DOI: 10.14621/ce.20170208

A Computational Study of the Impacts of Driving Aggressiveness on Fuel Consumption Sensitivity in a Parallel HEV

Jelena Andric*, Sudip Sarkar

Chalmers University of Technology
SE-41296 Göteborg, Sweden; jelena.andric@chalmers.se

Abstract

Hybrid electric vehicles (HEVs) have an advantage over their conventional counterparts in terms of reducing fuel consumption and meeting increasingly stringent emission reduction criteria. Nonetheless, the variation in fuel consumption due to differences in driving style and behaviour under real-world driving conditions is greater in HEVs than in the conventional ones. A reduction in variability of fuel consumption is hence of compelling relevance for design and optimization of HEVs. This work employs vehicle powertrain simulations to analyse the effects of driving style on fuel consumption sensitivity in parallel HEVs for a range of traffic conditions. The driving aggressiveness is modelled using velocity-scaling and acceleration-scaling methods, respectively, to account for various velocity characteristics and acceleration levels. Hybrid powertrain simulations assess and quantify the impacts of the engine performance, as well as the significance of the energy recovered by regenerative braking. The results presented in this paper provide valuable inputs for optimal control of HEVs to meet customer driving needs and expectations.

Keywords:	Parallel HEV; Driving aggressiveness; Fuel consumption sensitivity

Article history:	
Received:	31 March 2017
Revised:	24 October 2017
Accepted:	30 October 2017

1. Introduction

The automotive industry is facing great challenges due to mounting environmental threats. Highly efficient vehicles, driven by alternative powertrain systems, are needed to limit fossil fuel dependence and reduce the emissions of greenhouse gasses (GHG). Electrified powertrains emerge as powerful technology to reach stringent CO2 regulations and fuel economy requirements. Especially, hybrid electric vehicles (HEVs) that combine an internal combustion engine (ICE) and an electric motor (EM) offer significant improvement in fuel economy and emission reduction, while still benefiting from power and long driving range of conventional vehicles[1, 2]. Nonetheless, HEVs typically show higher sensitivity in the fuel consumption compared to conventional vehicles due to a number of different factors, including driving patterns and driving styles [3, 4]. In particular, specific driving behaviours have significant impact on the vehicle powertrain performance [5]. The fuel consumption sensitivity becomes critical when the testing and certification are carried out for a standard drive cycle and the real-world driving patterns differ substantially from the standard cycle. Therefore, it is important that a reduction of the fuel consumption sensitivity is considered along with potentials for fuel consumption savings to achieve optimum design and control of HEV powertrains.

A number of previous studies have addressed the impact of driving behaviour on vehicle fuel consumption. Berry [5] investigated the effects of driving style on real-world fuel consumption in conventional vehicles. Carlson *et al.* [6] performed dynamometer tests for plug-in HEVs. The experimental results showed that the PHEVs are less sensitive to aggressive driving compared to HEVs due to larger batteries. Sharer *et al.* [5] investigated the impact of drive cycle aggressiveness on fuel consumption of both HEV and conventional vehicles for two different multiplier modified drive cycles, representing highway and urban driving. The results showed that the HEV is more sensitive to drive cycle modification as the engine efficiency remains unchanged with the variations in the vehicle load. Feng and Chen [6] conducted a study of the impacts of aggressive driving on the HEV fuel consumption and the energy losses in the powertrain. Their findings showed that the higher driving aggressiveness increases the vehicle fuel consumption and the engine energy loss, while the effect of the energy recovered by regenerative braking is insignificant.

This work employs vehicle simulations to analyse and quantify the fuel consumption sensitivity of a parallel HEVs to various levels of driving aggressiveness. Four different driving patterns are considered to represent a variety traffic conditions (urban, highway and combined) and driving styles (from conservative to aggressive). The driving aggressiveness is here modelled by scaling the speed traces of the standard drive cycles using two different methods: velocity-modified and acceleration-modified. The observed fuel consumption sensitivity trends are explained and quantified in relation to vehicle operating mode, engine usage duration, engine operating conditions and energy losses, as well as energy recovery by regenerative braking.

2. Methodology

The methods used to model different levels of driving aggressiveness are described first. The HEV powertrain model is described afterwards.

2.1. Drive cycle modifications

In the present study four different drive cycles are chosen to represent a variety of driving patterns, namely urban, highway and combined traffic conditions. The Highway Fuel Economy Test (HWFET) represents free-flow traffic at highways with the highest average speed. The Urban Dynamometer Driving Schedule (UDDS) exemplifies city driving conditions with frequent stops with low average speed and low acceleration. The Worldwide harmonized Light vehicles Test Cycles (WLTC) Class 3 represents one average vehicle journey worldwide, consisting of four parts with low, medium, high, and extra high speed. The New York City Cycle (NYCC) features low speed stop-and-go traffic conditions. The basic characteristics of these four drive cycles are summarized in Table 1.

