ISSN: 1231-4005
e-ISSN: 2354-0133
DOI: 10.5604/01.3001.0012.4811

CHARACTERISTIC FEATURES OF THE PROCESS OF GROWTH IN THE MILEAGE OF HYBRID VEHICLES

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Abstract

For a few years, the sales of motor vehicles with hybrid drive systems (referred to as "hybrid vehicles" or "HVs") have been rapidly growing. However, there is a lack of information about the intensity of operation of vehicles classified in this category, which is completely new. A calculation procedure has been presented that enabled evaluation of the HV mileage growth rate. An analysis of this rate provides grounds for forecasting the changes that are likely to take place in the fleet of motor vehicles, such as the progress in the process of replacement of conventional vehicles with vehicles with alternative drive systems, and this may be a basis for predicting the reduction in fuel consumption and exhaust emissions. Models of the HV mileage growth process have been defined for three different countries. They indicate high mileage growth rates in the initial period of vehicle operation, e.g. until the fourth year of operation of the Auris H cars. The highest mileage growth rates in this period were observed in the Netherlands and Poland. In Germany, this rate was lower by 41%. Significant differences in the intensity of vehicle operation have been observed between the behaviour of HV owners in the countries under analysis. A considerable drop in the annual HV mileage as early as in the fifth and sixth year of vehicle operation is an alarming signal.

Keywords: *hybrid vehicles, mileage of hybrid vehicles, estimation of mileage growth models*

1. Introduction

A strong growth in the prices of diesel oil and petrol in 1997-2005 (from USD 0.7 to USD 1.5, on the average, for 1 dm^3) [16] and increasing importance of the social and ecological impacts on people's awareness contributed to the development of hybrid drive systems of motor vehicles. Such systems make it possible to cut down fuel consumption and, in consequence, to reduce exhaust emissions and vehicle operation costs. An analysis of the market of hybrid vehicles (HVs), where the intensity of operation of such vehicles was observed, has resulted in interesting findings:

- Toyota hybrid vehicles predominate: their share in the sales is rapidly growing; in 2016, it reached 37% of the sales of motorcars of this make [3].
- The main markets for HVs are Japan and the USA; as regards the EU countries, the Netherlands should be considered the leader.
- In 2001-2015 [3, 18], the share of HVs in the motorcar sales in the EU markets grew from 0.1% to 1.8%; in the Netherlands, it reached about 4% in the same time.
- The HV sales are to be intensively increasing until around 2030, after which the demand for such vehicles will stabilize, according to expectations [1]. However, the estimated levels of the stabilization are very diverse; in author's opinion, the forecast of 20-25% of the sales of new cars in the USA seems to be quite convincing.

The models that predominate in the European HV market are small or compact cars, such as Toyota Auris, Prius, Yaris, and Lexus CT 200h. Their technical specifications are very close to each other. In 2012, the Auris II model appeared on Toyota's offer. Its powertrain is identical to that of Prius III with a 1,800 cc internal combustion (IC) petrol engine.

The effects of encouraging people to environment-friendly behaviour, e.g. to the use of HVs rather than vehicles with conventional drive systems, are usually presented by quoting numerous statistics of sales of new hybrid vehicles [11]. The information like this is incomplete, because it only shows the presence of such cars in the market, while the actual measure of the use of motor vehicles is their mileage. Alas, numerical data on HV mileage in the EU are hardly available. There are many publications where the mileage of motor vehicles with conventional drive systems is analysed, above all in respect of the assessment of insurance risk [5, 12], exhaust emissions [10], or fuel, tyres, and spare parts costs [17]. However, the intensity of operation of such vehicles has been declining in the recent years [3, 8, 15].

Models of the mileage growth process are the main source of information for forecasting calculations concerning the trends and values of the indicators that help to manage the operation of a motor vehicle fleet and provide anticipating information on the state of the secondary market of motor vehicles, on the rate of approaching the target mileage, and on the time of cost-effective vehicle use. Such models may also be an important source of information on current changes in fuel consumption and exhaust emissions [2, 9].

