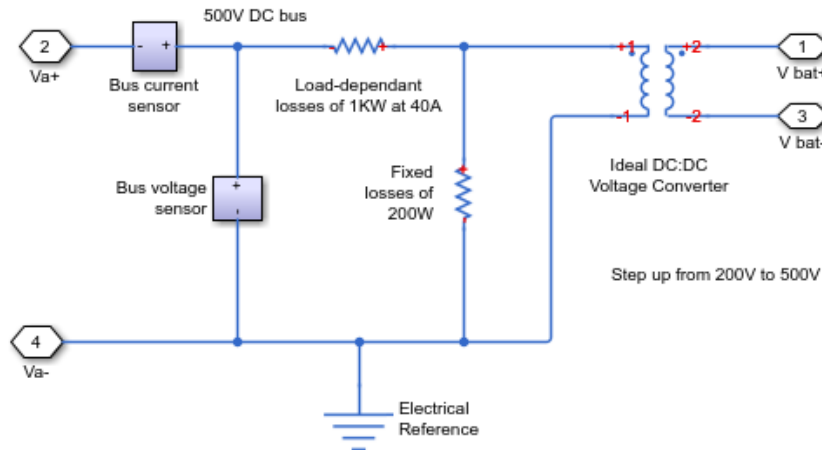


Figure 2. DC - DC converter in Simulink model

The mathematical relationship used for modelling the DC - DC converter

$$\text{Voltage transformation ratio} = \frac{N_{\text{Secondary}}}{N_{\text{Primary}}} = \frac{V_{\text{Secondary}}}{V_{\text{Primary}}}, \quad (3)$$

where V is voltage and N is the number of winding in turns. A transformer to increase the voltage from primary to secondary is named step-up transformer. A transformer produced to reduce voltage from primary to secondary is named step-down transformer. The ratio of transformation for a transformer being equal to the square rooted of inductance (L) primary to secondary ratio.

2.3. Electrical motor and generator model

The servomotor is used to represent the generator and the electrical motor, the required output torque is tracked from the torque demand reference from the control system. Both the servo motor and servo generator are connected to the DC supply. The function of the electrical motor is to supply torque to the transmission required for the propelling of the vehicle, while the generator is used to start the combustion engine and to charge the HEV battery through regenerative braking at certain mode in the control process. Criteria used for modeling the motor can be referred in (Liu, 2013) and generator can be referred in (Naik & Shim, 2015). Figure 3 and Figure 4 show the Simulink model of the electrical motor and generator, the blue lines in both figures indicate the electrical part of the model while the green parts indicate the mechanical system.