The instantaneous velocities and instantaneous accelerations/decelerations of drive cycles are important features that characterize different levels of driving aggressiveness. Thus, to account for different levels of driving aggressiveness, two different approaches are used in this study to modify speed traces of the standard drive cycles. These approaches comprise the velocity modified and the acceleration modified speed traces, as illustrated in Figures 1 and 2, respectively, using the WLTC drive cycle as an example.

Table 1: Drive cycle basic characteristics

Drive cycle name	Total time [s]	Total distance [km]	Average speed [km/h]	Maximum speed [km/h]	Maximum acceleration rate [m/s^2]
HWFET	765	16.5	77.5	96.32	1.4
UDDS	1369	12	31.5	91.2	1.6
WLTC	1800	23.27	46.5	56.5/76.6/97.4/1	1.6/1.6/1.6/1
NYCC	598	1.9	11.4	44.45	3.8

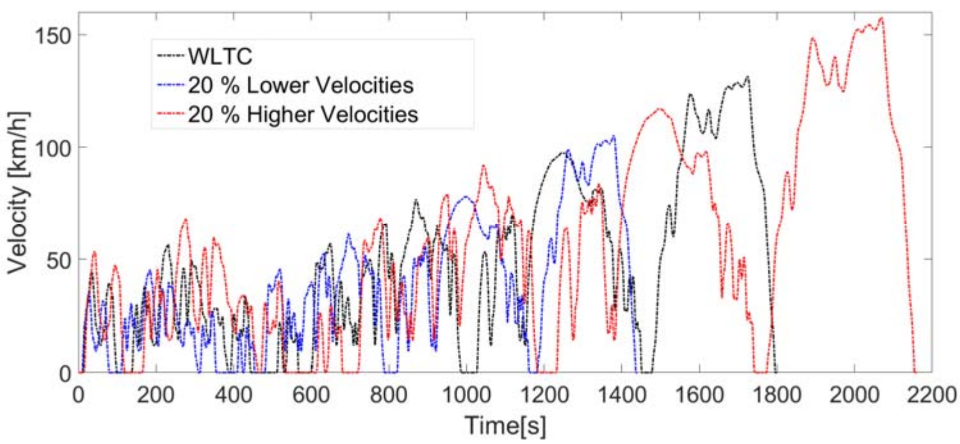

Figure 1. The WLTC drive cycle along with two velocity modified speed traces

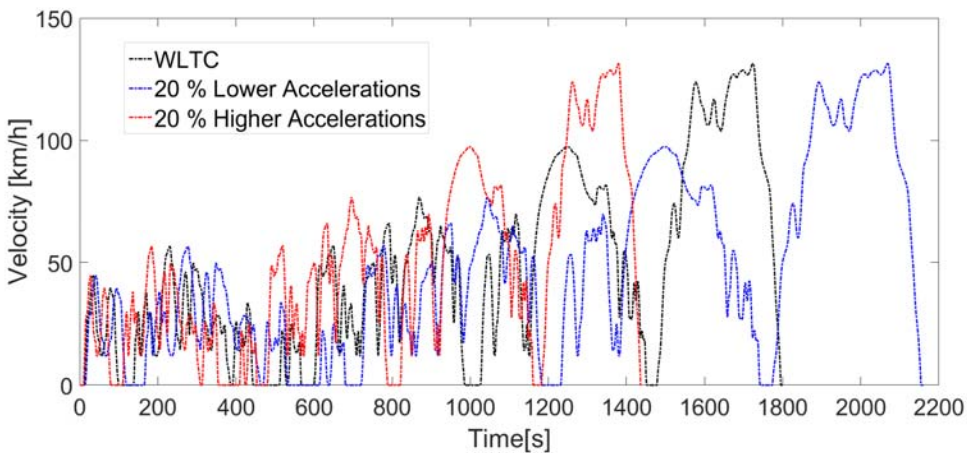

Figure 2. The WLTC drive cycle along with two acceleration modified speed traces

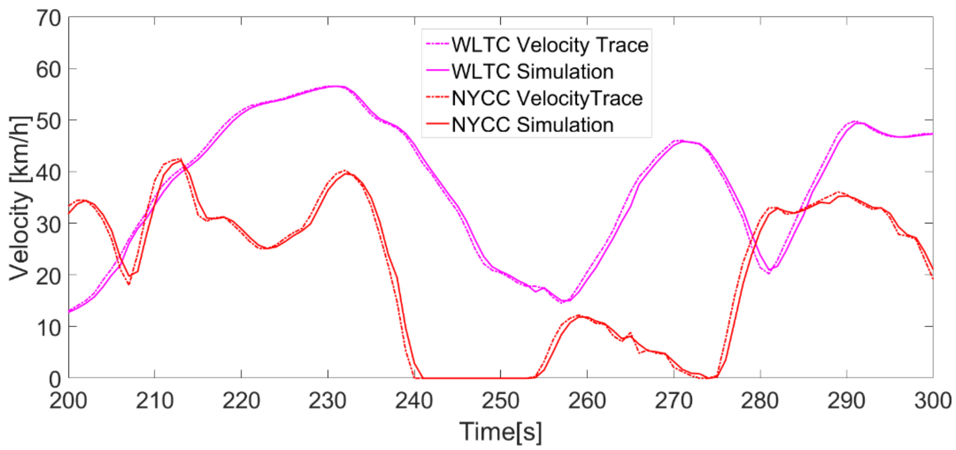

Figure 3. A fraction of the WLTC Class 3 and NYCC along with the actual velocity traces of the driver

- For the velocity modified speed traces both speed and time are multiplied by a scaling factor. Hence, the velocities are modified, as well as the distance and duration, while the accelerations remain unchanged. Nonetheless, it should be noted that these accelerations now take place at different speeds compared to the original cycle.
- In the acceleration modified speed traces only the time vector is being scaled by a certain factor. Thus, velocities remain unchanged, whereas the cycle duration is modified.

2.2. HEV powertrain model

The vehicle model considered in this work represents a parallel hybrid powertrain consisting of the ICE, the electric machine that acts both as an electric motor (EM) and as a generator, and the battery. The ICE is a 1.8L four-cylinder naturally aspirated (NA) spark–ignition (SI) engine with a peak power of 93 KW. The capacity of the battery is 8 Ah, and its initial state of charge (SOC) is 0.65. The main vehicle parameters are the vehicle mass 1450 kg, and the coastdown coefficients A=64.1 N, B=2.2 Ns/m, and C=0.41 Ns^2/m^2.

Supervisory controller regulates the power flow and manages the coordination among all the components of the powertrain. The supervisory control strategy ensures that the vehicle operates in fully electric mode when its speed is lower than a certain value and the battery SOC is higher than its lowest desirable level. The ICE is used in hybrid mode, when the vehicle velocity as a function of the battery SOC exceeds certain value, or the tractive power demand is higher that the EM power limit. EM acts as a generator and charges the battery by regenerative braking unless maximum regenerative power is exceeded, in which case friction brakes are used. The balancing of the battery SOC is accomplished to maintain its SOC level well around the target value of 0.6.