2. Objective and explanation

The work was chiefly undertaken to obtain numerical data that would characterize the intensity of operation of hybrid vehicles. A calculation procedure has been presented that enables an analysis and evaluation of the HV mileage growth process. The calculation results obtained apply to a special period, when a high rate of growth in the number of HVs was observed in several markets, such as the USA, Japan, and the Netherlands. Simultaneously, the number of hybrid vehicles in many countries has already reached a level that makes it possible to carry out statistical examinations of the processes taking place.

An analysis of the mileage growth process provides grounds for drawing conclusions about important changes in the motor vehicle market, including progress in the processes of replacement of conventional vehicles with vehicles with alternative drive systems, and for evaluating the processes of changes in fuel consumption and exhaust emissions. The analyses of this kind are of considerable economic and social importance for the selection of marketing strategies and possible economic interventions aimed at further promotion of the factors that would help to maintain the high rate of growth in the demand for HVs. The models having been developed will facilitate the analysis of the mileage growth rate and will help to identify the main trends in successive periods of operation of vehicles classified in a category that is completely new, i.e. hybrid vehicles. The calculation procedure has been based on the experience having already been gained by the author in this field [13, 14].

In this work, the intensity of operation of the Auris and Yaris hybrid vehicles, provided with petrol engines and electric motors powered from a battery of nickel-metal hydride (NiMH) cells has been analysed. The vehicles have been denoted by "Auris H" and "Yaris H", respectively (Tab. 1). Their range when exclusively driven by the electricity drawn from the batteries is up to 2 km at a speed not exceeding 50 km/h.

3. Calculation methods

The calculations were carried out with using numerical data collected for the years 2016-2018, put together in [6], and made available in a part for publication needs. The said data part that was published applied to the markets of three countries, i.e. the Netherlands, Germany, and Poland, and included data provided in offers for the sales of 2,500 hybrid vehicles manufactured in the period 2010-2016. An example of the information obtained from the dataset has been presented in Fig. 1, where the distribution of the mileage values around the national average has been shown. This distribution has been illustrated with taking as an example the monthly mileage value (denoted by "PM"), which was calculated as follows:

$$PM_i = \frac{L_i}{t_i}, \tag{1}$$

$$\overline{PM} = \frac{1}{N}\sum_{i=1}^{N} PM_i\,, \quad \overline{\overline{PM}}_i = \frac{PM_i}{\overline{PM}}100\%\,, \tag{2}$$

where: L_i is the mileage of the i^{th} vehicle (expressed in kilometres [km]), N is the number of the vehicles under analysis, and t_i is the vehicle operation period (expressed in months).

Tab. 1. Technical specifications of the HVs under analysis

Parameter	Auris H	Yaris H
Curb mass [kg]	1,310-1,465	1,085-1,095
Gross vehicle mass [kg]	1,815-1,865	1,565
Wheelbase [mm]	2,600	2,510
Rated power capacity of the IC engine and electric motor [kW]	73+60	54+45
Cubic capacity of the IC engine [cm^3]	1,800	1,500
Battery voltage [V]	201.6	144
Battery mass [kg]	41	31

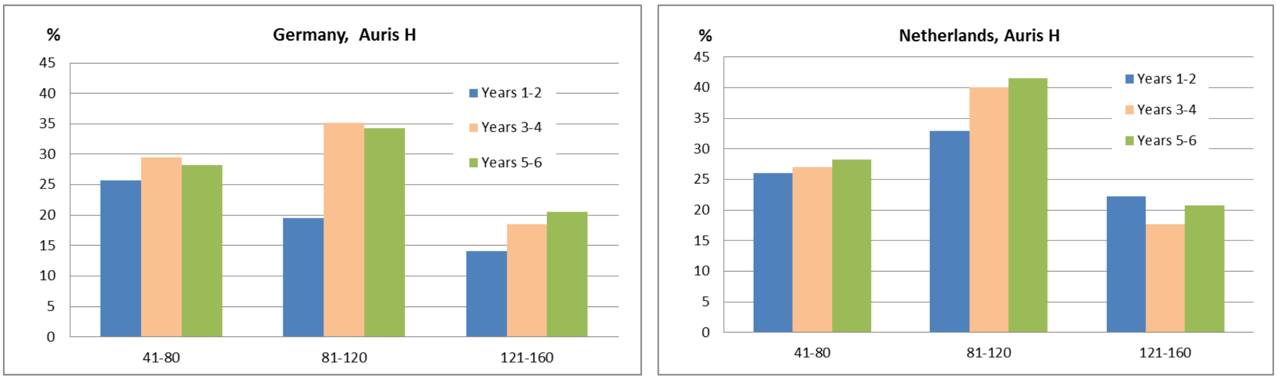

Fig. 1. Percentage grouping of the Auris H cars in the three central intervals of the percentage $\overline{\overline{PM}}_i$ values