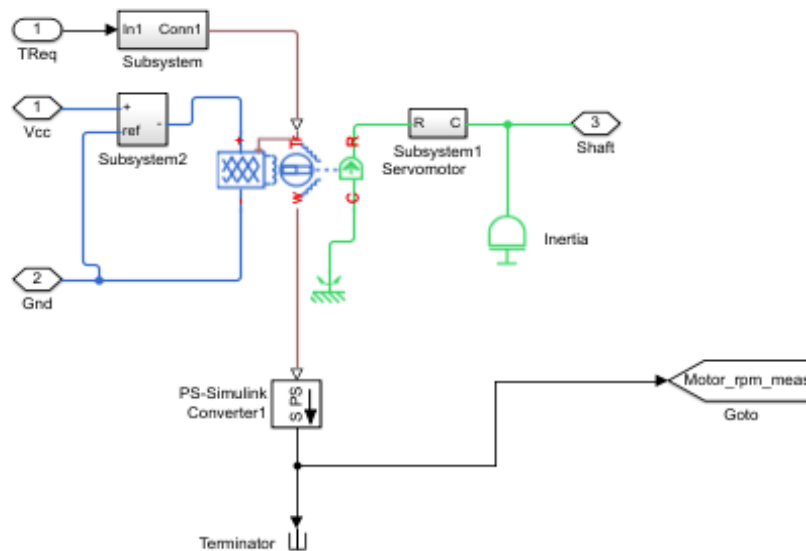


Figure 3. Motor in Simulink model

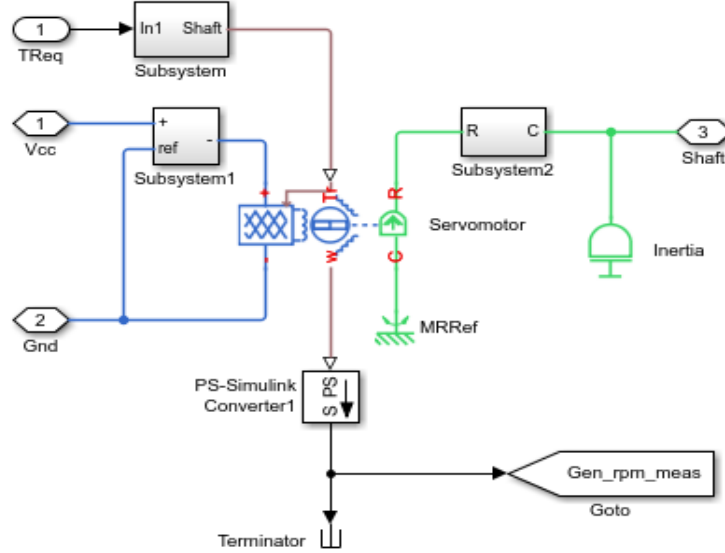


Figure 4. Generator in Simulink model

Three operational modes of motor and generator are as follows:

2.3.1. Operation of propulsion mode

When an electrical motor runs in this mode, it supplies the propulsion torque, and its behavior is depicted from following equations:

$$\tau_{mot} = \tau_{demand} + \tau_{spin_{loss}} + J_{mot} \frac{d\omega}{dt} \text{ (output torque)} \quad (4)$$

$$\tau_{mot} \leq \max(\tau_{mot}) = f(\omega) \text{ (constrain)} \quad (5)$$

$$\tau_{spin_{loss}} = \alpha_1 \delta(t) + \alpha_2 \omega + \alpha_3 \text{sgn}(\omega) \text{ (loss spin torque)} \quad (6)$$

$$P_{elec} = \frac{P_{mech}}{\eta_{mot}} = \frac{\tau_{mot} \cdot \omega}{\eta(\tau_{mot}, \omega)} \text{ (required electrical power)} \quad (7)$$

$$\eta_{mot} = \eta(\tau_{mot}, \omega) \text{ (motor efficiency)} \quad (8)$$

$$V_{mot} = V_{bus} \text{ (motor voltage)} \quad (9)$$

$$I_{mot} = \frac{P_{elec}}{V_{bus}} \text{ (motor required current)} \quad (10)$$

where J_{mot} is the inertia of motor, τ_{mot} is the torque propulsion delivered by the electrical motor (Nm), $\tau_{spin_{loss}}$ is the torque lost due to the friction (Nm), τ_{demand} is the torque demanding from the HEV (Nm), ω is the angular velocity of motor (rad/s), $\max(\tau_{mot}) = f(\omega)$ is the physical maximum torque of motor, α_1 , α_2 , and α_3 are the static coefficient friction, viscous coefficient friction, and friction Coulomb

coefficient, respectively, η_{mot} is the efficiency lumped of the electrical motor, controller and inverter. V_{bus} is the bus high-voltage.

2.3.2. Operation in regenerative mode

When an electrical motor runs in the regenerative mode, the generator supplies charge for the battery and provides negative (brake) torque for the vehicle. In this mode, the generator behavior can be determined by the following equations.

$$|\tau_{regen}| = |\tau_{demand}| - \tau_{spin_loss} + J_{mot} \frac{d\omega}{dt} \text{ (brake torque)} \quad (11)$$

$$|\tau_{regen}| \leq \max(\tau_{regen}) = g(\omega) \text{ (constrain)} \quad (12)$$

$$\tau_{spin_loss} = \alpha_1 + \alpha_2\omega + \alpha_3 \text{sgn}(\omega) \text{ (lost spin torque)} \quad (13)$$

$$P_{elec} = \eta_{regen} P_{mech} = \eta(\tau_{regen}, \omega) \tau_{regen} \omega \text{ (general electrical power)} \quad (14)$$

