Energy demand assessment for long term operation of hybrid electric vehicles

Lech J Sitnik¹,², Zdravko D Ivanov² and Zbigniew J Sroka¹

¹ Wroclaw University of Science and Technology, Department of Automotive Engineering, Wyb. Wyspianskiego 27, 50-370 Wroclaw Poland
² Technical University Varna, Transport Engineering and Technologies Dpt., Studentska 1, 9000 Varna, Bulgaria

³ E-mail: lech.sitnik@pwr.edu.pl

Abstract. This publication deals with the assessment of fuel demand for long-term operation of hybrid vehicles, because only with this kind of analysis it could be possible to clearly and unequivocally assess the actual progress in achieving the intended goals. The long-term test is the opposite of short-term tests – currently WLTP and RDE or other tests developed mostly by specialized magazines. Long-term car use means mileage measured in thousands of kilometers over a period of several years. The assessment of fuel consumption during long-term operation of HEVs from the presented point of view is new, in which the theory of demand for cumulated energy (as fuel) proved to be very useful. Mathematical models of fuel consumption along with an assessment of its intensity and a description of fuel economy constitute the vehicle’s “energy footprint”. Cumulative fuel consumption increases as mileage increases, but the increase is not a linear function. The discrepancy between fuel consumption in a group of vehicles of the same make and type is significant and increases as mileage increases. The average fuel consumption of the analyzed HEVs during their long-term operation significantly exceeds what is determined by the short tests, e.g. WLTP (and earlier NEDC). The actual fuel consumption is much higher than the one from the short tests.

1. Introduction

The average emission of all cars sold in the European Union in 2018 was 120.5 g CO₂/km. From 1 January 2020, 95 percent of cars sold within the European Union must meet the average maximum emission limit of 95 g CO₂/km. The European Commission proposes that in 2025 this value should be reduced by 15 % and in 2035 by 30 %. Targets are expressed in percentages because the new standard will have to be recalculated according to the new (more rigorous) WLTP emissions test [1].

The hopes associated with the WLTP test are greater because the discrepancies between the results obtained in the NEDC test compared to the real ones, were not respectively satisfying (were too large) [2] – shown in figure 1.

In 2001, the average CO₂ emissions, determined in the test (NEDC) were 170 g/km with a spread about of 20 g/km. In real life emissions were by 10 % higher.

In 2015, in the test (NEDC), is achieved reduction in the average values of emissions below 120 g/km. The dispersion also decreased to about 10 g/km. On the other hand, the average values from real operation differed from the test ones by over 40 % – which means that the actual progress in reducing emissions was unsatisfactory.
Figure 1. CO₂ emissions in test and real drive conditions over years (on the basis of data in [2]).

Despite this, especially in the opinion of the car industry, the European Commission proposals of reduction of CO₂ emissions targets for cars and vans for years 2025 and 2030, are criticized because they fail in 3 key respects:

1) The 30% reduction from 2021 to 2030 is far below the trajectory needed to achieve the "Paris Climate goals".

2) The regulation fails to require the supply of zero emission vehicles – instead this is only incentivized.

3) There is no mechanism to ensure emissions reductions are delivered on the road – not just in the laboratory – or that the 2021 baseline will be not manipulated.

The conclusion of 3) is very important for this publication. Such organizations as T&E [3], for example, are therefore proposing the following goals:

a) A 20% (instead of EC 15%) average CO₂ emissions reduction from new fleet of cars of each carmaker from 2021 to 2025, to apply to both cars and vans.

b) A 50-60% (instead of EC 30%) reduction of CO₂ emissions by 2030 – the target to be reviewed in 2022 to allow for sufficient lead time.

c) A 0g CO₂/km (zero g CO₂/km) target for 2035 – in order to have the time to indicate the required direction and speed relevant for improvement of industry solutions.

The inclusion of c) target is essential since it doubles the lowering of the anticipated carbon emissions by 2030. In the absence of target c), much less improvement is envisaged in new car and van CO₂ emissions between 2021 and 2025 and, as a result, the fleet will use more fuel (it will emit more CO₂) as if it were possible if the 2025 limit was introduced.