The $\overline{\overline{PM}}_i$ values having been calculated were divided into intervals: < 40%, 41-80%, 81-120%, 121-160% and > 160%. The numbers of the vehicles whose mileage fell within each of the three central intervals have been shown in Fig. 1 in the form of their percentage values in relation to N.

The distribution of the monthly mileage values confirms the very wide scatter of the mileage of individual vehicles after their operation periods of the same duration. This wide scatter has an impact on the course of subsequent calculations. In consideration of the above and of results of the works reported in [4, 13, 14], the following procedure of data analysis was adopted:

- preliminary analysis of the data, with dividing the dataset into subsets;
- estimation of the average mileage values in individual subsets, with determining the coefficient of variation;
- removal of outliers;
- approximation of the relation between the mileage and the vehicle operation time;
- estimation of an averaged function of mileage growth.

In the calculations, the following notation was adopted for the basic quantities:

X, M, S – arithmetic mean, median, and standard deviation, respectively,
W – relative coefficient of variation,
R – coefficient of determination.

The HVs whose operation time t_i was within the interval:

$$T_k < t_i \le T_{k+1}, \tag{3}$$

were counted in the k^{th} subset. The vehicles were divided into subsets where the vehicle operation time fell into consecutive vehicle operation time intervals with a span of $T_0 = 12$ months each. The vehicle mileage L was treated as a random variable and L_i was the i^{th} value of this variable. The following operations were carried out in the subsets:

– the mileage values were arranged in ascending order to form a series $L_{0k}\{L_1, \ldots, L_i, \ldots, L_m\}$,
– the following estimators were calculated: arithmetic mean $X_{0k}(\tau_k)$, median $M_{0k}(\tau_k)$, and relative coefficient of variation $W_{0k}(\tau)$ as the following quotient:

$$W_{0k} = \frac{S_{0k}}{X_{0k}}, \tag{4}$$

where S_{0k} is standard deviation and τ_k is the central value of the vehicle operation period in the k^{th} subset.

In result of these calculations, the following sets of discrete values were obtained:

$$X_0\{X_{0k}(\tau_k), k = 1, 2, \ldots, n\},\ M_0\{M_{0k}(\tau_k), k = 1, 2, \ldots, n\},\ W_0\{W_{0k}(\tau_k), k = 1, 2, \ldots, n\}. \tag{5}$$

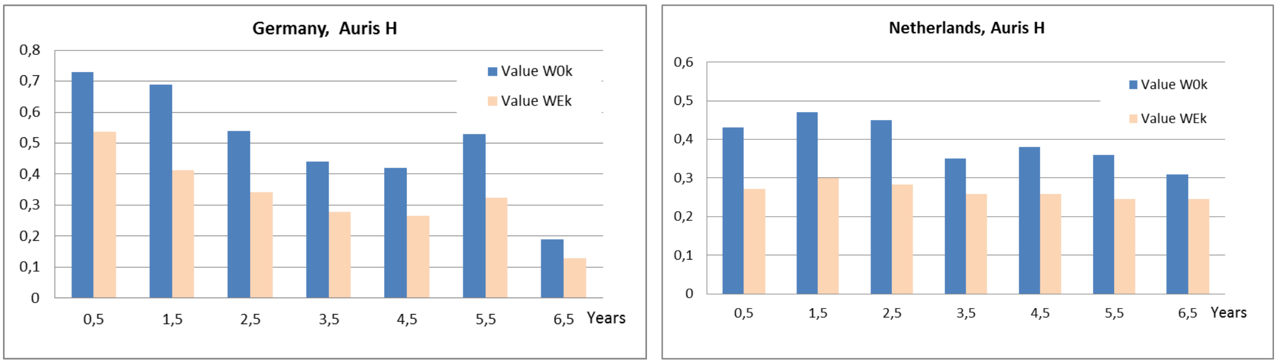

Fig. 2. Summary of values of the coefficient of mileage variation W_{0k} and W_{Ek} (example for the Auris H car), for the meaning of the symbol "Value WEk" see the text