$$\eta_{mot} = \eta(\tau_{regen}, \omega) \text{ (motor efficiency)} \quad (15)$$

$$V_{mot} = V_{bus} \text{ (motor voltage)} \quad (16)$$

$$I_{regen} = \frac{P_{elec}}{V_{bus}} \text{ (generated current)} \quad (17)$$

where J_{mot} is the inertia of motor, τ_{regen} is the negative brake motor torque (Nm), τ_{demand} is the torque demanding from the HEV (Nm), ω is the angular velocity of motor (rad/s), $\max(\tau_{regen})$ is the maximum motor regenerative torque, and η_{mot} is the regenerative efficiency lumped of the electrical motor, controller and inverter.

2.3.3. Operation in spinning mode

When an electrical motor runs in this mode, it is passively spun and supplies a minor negative torque friction for the HEV as:

$$\tau_{mot} = \tau_{spin_loss} = \alpha_1\delta(t) + \alpha_2\omega + \alpha_3 \text{sgn}(\omega), \quad (18)$$

where τ_{mot} is the output torque, τ_{spin_loss} is the loss spin torque, α_1 , α_2 , and α_3 are the static friction viscous friction coefficient, coefficient, and friction Coulomb coefficient on electrical motor and generator.

2.4. Planetary gear (power split)

Planetary gear is used in the series parallel HEV configuration for power split functionality between the mechanical (ICE) and the electrical link (Electrical Motor). The planetary gear connects the gasoline engine, generator and electric motor together allowing the vehicle to operate at different mode (ICE, Motor, ICE and Motor combine). The set of planetary gear (Power Split) includes of the sun gear, carrier, ring gear, and several pinion gears, carrier. The planetary gear scheme is drawn in Figure 5.

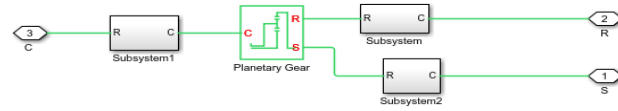


Figure 5. Planetary gear in Simulink model

2.5. Vehicle dynamics

The vehicle dynamics is consisted of gear box, differential, left and right tires, and vehicle body. The vehicle body model is drawn in Figure 6.

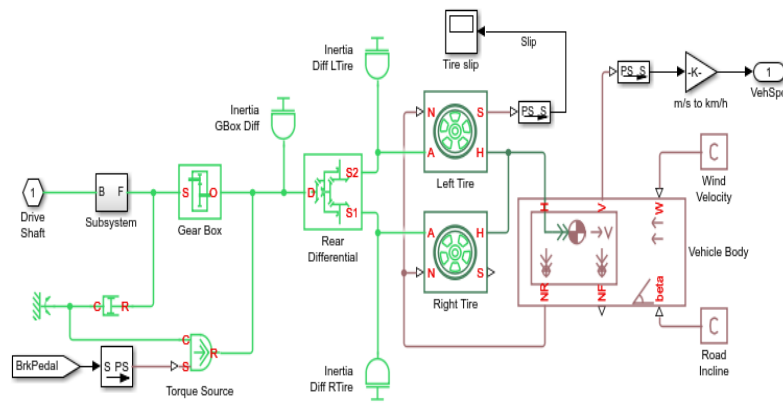


Figure 6. Simulink model of vehicle body model

The HEV body provides the resistance rolling and aero-drag resistance forces of the HEV. The retarding forces of the HEV when the motionless is set equal to $F_{fric} + F_{grade}$. The propulsion force required at the given speed is presented by the relationship below.