The fuel consumption of the HEV powertrain is computed using the forward-looking computations. In this simulation approach, the driver model generates the accelerator or brake pedal positions that send signals to different powertrain and controller components in order to follow the desired speed trace. Figure 3 presents the simulated vehicle speed along with the desired speed trace for a fraction of time in the WLTC and NYCC drive cycles, illustrating that the vehicle closely follows the desired speed trace. It should be noted that the calculations are based on the simulated vehicle speed, not the drive cycle speed trace.

3. Results and discussion

Vehicle simulations are carried out using GT-SUITE, a leading vehicle and powertrain simulation software. Standard speed traces are scaled to modify velocities and accelerations, as previously described in subsection 2.1, using the following set of scale factors: 0.8, 0.9, 1.0, 1.1 and 1.2. The simulation results predict the vehicle energy requirements and its fuel consumption for the considered drive cycles and their modifications.

3.1. Fuel consumption sensitivity

To characterize the impact of driving aggressiveness on vehicle fuel consumption sensitivity, the relationship between vehicle wheel work that is vehicle load in units of energy per unit distance and vehicle fuel consumption per unit distance travelled is considered. It should be noted that wheel work takes into account a number of different parameters that are useful for characterizing drive cycle aggressiveness, such as average and maximum vehicle speed and average and maximum acceleration, to name a few. Hence, wheel work represents a suitable parameter to characterize vehicle fuel consumption sensitivity to drive cycle aggressiveness [5, 7]. The fuel consumption can be expressed in the same units as wheel work by taking into account the energy density of the fuel. Vehicle fuel consumption sensitivity is then defined as the ratio of the change in fuel energy consumption per distance travelled to the change in wheel work. This definition makes it possible to compare the results for different drive cycles [7].

3.2. Velocity-modified driving aggressiveness

Figure 4 illustrates the fuel consumption sensitivity of the HEV for the velocity-modified drive cycles. The fuel consumption sensitivity is represented by the slope of the corresponding straight line. Significant differences can be noticed among the considered drive cycles. To fully understand the observed sensitivity trends, it is necessary to characterize the following: the influence of engine usage in percentage of total cycle duration, engine efficiency and engine energy losses, as well as the effect of regenerative braking.