We could and should ask a question – is electricity really clean, i.e. is it CO₂ free? And, is the short test relevant for assessing energy (fuel) demand?

The answer to the last question is the key for all efforts to really reduce CO₂ emissions from transport.

For this reason, the paper is about energy demand assessment of long term operation of real hybrid vehicles in everyday conditions. The mileage is in thousands of kilometers over a period of several years measured. That is in contrast to short-term tests – such as WLTP [1] and RDC [4, 5] or various specialist tests [6-8].

The assessment of long term energy demand as a cumulative fuel consumption of HEV, from the presented point of view, is brand new concept. Therefore, there are no papers with direct discussion or
comparison of results. Also the earlier works of the authors are concerned with the use of the theory of cumulative fuel consumption for assessing fuel consumption of standard motor vehicles (e.g. [9-13]) but not HEVs. The authors’ experience lead to the conclusion that a description of fuel consumption in long term operation of HEV using the theory of cumulative fuel consumption makes sense. Very good adequacy of the mathematical models was obtained. Mathematical models of cumulative fuel consumption, the intensity of this consumption and specific fuel economy together form the vehicle's "energy footprint".

In chapter 3 the analysis of fuel consumption in the long term operation of HEVs of the same make and type are presented. The obtained analysis results seem to be interesting.

Chapter 4 contains the conclusions. The main one is that the theory of cumulative fuel consumption in long term operation is a very good tool for energy consumption analysis. That is only beginning. The analysis with the use of the theory, lead to much more interesting and unexpected next conclusions.

By assessing fuel consumption in the long term operation of vehicles over the years and thousands of kilometers then the question is, what methods for those assessments are sensible to use.

First of all it must be clearly defined – is the operational fuel consumption a linear function to the mileage. Maybe in some cases it is true, but there is not a base for this assumption for all cases in long term operation of vehicles.

Secondly, it should be clarified whether the fuel consumption determined in the test (e.g. WLTP) is appropriate to assess such consumption, but in standard long term operation. In particular the question is – can the test results be overstated or understated in relation to real life.

A typical, most used, factor for assessing the fuel consumption of cars during standard operation is e.g. fuel economy $FE$. This is calculated as a $dm^3/100km$ ratio (or in Anglo-Saxons countries as MPG – miles per gallon). An example of $FE$ values are given in figure 2.

![Figure 2. Typical results of fuel economy between refuelling HEV LEXUS GS 450h. Numbers on the figure right side are dedicated to the separate cars ams-test of fuel economy [14].](image_url)

The presented results of fuel economy between refueling are for HEV LEXUS GS 450h calculated. The fuel consumption and trip distance data are from the German website spritmonitor.de [14]. The data are publicly available for car with given code number. The technical data of the studied HEV Lexus GS 450h can be found in [15].
The results are from long term operation of cars, including urban, peri-urban and high way drive. When these results are compared with the short test, for example with ams-tests result for LEXUS GS 450h, the extensive discrepancies are visible.

The ams-ECO result is too low. Practically no driver (here analyzed) achieves such low fuel economy.

The ams-TEST average is too high vs. other values. Without statistical dispersion analyses it can be seen that the density of fuel economy (shown in figure 2) is between ams-ECO and ams-TEST placed.

The ams-MAX is on the one hand too low – they is higher fuel economy noticed. On the other hand it is perhaps too high because only some drivers achieved such high fuel economy. Figure 2 demonstrates that most results of fuel economy reach 9 liters per 100 km.

From these results, it is not possible to form an opinion about the real changes of fuel economy vs. mileage. The same results as in figure 2 are in figure 3, but with trends line (predictions) presented. All the trends are equivalent. It is not possible to decide which line is to be taken in account.

![Figure 3. Fuel economy and its trends over mileage.](image)

However, it seems that with increased mileage fuel economy also increase. That is very good to show by the linear trend ("A" in figure 3). In "B" case, fuel economy at the beginning decreases and then increases. In case "C", it is the opposite. There is not any clarity in assessing this possibility. Such clarity can be achieved if the theory of cumulative fuel consumption is used.