$$F_{wh} = F_{rolling} + F_{aero} + F_{grade} + m_v a \quad (19)$$

where, F_{wh} is the force traction on the wheel by the powertrain, m_v is the mass (kg), a is the HEV acceleration (m/s^2), and $F_{rolling}$, F_{aero} , F_{grade} are resistance rolling, aero drag resistance, and weighing forces, respectively, expressed as:

$$F_{\text{rolling}} \approx k_{\text{rrc}} k_{\text{sc}} m_v g \tag{20}$$

$$F_{\text{aero}} = k_{\text{aero}} v^2 \tag{21}$$

$$k_{\text{aero}} = \frac{1}{2} C_a A_d C_d F_a \tag{22}$$

$$F_{\text{grade}} = m_v g \sin(\alpha) \tag{23}$$

where k_{rrc} is the resistance rolling coefficient, k_{sc} is the coefficient of road surface, k_{aero} is the factor aero drag, C_a is the density of air correction at the given altitude, A_d is air density of mass (kg/m^3), C_d is the drag aerodynamic coefficient of HEV ($N \frac{s^2}{kg} m$), F_a is the area frontal of HEV (m^2), and α is the incline angle of road (rad).

2.6. Internal combustion engine

The engine generates driving torque of $T_e(\omega_e, x_{\theta_e})$ and the gearbox applies T_g as the load to the engine. The equation of the engine rotational motion can then be formulated as:

$$T_e(\omega_e, x_{\theta_e}) - T_g = I_e \frac{d\omega_e}{dt}, \tag{24}$$

where ω_e , x_{θ_e} and I_e are engine rotational speed, throttle position, and equivalent rotational inertia of engine respectively. While x_{θ_e} is assume as a variable in the range of [0%–100%]. The vehicle engine scheme is drawn in Figure 7.

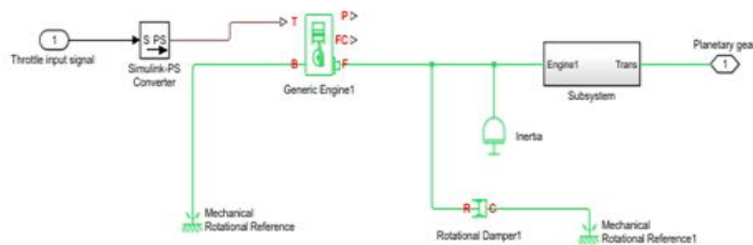


Figure 7. Vehicle engine in Simulink model

2.7. Control system

The control system is designed from five separated sub blocks namely: Motor Controller; Mode Logic; Battery Controller; Generator Controller; and Engine Controller. The system control performs decisions required for the control of the HEV and drawn in Figure 8.

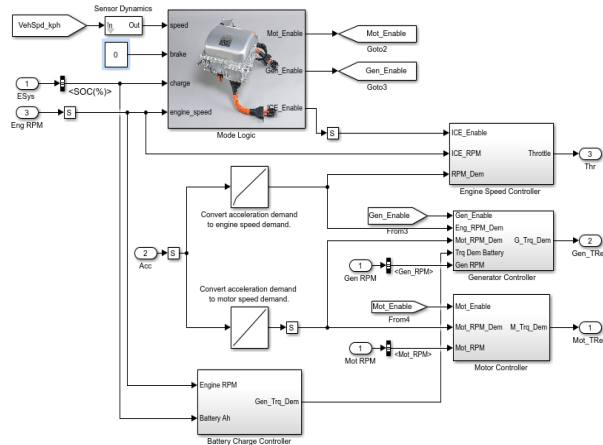


Figure 8. Control system in Simulink model

3. Fuel economy regression analyses

Based on the high-level Simulink mode of HEV, eight (8) different HEVs on ten (10) different standardized tire sizes are selected to simulate for 100 seconds on the typical urban driving cycle FTP75. Table 1 shows the data of 8 vehicle curb weights (curb weight is the authentic weight of a vehicle including all the factory-installed equipment, facilities, and 90% full fuel tank).

Table 1. Vehicle curb weights

No	Car model and year	Curb weight Kg
1	Toyota Prius (2009-2015)	1325 (Toyota, 2015)
2	Honda Insight Hybrid (2009-2014)	1237 (Honda, Honda Insight, 2014)
3	Kia Niro Hybrid (2016)	1409 (Kia, 2016)
4	Hyundai Sonata Hybrid (2011-2013)	1568 (Hyundai, 2014)
5	Kia Optima Hybrid (2016)	1585 (KiaOpti, 2016)
6	Hyundai Avante LPi Hybrid	1297 (HyundaiCat, 2010)
7	Toyota Camry Hybrid (2007)	1649 (CamryHybrid, 2015)
8	Honda Civic hybrid (2011-2016)	1280 (Honda, Honda Civic Hybrid, 2016)