For the UDDS drive cycle there is a significant difference in the fuel consumption sensitivity at lower and higher vehicle load. For the first two points, there is a rapid increase in the engine usage from 27-39% of the total cycle time, as shown in Figure 5, leading to high fuel consumption sensitivity $S_{fc} = 24.4547$, the slope of fitted local line. For the last three points, the engine usage varies insignificantly from 45-51% of the total cycle time, yielding substantially lower sensitivity $S_{fc} = 3.4386$. The NYCC drive cycle is characterized by low average speeds at which the EM supplies all the driving torque for most of the time, and the engine usage is minimal. Nonetheless, the rate at which the engine usage increases with more aggressive driving is very rapid, from 1 to 13% of the total cycle duration. This swift in the vehicle operation mode yields the fuel consumption sensitivity of $S_{fc} = 106.3139$. On the

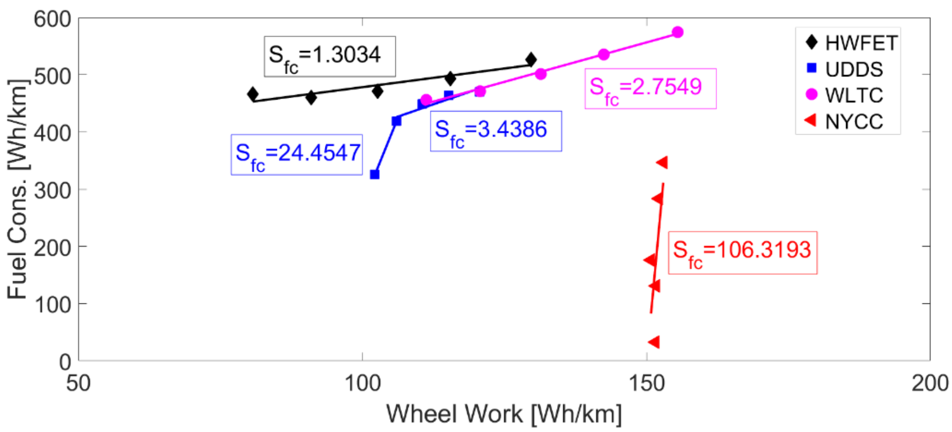

Figure 4. Fuel consumption versus wheel work for velocity modified speed traces

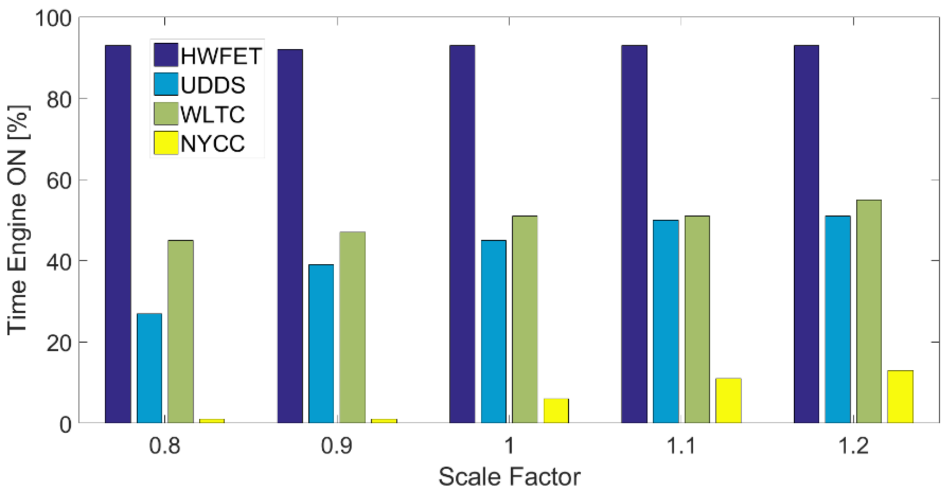

Figure 5. Engine usage in percentage of total cycle time for velocity modified drive cycles

HWFET cycle, the engine is used most of the time due to high velocities and low regenerative braking, which is discussed later in this subsection. Thus, the HEV operates almost equivalently as the corresponding conventional vehicle. Its fuel consumption sensitivity is $S_{fc} = 1.3034$, which is the lowest among the considered cycles. Finally, on the WLTC cycle there is a rather negligible variation in the engine usage with vehicle load. The cycle shows approximately the average sensitivity $S_{fc} = 2.7549$ of the urban driving (UDDS for higher vehicle load) and highway driving (HWFET).