2. Theory of cumulative fuel consumption

As mentioned above, traditionally, if the energy demand of ICEV is analyzed, then the analyzed fuel consumption is expressed as fuel economy \((FE)\) in \(\text{dm}^3/100\text{km}\) or MPG. It is the same for HEV because the energy to drive a vehicle comes from the combustion of fuel in the internal combustion engine.

Through the assumptions that \(F_i\) – \(i\)-th refueling; \(t_{di}\) – mileage to \(F_n\) then the fuel economy can be expressed as:

\[
FE_i = \frac{100}{Fi} (t_{di} - t_{di-1})
\]  
(1)

By \(n\) refueling the average fuel economy \((FEA)\) can be expressed as

\[
FEA_n = \frac{1}{n} \sum_{i=1}^{n} FE_i
\]  
(2)
The cumulative fuel consumption to achieve mileage \( t_{dn} \) can be described as

\[
CFC(t_{dn}) = \sum_{i=1}^{n} F_i
\]  

(3)

A sample presentation of FEV data ([spritmonitor.de], vehicle code 783466) is shown in figure 4. The mileage of the car was in the range 181758 to 227713 of kilometers, in the time period 09.09.2016 to 02.03.2019.

Figure 4. Fuel consumption of analyzed middle class of HEV.

The fuel economy \((FE)\) in operation time changes between 8 and 11 dm\(^3\)/100km.

Figure 4 also presents the values of the average fuel economies (FEA). They are in the narrower range of 9 to 10 dm\(^3\)/100km. As the car mileage increases, the average fuel economy generally decreases (in the case of the data of this car).

The cumulative fuel consumption changes (quasi linear) from 16472 to 20532 dm\(^3\).

Without knowledge of any functional relationship describing cumulative fuel consumption as a function of time, (and traditionally as a function of vehicle mileage), it is not possible to answer such a simple question as: Is it really a quasi-linear function or another relationship?

A function is therefore sought

\[
CFC = f(Mileage)
\]  

(4)

The answer to the above question is given by the theory of cumulative fuel consumption.

The consumption of fuel by a car, in its natural operation, is a random process. It is described in a quantum model. Fuel quanta has a random size. Random size has also time between the quanta of fuel consumption. The ratio of the total amount of quanta of fuel supplied by the car engine in its operating period to the time \( t \) is called cumulative fuel consumption and can be determined as follows:

\[
CFC(t) = \sum_{i=1}^{n(t)} f_i = n(t)\bar{f}(t)
\]  

(5)

where \( f_i \) – \( i \)-th quantum of fuel, \( \bar{f}(t) \) – the average size of the quantum of fuel supplied for time \( t \), \( n(t) \) – fuel quantum number supplied for time \( t \), \( CFC(t) \) –cumulative fuel consumption for time \( t \).

After many transformations, described in detail in [3], and assuming that the time between successive quantum of fuel is described by the Poisson distribution [7] there is a relationship

\[
CFC(t) = ct^{a+1}
\]  

(6)

where: \( c, a \) – constants.
This is a relatively simple relationship describing cumulative fuel consumption as a function of time. On the assumption that mileage \( t_d \) is proportional to operation time \( t \) is, also \( (t \rightarrow t_d) \), the relationship (6) can be shown in the form (7)

\[
CFC(t_d) = ct_d^{a+1}
\]

The intensity of the cumulative fuel consumption is Derivative of the cumulative energy consumption based on the vehicle engine run time \( t_d \).

\[
ICFC(t_d) = \frac{dCFC(t_d)}{dt_d} = c(a + 1)t_d^a
\]

The intensity of the cumulative fuel consumption takes infinitely large values, when \( a < 0 \) and at the same time where \( t_d \rightarrow 0 \) and almost immediately after the beginning of the trip (but it decreases rapidly when the travelled distance increases). By \( t_d \neq 0 \) the ICFC not exist.