And Table 2 shows the 10 different standardized tires that are able to install into those vehicles (Errolstyres, 2016):

Table 2. Tire sizes with rolling radius

No	Tires size	Rolling radius M	Recommended rim Inch
1	155/65 R13	0,241	4,5
2	155/80 R13	0,261	4,5
3	165/60 R14	0,251	5,0
4	165/65 R13	0,247	5,0
5	165/65 R14	0,258	5,0
6	165/70 R14	0,266	5,0
7	165/80 R13	0,269	4,5
8	175/65 R14	0,264	5,0
9	175/65 R15	0,276	5,0
10	205/50 R15	0,277	6,5

Results of fuel consumption data for 80 simulations of different eight HEVs on different ten tire sizes for 100 seconds over the driving cycle FEP75 are shown in Table 3.

Table 3. Fuel consumption (liter/s) (weight kg (W) Vs Rolling radius m (R))

W	1325	1237	1409	1568	1585	1297	1649	1280
R								
0.241	0.01984	0.01984	0.01985	0.01993	0.01995	0.01984	0.02009	0.01984
0.261	0.01961	0.01961	0.01964	0.02032	0.02052	0.01961	0.02181	0.01961
0.251	0.01973	0.01973	0.01973	0.0199	0.01995	0.01973	0.02053	0.01973
0.247	0.01977	0.01977	0.01977	0.01991	0.01993	0.01997	0.02024	0.01977
0.258	0.01966	0.01964	0.01968	0.01995	0.02025	0.01964	0.02121	0.01964
0.266	0.01956	0.01957	0.01957	0.02057	0.02088	0.01957	0.02255	0.01957
0.269	0.01953	0.01954	0.01959	0.02091	0.02129	0.01953	0.02322	0.01954
0.264	0.01958	0.01959	0.01962	0.02045	0.02063	0.01958	0.02209	0.01958
0.276	0.01948	0.01948	0.01956	0.02188	0.02238	0.01947	0.02511	0.01947
0.277	0.01962	0.01962	0.01965	0.02025	0.02046	0.01962	0.0216	0.01962

Fuel consumption data is processed on several regression analyses to find out the best fit regression model to estimate the fuel consumption for HEVs. Matlab supports calculation of the best fit regression via several equation orders.

Fuel consumption F = function (Vehicle weight W , and Tire radius T) (25)

Regression model for the first equation order:

$$F_1 = f_1(W, T) = P_{00} + P_{10}W + P_{01}T \quad (26)$$

where F_1 is the first order fuel consumption calculation, W is the vehicle Weight, T is Tire radius, coefficients are calculated as $P_{00}=0.02014$; $P_{10}=0.0006671$; $P_{01}=0.0002533$; Coefficient of determination for this first regression model R-square = 0.5365.

Regression model for the second equation order:

$$F_2 = f_2(W, T) = P_{00} + P_{10}W + P_{01}T + P_{20}W^2 + P_{11}WT + P_{02}T^2, \quad (27)$$

where F_2 is the second order fuel consumption calculation, W is the vehicle Weight, T is Tire radius, coefficients are calculated as $P_{00}=0.01947$; $P_{10}=0.0004895$; $P_{01}=0.0002959$; $P_{20}=0.0005423$; $P_{11}=0.0004615$; $P_{02}=0.0001365$. Coefficient of determination for this second regression model R-square = 0.8876.

Regression model for the third equation order:

$$F_3 = f_3(W, T) = P_{00} + P_{10}W + P_{01}T + P_{20}W^2 + P_{11}WT + P_{02}T^2 + P_{30}W^3 + P_{21}W^2T + P_{12}WT^2 + P_{03}T^3, \quad (28)$$

where F_3 is the third order fuel consumption calculation, W is the vehicle Weight, T is Tire radius, coefficients are calculated as $P_{00}=0.01949$; $P_{10}=-8.058e-05$; $P_{01}=-8.597e-05$; $P_{20}=0.0004236$; $P_{11}=0.0004005$; $P_{02}=0.0001392$; $P_{30}=0.0003121$; $P_{21}=0.0003402$; $P_{12}=0.0001619$; $P_{03}=2.071e-05$. Coefficient of determination for this first regression model R-square = 0.9913.