The sensitivity of the average engine efficiency and engine energy losses to changes in vehicle load are presented in Figures 6 and 7, respectively. Higher engine efficiency reduces the effects of more aggressive driving and consequently the fuel consumption sensitivity. The engine average efficiency increases with vehicle load on the HWFET cycle, so that the engine losses decrease at low loads and only slightly increase at higher loads. Hence, the vehicle fuel consumption is less sensitive for the HWFET cycle compared to UDDS and WLTC cycles where the increase in engine average efficiency with vehicle load is smaller. On the NYCC cycle, the fast increase in engine energy losses is governed by the rapid increase in engine usage and the effect of the improved engine efficiency is insignificant.

Figure 8 illustrates the sensitivity of the energy recovered by regenerative braking to vehicle load. The regenerative braking recharges the battery and hence reduced the amount of energy required from the engine so that the change in the battery SOC is minimized. As anticipated, the regenerative energy does not vary significantly on the HWFET cycle, where there is little braking. The amount of regenerative braking decreases on the UDDS and WLTC with increasing vehicle load. The sensitivity of regenerative braking is higher on the UDDS compared to the WLTC, and that is another contribution to a higher fuel consumption sensitivity on the UDDS compared to the WLTC cycle. On the NYCC, the regenerative energy increases with vehicle load, however, the effect of the engine usage is a dominant parameter that affects the fuel consumption sensitivity.

3.3. Acceleration-modified driving aggressiveness

The fuel consumption sensitivity for the acceleration modified drive cycles is shown in Figure 9. Before analysing the results in detail, it should be observed that the engine usage (see Figure 10) does not vary significantly with driving aggressiveness for the considered cycles. The highest sensitivity $S_{fc} = 2.1219$ is observed for the HWFET cycle, where most of the vehicle energy requirements is provided by the engine, and the vehicle again operates quite similarly as its conventional counterpart. It should also be noted that the sensitivity is higher compared to that for the velocity-modified HWFET speed traces, since the engine average efficiency (see Figure 11) does not increase significantly with vehicle load. The vehicle sensitivity on the UDDS is about twice smaller in comparison with that on the HWFET cycle, with the engine operating around 45% of the total cycle time. On the WLTC cycle the vehicle shows about the same sensitivity as on the HWFET, with the engine being used around 50% of time. At higher vehicle loads, the engine energy losses increase and so does the vehicle fuel consumption sensitivity. Finally, a slight decrease in the vehicle sensitivity $S_{fc} = -0.1033$, as well as in the engine losses is observed for on the NYCC, where EM supplies the vast fraction of the energy required by the vehicle.

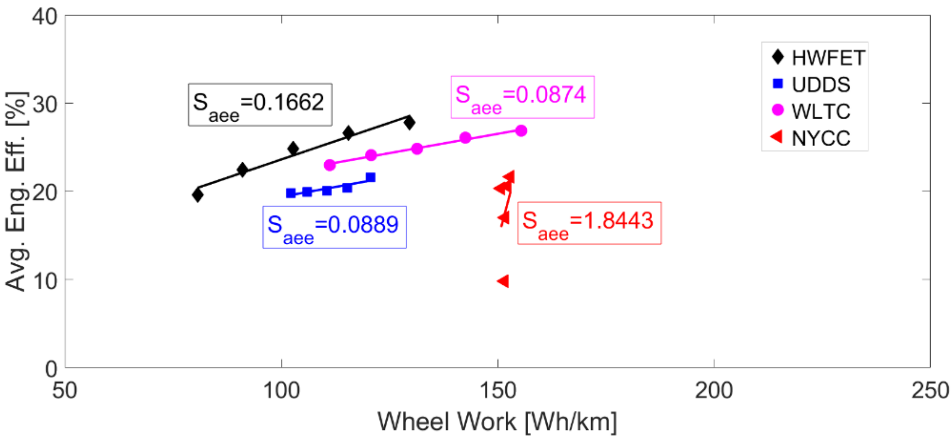

Figure 6. Average engine efficiency versus wheel work for velocity modified speed traces