The high W_{0k} values presented in Fig. 2, calculated from the data gathered in the L_{0k} subsets, confirm the excessive scatter of the mileage values. This means that the average in a subset not always adequately characterizes the mean mileage level. Therefore, an operation was carried out to clear the subsets of outliers. Actually, 10% of the first and last members of the L_{0k} series were removed. Thus, subsets denoted by L_{Ek} were obtained, which were then used for determining $X_{Ek}(\tau)$ and $W_{Ek}(\tau)$. The result of these calculations has been shown in Fig. 2 ("*Value WEk*"); it confirms the fact that the value of coefficient W was definitely reduced by the removal of outliers. Afterwards, a transition from the set of discrete averaged values M_0 and X_E to a continuous function was done by going through a process of approximation based on regression lines. Thus, the following functions were obtained, which described the growth in vehicle mileage with vehicle operation time (an example has been shown in Fig. 3):

$$\hat{y}_a = f_a(\tau). \tag{6}$$

In consideration of strong dependence of the course of regression lines on the degree of the approximating polynomial and on the number of the data available and on their nature, the approximating functions were determined by selecting models with 2nd and 3rd or 4th degree polynomials:

$$\hat{y}_{E,M} = f_{E,M}(\tau), \tag{7}$$

where subscripts $_E$ and $_M$ inform about using the values of X_E or M_0, respectively, to the calculations according to (7).

Altogether, four approximating functions were calculated for each of the countries and HV makes under analysis. In Fig. 3, the example curves representing the approximating functions have been denoted by "*Polynomial XE*" and "*Polynomial M0*" as appropriate and the numerals added to these symbols inform about the degree of the polynomial used. The values of the R^2 coefficient for the models based on the 2nd degree polynomials are 0.82-0.94; for the 3rd and 4th degree polynomials, they are within a range of 0.85-0.98.

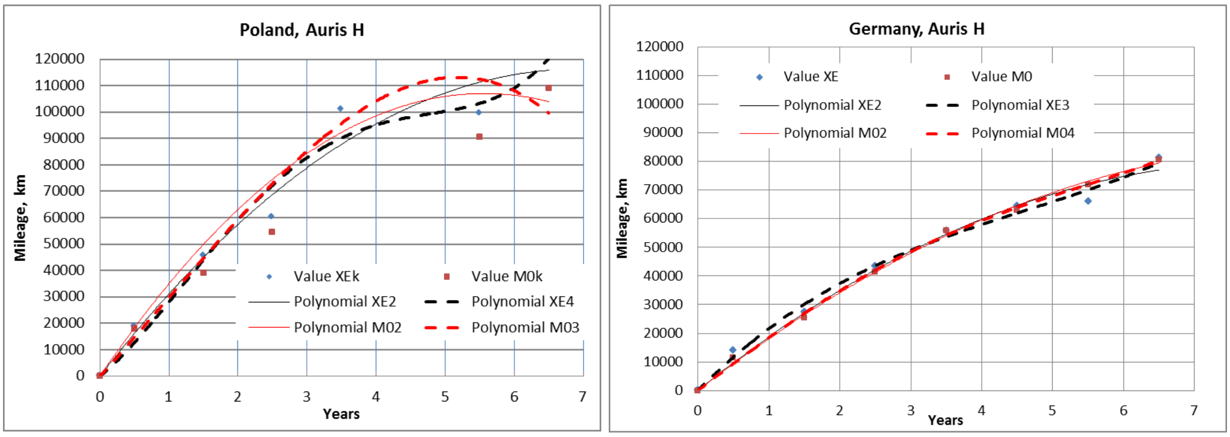

Fig. 3. Examples of the curves representing the approximating functions calculated according to (7)