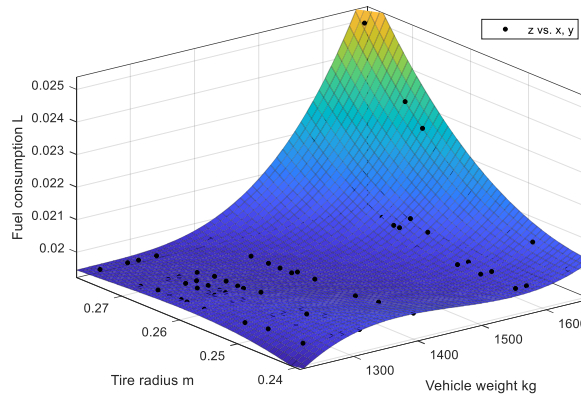


Figure 10. Fuel consumption fit curve model for HEV

With the coefficient of determination R-square = 0.9913 or more than 99% of the fuel consumption being correctly calculated from the vehicle weight and tire radius, formula equation (28) is selected as the final decision to predict the fuel consumption on the city driving cycle FEP75. The third order relationship of vehicle weight (kg) and tire radius (meter) to the fuel consumption (liter) is shown in Figure 10.

Differentiation of equation (28) or $F'_3 = f_3(W'T')$ with respect to W and T leads to an optimal first order linear equation for fuel consumption as follows

$$3,0540e^{-6}W + 0,0212T - 0,0096 = 0 \tag{29}$$

Equation (29) allows calculating the optimal vehicle weights subject to the standardized tire rolling radius as shown in Table 4

Table 4. Optimal vehicle weight subject to tire rolling radius

Tire Rolling radius (m)	0.241	0.247	0.251	0.258	0.261	0.264	0.266	0.269	0.276	0.277
HEV optimal Wight (kg)	1471	1429	1401	1353	1332	1311	1297	1276	1228	1221

In order to verify the optimal fuel consumption in equation (28) and (29), simulations are carried out on different drive cycles (FTP75, NYCC, HWFET, EUDC) for an optimal HEV having optimal weight of 1221 Kg with tire radius of 0.277 m to a lighter HEV of 1200 Kg using smaller tire radius of 0.261 m. Results of fuel consumptions are indicated in table 5.

Table 5. Comparison of fuel consumption between two HEVs

No	Vehicle type	Drive cycle	Vehicle weight kg	Tire rolling radius m	Fuel consumed l/s
1	HEV Optimal HEV	FTP75	1200	0,261	0,03668
			1221	0,277	0,03649
2	HEV Optimal HEV	NYCC	1200	0,261	0,03295
			1221	0,277	0,03263
3	HEV Optimal HEV	HWFET	1200	0,261	0,03969
			1221	0,277	0,03915
4	HEV Optimal HEV	EUDC	1200	0,261	0,03715
			1221	0,277	0,03655

Table 5 shows that the fuel consumption of optimal vehicle is always less than the nearby lighter weight and smaller tire rolling radius vehicle.

4. Conclusion

This study successfully builds up a high-level modeling of HEV with battery, converter, electric motor and generator, planetary gear, internal combustion engine, vehicle body, vehicle dynamics and the control system for HEV. Different HEVs are selected with different weights to simulate the fuel consumption on different tire rolling radiuses. Results of fuel consumption are analyzed and processed on several regression models. The best regression model is the third order polynomial equation with more than 99% of the fuel consumption being able exactly estimated. The fuel consumption regression model helps to identify the HEVs optimal weight subject to their tire rolling radius. Results of HEV optimal weight vs tire radius are also re-verified by simulations of optimal HEV and non-optimal HEV. HEV designers can refer to this study to select their HEV parameter to achieve the best fuel economy performance.

Acknowledgment

The authors would like to thank Tallinn University of Technology (TalTech) for supporting this research project.

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