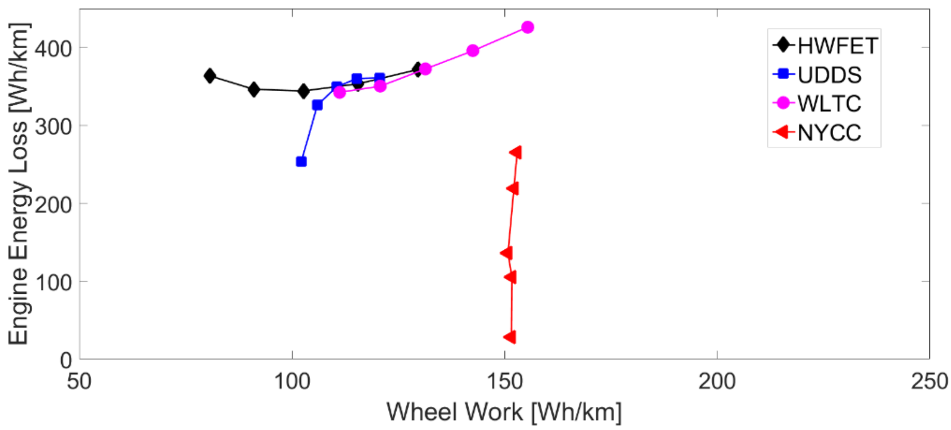

Figure 7. Engine energy loss versus wheel work for velocity modified speed traces

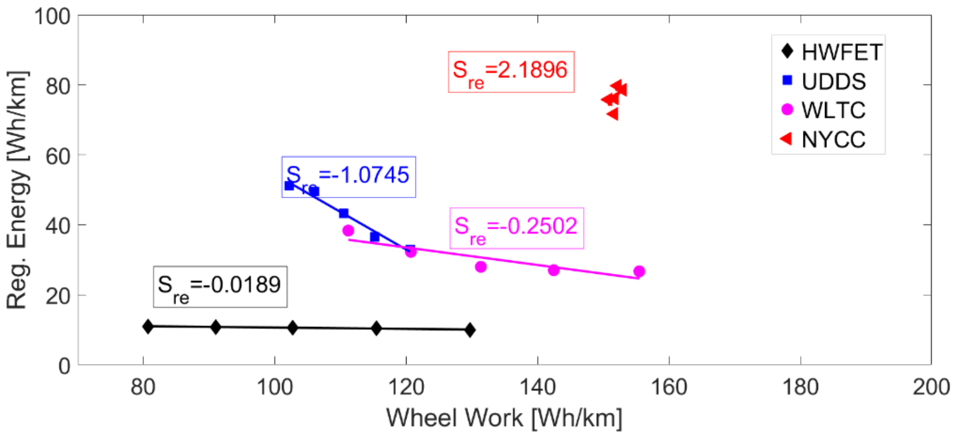

Figure 8. Regenerative energy versus wheel work for velocity modified speed traces

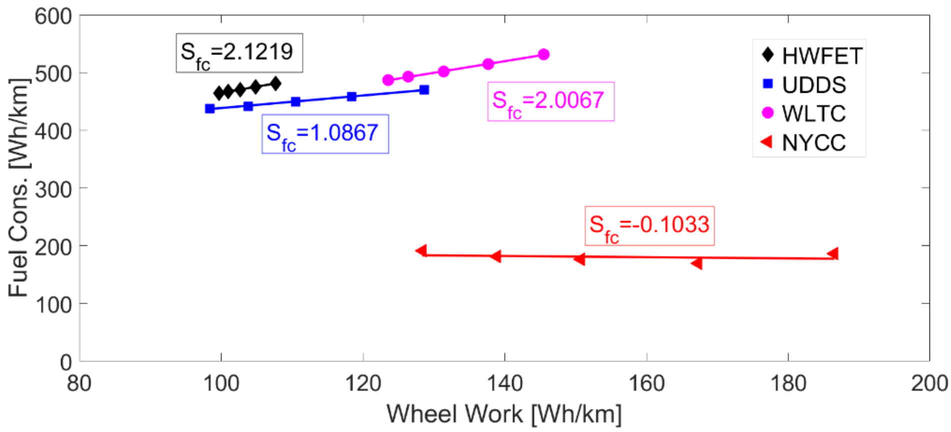

Figure 9. Fuel consumption versus wheel work for acceleration modified speed traces

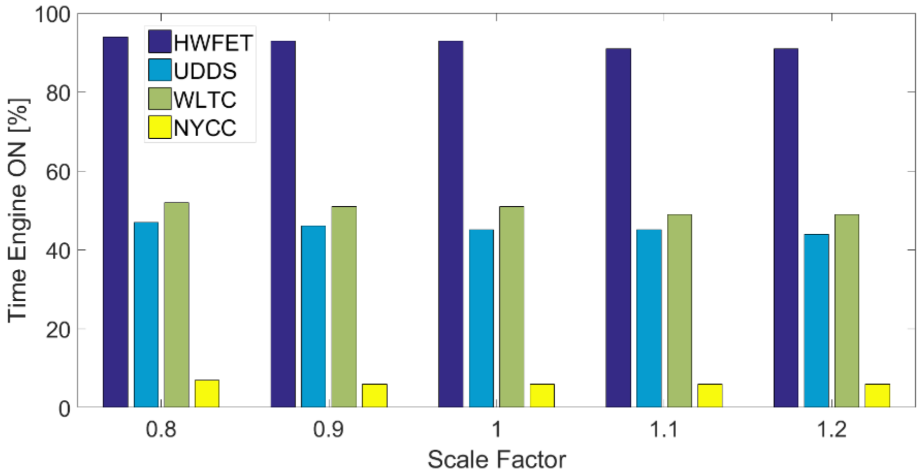

Figure 10. Engine usage in percentage of time for acceleration modified drive cycles