The estimation of the vehicle mileage growth models burdened with the smallest possible error was based on the combined use of approximating functions (7) for determining averaged functions on these grounds. The method of moving average (calculated from e.g. the four approximating functions shown in Fig. 3) was used to estimate the averaged approximating function

$$\hat{y}_A = f_A(\tau). \tag{8}$$

4. Calculation results and discussion

Figures 4 and 5 show averaged approximating functions, which are treated in the subsequent part of this work as estimators of the HV mileage growth model. The points that represent the values obtained at intermediate stages of the calculations, i.e. $X_{0k}(\tau_k)$, $M_{0k}(\tau_k)$, and $X_{Ek}(\tau_k)$, as well as results of averaging the approximating functions (7) by the method of moving average have also been plotted in the graphs. The averaging results have been denoted by words "Auris" and "Yaris" as appropriate. The arrangement of the said points in relation to the mileage growth model provides grounds for the following statements:

– the mileage growth models having been determined are very close to the results of calculations of the arithmetic mean and median of the mileage values recorded for the Auris H and Yaris H cars in the Netherlands and Germany,
– the intermediate calculation results based on data on the HV mileage in Poland are characterized by a wide scatter already after the second year of vehicle operation; this particularly applies to the Yaris H mileage data, which resulted in limiting the mileage growth model to the first four years of vehicle operation although the R^2 coefficient values were within a range of 0.96-1.

It can be seen in the graphs that in the case of the Auris H car, the mileage growth rate remained high until the fourth year of operation of these vehicles. The highest values of this rate were recorded in the Netherlands (23 500 km/a) and Poland (24 600 km/a). In Germany, this rate was lower (14 800 km/a). In the next years, this rate considerably dropped, e.g. by more than 70% in Poland and 41% in Germany. Similar trends were observed in the Yaris H mileage growth rates. In the case of these cars, however, the annual mileage values were definitely lower, which also applied to the early vehicle operation period (up to 4 years). These values ranged from 11 900 km/a in Germany through 15 700 km/a in Poland to 16 600 km/a in the Netherlands.