To analyze the specific cumulative fuel consumption there exists a new relationship

\[
SCFC(t_d) = \frac{CFC(t_d)}{t_d} = ct_d^a
\]

The \( SCFC(t_d) \) can be expressed in \( \text{dm}^3/\text{km} \) or parallel to fuel economy as \( FEC \) in \( \text{dm}^3/100\text{km} \) or MPG.

\[
FEC(t_d) = 100 \frac{dCFC(t_d)}{t_d} = 100ct_d^a
\]

Constants \( c \) and \( a \) can be derived from the data obtained from the use of vehicles in natural operation.

With the data presented earlier for car of the HEV 783466 type the achieved coefficients \( c \) and \( a \) are the following: \( c = 0.107235 \), \( a = -0.013887 \).

Knowing coefficients \( c \) and \( a \), it is possible to present all above mentioned indicators regarding fuel consumption to present. Graphic illustration of their course is as follows (figure 5).

![Graphic illustration of course of cumulative fuel consumption and its intensity for HEV 783466.](image)

Figure 5. Graphic illustration of course of cumulative fuel consumption and its intensity for HEV 783466.

The correlation between the measurement points and mathematical model points (for \( CFC \)) gets unexpected high values. That is also confirmed by the statistical coefficients (table 1).
Table 1. Results of statistical analysis of the correlation of mathematical model (7) for cumulative fuel consumption of HEV 783466.

|                  | Value          |
|------------------|----------------|
| Multiple R       | 0.999968       |
| R Square         | 0.999936       |
| Adjusted R Square| 0.999935       |
| Standard Error   | 0.000524       |
| Observations     | 82             |

The data presented can be considered sensational. This is not an exception – as was presented earlier in [9-12].

It is worth noting the relatively steep decrease in the intensity of cumulative fuel consumption (ICFC), however it is worth noting the axle values, which are contained within very narrow limits. However, based on these data, it can be concluded that this intensity although slightly decreases as the mileage increases.

It was mentioned earlier that the presented indicators are a kind of "footprint" regarding the fuel consumption of a vehicle. For HEV 783466 this "footprint" is shown in figure 6.

![Figure 6. Energetic (fuel consumption) footprint of HEV 783466.](image)

The cumulative fuel consumption for a mileage to 350,000 km gets a quasi-linear function. In reality it is not a linear relation. Also fuel economy decreases with the increase in mileage. However, this change does not exceed 1 dm³/100 km.

3. Results and discussion

The data for fifteen HEVs were used for further analysis to determine the energy footprint of each analyzed vehicle and on this basis also for brand and type of analyzed cars.

The calculations results are presented in figure 7.
The points lying on the cumulative fuel consumption curves correspond to the individual refueling of the vehicle.

There are values of coefficients $c$ and $a$ in table 2 in addition to the results of the statistical analyses of the model (7) adequacy for all analyzed HEVs.

### Table 2. Results of the statistical analysis of the correlation of mathematical model (7) for cumulative fuel consumption of the analyzed HEVs.