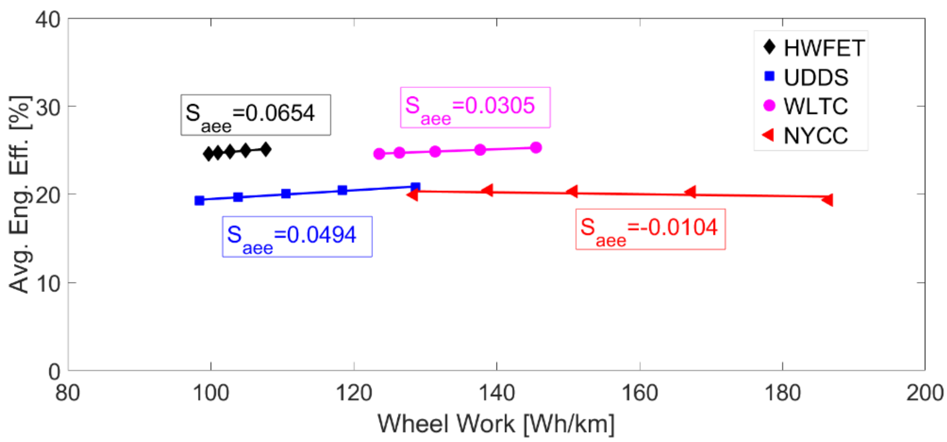

Figure 11. Average engine efficiency versus wheel work for acceleration modified speed traces

The sensitivity of the regenerative braking to the changes in vehicle load is shown in Figure 13. The amount of regenerative braking increases with vehicle load for all four drive cycles. The fastest increase in the energy recovered by regenerative braking is seen for the WLTC cycle. Nonetheless, the total amount of recovered energy is substantially smaller in comparison with the UDDS cycle, being another contribution factor to the higher vehicle fuel consumption sensitivity on the WLTC.

4. Conclusions

Vehicle powetrain simulations were carried out to investigate the effect of driving aggressiveness on fuel consumption sensitivity in a parallel HEV. For that purpose, four standard drive cycles, representing various driving conditions, were modified using velocity- and acceleration-scaling methods to account for different velocity and acceleration characteristics.

The simulation results show that fuel consumption sensitivity for the velocity-modified cycles is particularly high in city driving due to the rapid increase in engine usage with higher cycle aggressiveness. For highway driving, where the engine is used most of the cycle duration, the sensitivity of fuel consumption is significantly lower, since the average engine efficiency increases fast enough with vehicle load, limiting the increase in the engine energy losses, and thus reducing the impact on the vehicle fuel consumption sensitivity. The faster decrease in the energy recovered by regenerative braking is another factor that can increase the vehicle sensitivity.

For the acceleration-modified cycles, on the other hand, there is insignificant change in engine usage and engine operating region with vehicle load. Consequently, the greatest vehicle fuel consumption sensitivity is observed for highway driving. The regenerative braking increases with driving aggressiveness, however, its impact on the vehicle sensitivity is not substantial.

The findings presented in this work provide useful inputs for optimal design of parallel HEVs for chosen drive cycles. The additional degrees of freedom in the HEV powertrain make it possible to adjust control strategy to specific velocity levels and acceleration rates so that the fuel consumption sensitivity is minimized.

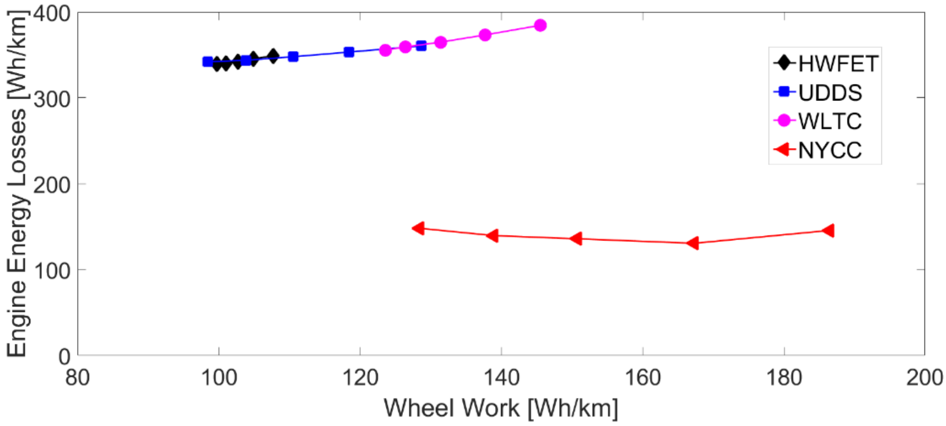

Figure 12. Engine energy loss versus wheel work for acceleration modified speed traces