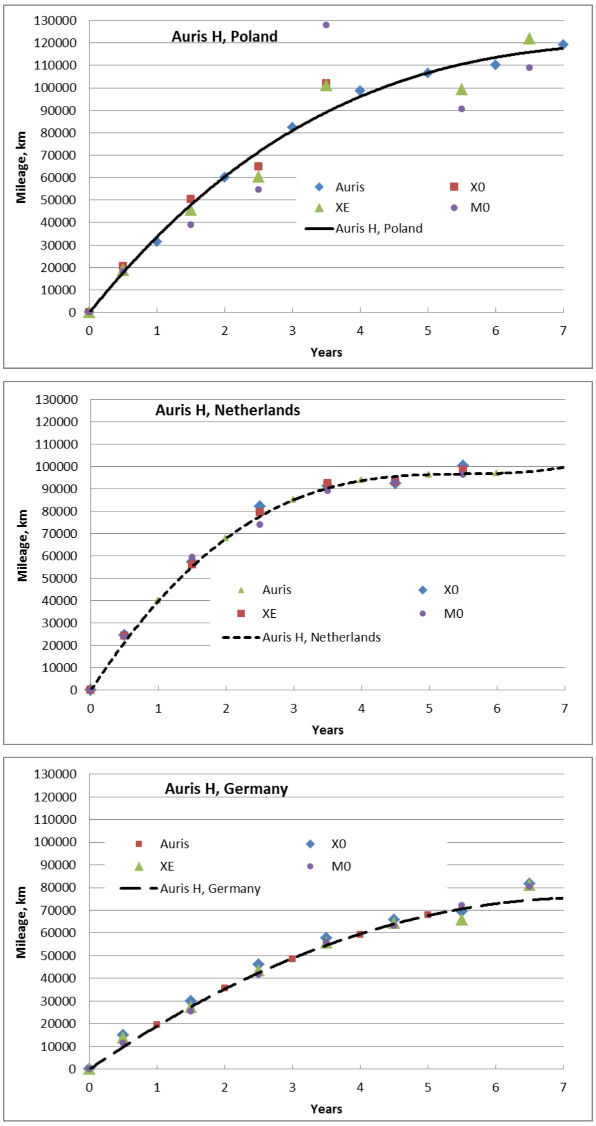

Fig. 4. Auris H mileage growth process

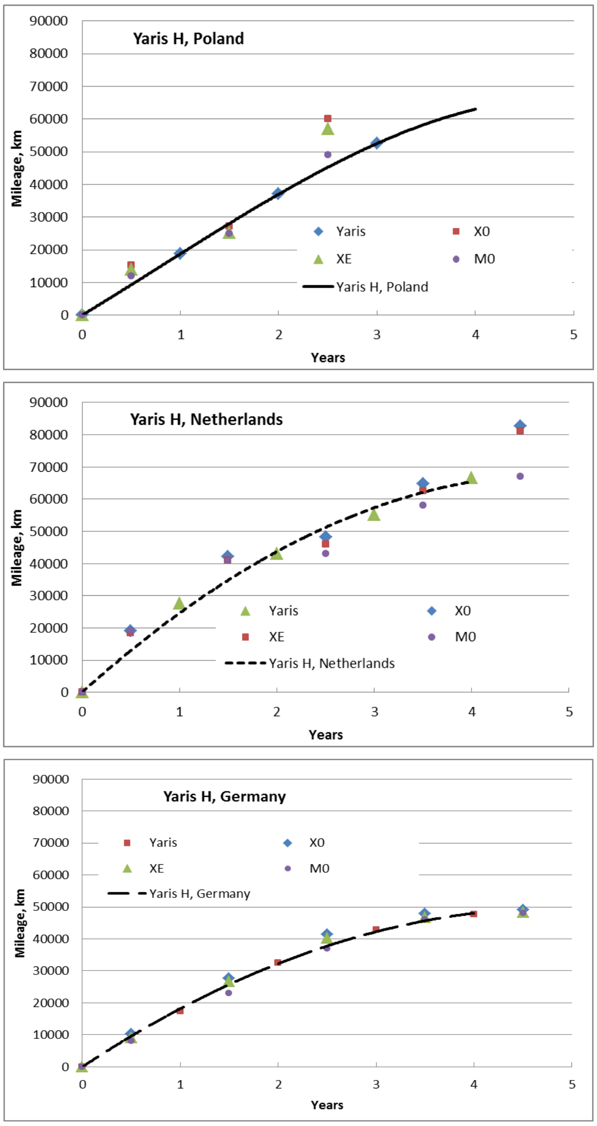

Fig. 5. Yaris H mileage growth process

5. Recapitulation

In this work, numerical data gathered in [6] were used. A fragment of these data based on observations of three characteristic European markets was obtained from the data administrator. A several-stage estimation process was carried out, in result of which models of hybrid vehicle (HV) mileage growth were obtained that were burdened with the smallest possible error in spite of a wide scatter in some data taken for the calculations. This made it possible to reveal a few characteristic features of the HV mileage growth process as described below:

1. A high mileage growth rate could be observed until the fourth year of operation of the

Auris H cars in the Netherlands and Poland; this rate was almost twice as high as that recorded in Germany.

2. In the next years of operation of the Auris H cars, their annual mileage values dropped by more than 41% in Germany and 70% in Poland. This means that the Auris H cars are bought in the Netherlands and Poland by people interested in high annual mileage, the values of which are almost twice as high as those considered typical for passenger cars with conventional drive systems.
3. The Yaris H cars are also intensively operated, but their annual mileage values are lower by over 30% than those of the Auris H cars are.
4. The high values of the annual mileage in the Netherlands and Poland and the moderate annual mileage values in Germany show that the intensity of operation of such vehicles depend to rather a small degree on the amounts of promotion payments or reliefs and to a higher degree on users' opinions on the actual vehicle operation costs.
5. After four years of intensive vehicle operation, the annual mileage of the Auris H cars drops to about 10 000 km/a, i.e. to a level similar to that recorded during a five-year observation period (2009-2013) in Japan, where the annual mileage of HVs aged 5 years averaged out at 10 019 km/a [7].

Other research results show that HVs are chiefly bought by the people who daily and annually travel definitely longer distances than others do. This difference in the mileage covered by HVs and vehicles with conventional drive systems is about 20% in Japan and 10% in the USA [4].

The availability of vehicles with hybrid powertrains in European countries is comparable with that of conventional vehicles, but the interest in purchasing such vehicles and the intensity of their operation are very diverse. The observed considerable drop in the annual mileage values as early as in the fifth or sixth year of HV operation is an alarming signal. It may show that the forecasted changes in the structure of the fleet of passenger cars will not be very big and will not come very soon [1, 2, 11].

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Manuscript received 10 July 2018; approved for printing 12 October 2018