| No of probe | HEV code    | Coefficients | Statistics | Numbers of Observations |
|------------|-------------|--------------|------------|-------------------------|
|            |             | $c$          | $a$        | Multiple R | R-Square | Adjusted R-Square | Standard Error |                     |
| 1          | 623705      | 0.110896     | -0.013202  | 0.999791   | 0.999582  | 0.999579        | 0.004213       | 152                   |
| 2          | 952413      | 0.095743     | -0.002292  | 0.999795   | 0.999590  | 0.999561        | 0.000306       | 16                    |
| 3          | 661433      | 0.136929     | -0.033048  | 0.999567   | 0.999135  | 0.999124        | 0.003724       | 86                    |
| 4          | 552031      | 0.114006     | -0.021083  | 0.999649   | 0.999299  | 0.999290        | 0.030652       | 80                    |
| 5          | 783466      | 0.107235     | -0.013887  | 0.999968   | 0.999936  | 0.999935        | 0.000524       | 82                    |
| 6          | 760085      | 0.075480     | 0.015431   | 0.999407   | 0.998814  | 0.998781        | 0.002653       | 38                    |
| 7          | 951879      | 0.098589     | -0.007028  | 0.999387   | 0.998775  | 0.998722        | 0.000544       | 25                    |
| 8          | 866805      | 0.093372     | -0.004373  | 0.999620   | 0.999240  | 0.999224        | 0.001724       | 48                    |
| 9          | 762765      | 0.089745     | -0.001666  | 0.999951   | 0.999902  | 0.999901        | 0.009157       | 113                   |
| 10         | 762679      | 0.091714     | -0.003779  | 0.999963   | 0.999925  | 0.999924        | 0.000993       | 66                    |
| 11         | 760055      | 0.078709     | -0.004642  | 0.999964   | 0.999928  | 0.999926        | 0.000306       | 37                    |
| 12         | 919425      | 0.083097     | -0.005624  | 0.999541   | 0.999082  | 0.998929        | 0.00643        | 8                     |
| 13         | 906113      | 0.082063     | -0.006025  | 0.999907   | 0.999814  | 0.999808        | 0.003360       | 37                    |
| 14         | 608498      | 0.196559     | -0.064007  | 0.998123   | 0.996250  | 0.996136        | 0.066573       | 35                    |
| 15         | 694074      | 0.147210     | -0.018636  | 0.999872   | 0.999745  | 0.999743        | 0.001095       | 160                   |

The adequacy of model (7) is very high in all cases.
The course of CFC is quasi linear (it would be linear if factor $a = 0$). It is interesting that in case of the HEV 760085 the course has got another character as for the rest of analyzed cars have.

Some waveforms (e.g. HEV 694074) clearly differ from others. However, this is neither a mistake in entering the data nor a calculation error. These data reflect the operating conditions.

Knowing the mathematical model (vehicle energy footprint), we can approximate virtually the fuel amount for any mileage, because the prediction of the mathematical model gets very high.

The presented data shows a large dispersion of cumulative fuel consumption courses (although the vehicles of the same brand and type analyzed). This dispersion increases with the increase of the vehicle mileage (figure 8).

With the data on the vehicle group, various statistical analyzes can be carried out. Figure 8 presents not only the averages values of CFC and FEC but also the confidence intervals for these averages.

It is clear that the cumulative fuel consumption is not constant over the long term of use of the vehicle. Generally, there is an opinion that that fuel economy increases as the vehicle mileage increases, while in most cases presented here it decreases. Therefore without clear analysis with mathematically based on-line methods, assessment of real fuel consumption is difficult.

Figure 8. CFC and FEC of analyzed HEVs.

Knowing the long term fuel economy, for a specific make and type of cars, broader analyses are possible. An example of data (for LEXUS GS 450h) for further analysis is given in figure 9.

Figure 9 shows the results of fuel economy from long and short term operation.

The data of FEC are the long term result. Other data are for the short term. They are presented so because it is believed that the results of short tests (for example WLTP) are valid for the whole life of the vehicle.

The FEC data in figures 8 and 9 differ slightly. Figure 8 gives the average FEC and confidence interval for this mean. Figure 9 shows the average and the range of volatility. The volatility range is slightly wider than the confidence interval.
It is interesting that the results are very close to the average ones determined for a randomly selected group of 15 vehicles. This is of course accidental. In principle, however, this confirms the sense of using the presented methods of fuel consumption assessment.

The introduction of WLTP slightly improves the situation, but still the test results are lower in relation to the values obtained in natural exploitation of cars. They do not even fall into a wide range of volatility. If the results of other analyses confirm this, it will mean that work on the WLTP test should be carried out permanently.

4. Conclusions

One of the many important challenges of the modern world is the reduction of CO₂ concentration in the ambient air. Various actions are taken, including in the area of transport, in which the internal combustion engine still occupies a leading place among the sources of propulsion.

To eliminate the effects of internal combustion engines, hybrid vehicle technologies are developing relatively quickly, in which CO₂ emissions are reduced by reducing fuel consumption. However, the question arises how to assess the energy efficiency of hybrid vehicles?

The authors of this publication have undertaken to indicate a new approach to the energy assessment of the use of HEVs.