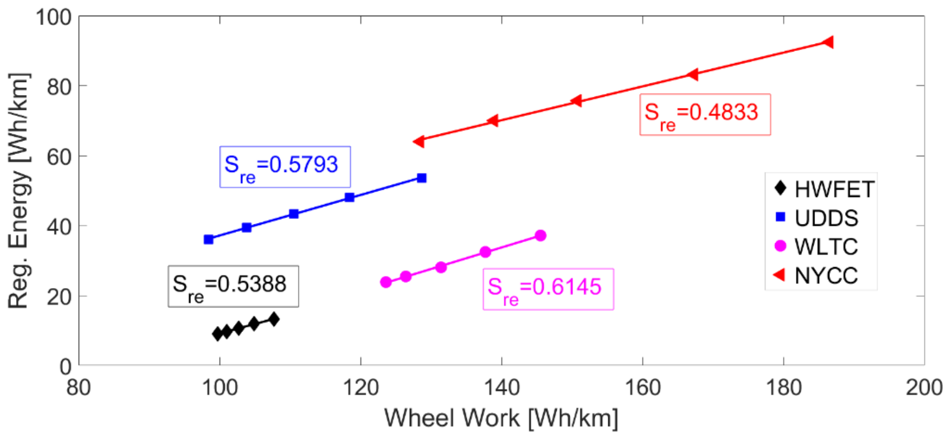

Figure 13. Regenerative energy versus wheel work for acceleration modified speed traces

Nomenclature

Abbreviation	Full Meaning
HEV	Hybrid Electric Vehicle
GHG	Green House Gasses
ICE	Internal Combustion Engine
EM	Electric Motor
HWFET	Highway Fuel Economy Test
UDDS	Urban Dynamometer Driving Schedule
WLTC	Worldwide harmonized Light vehicles Test Cycle
NYCC	New York City Cycle
NA	Naturally Aspirated
SI	Spark Ignition
SOC	State Of Charge

Symbol	Meaning
A, B, C	Coastdown coefficients
S_{fc}	Fuel consumption sensitivity
S_{aee}	Average engine efficiency sensitivity
S_{re}	Regenerative energy sensitivity

References

[1] Ehsani M., Gao, Y., Gay S. E., and Emadi A., *Modern Electric, Hybrid Electric and Fuel Cell Vehicles: Fundamentals, Theory and Design*, CRC Press, Boca Raton, Florida, 2005.

[2] Guzzella L. and Sciarretta A., *Vehicle Propulsion Systems: Introduction to Modeling and Optimization*, Springer, Berlin; New York, 2005.

[3] Erikson, E., Independent Driving Pattern Factors and Their Influence on Fuel-Use and Exhaust Emission Factor, *Transportation Research Part D Transport and Environment 6*, (2001), 5, pp.325-345, DOI: 10.1016/S1361-9209(01)00003-7.

[4] Raykin, L., Roorda, J. M., and MacLean H. L., Impacts of driving patterns on tank-to-wheel energy use of plug-in hybrid electric vehicles, *Transportation Research Part D: Transport and Environment* 17 (2012), 3, pp. 243-250, DOI:10.1016/j.trd.2011.12.002.

[5] Berry M. I., The Effects of Driving Style and Vehicle Performance on the Real-World Fuel Consumption of U.S. Light-Duty Vehicles, MSc Thesis, Massachusetts University of Technology, Boston, USA, 2010.

[6] Carlson, R.B. *et al.*, Drive Cycle Fuel Consumption Variability of Plug-In Hybrid Electric Vehicles due to Aggressive Driving, *in SAE World Congress & Exhibition*, Detroit, MI, USA, 2009.

[7] Sharer, P., Leydier, R., and Rousseau, A., Impact of Drive Cycle Aggressiveness and Speed on HEVs Fuel Consumption Sensitivity, *SAE Technical Paper* 2007-01-0281, 2007, doi: 10.4271/2007-01-0281.

[8] Feng L. and Chen B., Study the Impact of Driver's Behavior on the Energy Efficiency of Hybrid Electric Vehicles, *In ASME 2013 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference,* Portland, Oregon, USA, 2013.