The method refers to the assessment of fuel consumption during the long-term operation of vehicles, which will ensure that only then will it be possible to properly assess the progress in achieving the intended goal of reducing CO₂.

This assumption is in opposition to the use of short-term tests – currently WLTP and RDE or various tests created by the editors of popular car magazines. The presented point of view is relatively new.

The work concerns the method of assessing fuel consumption in the long-term operation of hybrid vehicles. The assessment method is based on the theory of cumulative fuel consumption. The theory of cumulative fuel has proven to be very useful.

Data from long-term operation of 15 randomly selected HEVs of the middle class were taken for calculations. Very good adequacy of mathematical models was obtained. The R-Square ratio ranged from 0.99625 to 0.99994, which was an unexpectedly positive high value.

Mathematical models of cumulative fuel consumption, intensity of this fuel consumption and fuel economy together form the vehicle's "energy footprint". The footprint is individual for each car.
The cumulative fuel consumption, as the average for specific make and type of cars, increases as mileage increases, but the increase is not linear. The discrepancies between the fuel consumption in the vehicles group (the same brand and type) are large and increase as mileage increases.

The average fuel consumption of analyzed HEVs in their long-term operation, exceeds significantly what is determined in short tests, e.g. WLTP (and earlier NEDC).

The real fuel consumption is significantly higher than the one obtained by short tests. On the other hand the results are positive –fuel consumption is lower in long term operation in comparison to the average one – published in magazines, from their short tests.

Use of the presented methodology is possible to compare the fuel consumption of the same make and type cars with and without a hybrid drive. The result should be given as information on the real sense of HEV implementation, especially in the aspect of CO₂ reduction. The relevant operation data is collected. A comparison work will be presented in Authors’ near future publications.

References

[1] Younes Z, Boudet L, Suard F, Gerard M and Rioux R 2013 Analysis of the main factors influencing the energy consumption of electric vehicles Electric Machines & Drives Conf. pp 247–53

[2] Tietge U, Diaz S, Mock P, German J, Bandivadekar A and Ligterink N 2016 From laboratory to road. A 2016 update of official and real-world fuel consumption and CO₂ values for passenger cars in Europe ICCT White Paper

[3] Earl T, Ambel C, Poliscanova J, Murphy A, Abasov F, Nix J and Buffet L 2020 How European transport can contribute to an EU -55% GHG emissions target in 2030 Transport & Environment

[4] Holmén B and Sentoff K 2015 Hybrid-electric passenger car carbon dioxide and fuel consumption benefits based on real-world driving Environ. Sci. Technol. 49(16) 10199–208

[5] Mock P 2017 Real-driving emissions test procedure for exhaust gas pollutant emissions of cars and light commercial vehicles in Europe Int. Counc. Clean Transp. pp 1–10

[6] Bennion K and Thornton M 2009 Fuel savings from hybrid electric vehicles Technical Report NREL/TP-540-42681

[7] Heejung J 2020 Fuel Economy of plug-in hybrid electric and hybrid electric vehicles: effects of vehicle weight, hybridization ratio and ambient temperature World Electr. Veh. J. 11(2)

[8] Kyoungho A and Hesham A 2019 A simple hybrid electric vehicle fuel consumption model for transportation applications (IntechOpen)

[9] Sitnik L 2004 Cumulated fuel consumption Archiwum Motoryzacji 7(3) pp 227–54

[10] Sitnik L 2009 Cumulated LPG consumption supplied of cars engines J. of KONES 16(4) pp 429–34

[11] Sitnik L 2014 Theory of cumulative fuel consumption and example for its application 22nd Int. Sci. Tech. Conf. Trans&Motauto pp 17–20

[12] Sitnik L 2015 Theory of cumulative fuel consumption by LPG powered cars J. of KONES 22(4) pp 275–80

[13] Sitnik L 2004 Ekopaliwa silnikowe Oficyna Wydawnicza PWr pp 0–336

[14] https://www.spritmonitor.de Accessed on: 15.02.2020

[15] https://www.lexus.com Accessed on: 15.02.2020