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INTENSITY OF USE OF HYBRID VEHICLES DURING THE INITIAL PERIOD OF THEIR OPERATION

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Abstract

Extensive environmental protection activities include the promotion of alternative drive systems for motor vehicles. An important role in this field is played by hybrid vehicles, with their low operation costs being a strong marketing argument. Can such economies be conducive to the intensity of use of hybrid vehicles compared with vehicles with conventional drive systems? To answer this question, the intensity of use of hybrid vehicles was observed in a few different countries. The attention was focused on the occurrence of extreme (very low and very high) mileage values within comparable vehicle groups.

The survey carried out has revealed distinct differences in the intensity of use of hybrid vehicles compared with motor vehicles with conventional drive systems (IC). The average mileage values for hybrid vehicles are higher than those recorded for conventional ones during the same period, but this difference can only be seen in the initial period of vehicle use, rapidly decreasing with vehicle operation years. The share of vehicles with extreme mileage values recorded during the period under observation, presented in the paper in several ways, declines with the years of vehicle use. In spite of that, however, the percentage of vehicles with extreme mileage values is high in HVs group against IC.

Keywords: hybrid vehicles; intensity of vehicle operation; mileage of hybrid vehicles; extreme vehicles' mileage; satisfaction of hybrid vehicles buyers

1. Introduction

The numerous available forecasts about hybrid vehicle sales [10, 18, 22] are optimistic, which is also reflected in the estimated reductions in combustion gas emissions. This can be seen especially in the forecasts prepared for highly developed countries, e.g. Japan [5]. However,

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the actual sales statistics are lower than anticipated in the forecasts [4, 18]. Despite, the introduction of alternative drive systems is commonly seen as a basic means to achieve significant reductions in the CO_2 emission [19, 23, 32]. Research [17] shows increasing interest in buying hybrid vehicles (HVs). Simultaneously, the estimation of reduced vehicle operation costs [4, 20, 28] does not produce unequivocally encouraging results. It was established in [13] that the use of a hybrid vehicle is economically viable in the event of its intensive exploitation (realization significantly higher mileages than by a vehicle with a conventional power unit). Hence, a question arises whether the major effect, i.e. a reduction in the CO_2 emission, would result from an increase in the sales of vehicles with the alternative drive system or from a growth in their share in the execution of transportation tasks.

To find an answer, the intensity of use of hybrid vehicles was observed in a few different countries. Annual vehicle mileage is a measure of the intensity of use. The attention has been focused on characteristic features of the distribution of HVs' mileage values and on finding out whether this distribution is similar to that of the mileage of vehicles with conventional drive systems (hereinafter, such vehicles will be denoted by a symbol "IC" after "internal combustion engine"). When the intensity of use of HVs is compared with that of IC vehicles, one more question arises: why are the HVs being bought though they are considerably more expensive than the IC ones? If this is because of environmental and economic considerations (much lower fuel consumption), then may it happen that the people whose vehicles are intended for longer mileages than usually travelled by IC vehicles of the same vehicle group make a noticeable part of the group of HV purchasers?

The HV buyers' market has been described quite well for a few years. It has been ascertained that:

- for most of the buyers, the predominating criterion is fuel economy and, additionally, reduction of exhaust emissions [7, 9, 12];
- the higher income per family member, the stronger people's disposition to buy HVs [3, 7, 41];
- the higher people's education level, the greater their interest in HVs [29, 41].

However, there is a lack of sufficient information about the intensity of use of HVs and about changes in this intensity with vehicle operation years in comparison with IC vehicles. Regarding this issue, there are some data collected in the USA, according to which the mileage travelled during the initial (1–3) years of vehicle operation has been specified as (25 000–28 600) km/a [24, 29], but the annual mileage averaged for the whole period of vehicle operation was 23 100 km/a [9]. Besides, the HVs buyers in that country prefer vehicles that are new of have been used for a short period [9]. However, there is a lack of publications about the mileage travelled by HVs in the EU countries during the initial operation period, especially in comparison with the IC vehicles.

The problem has been analyzed on the grounds of characteristic features of the distribution of HVs and IC vehicles' mileage values, including the occurrence of extreme values of the mileage during the vehicle operation. This paper is to be an attempt to answer the question whether the choice between the HV and IC drive system has an impact on the vehicle oper-

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ation model, in particular on the intensity of vehicle use. The answer is sought by analyzing characteristic features of the distribution of the values of mileage travelled by vehicles having similar technical specifications and used for similar transportation tasks, i.e. by survey carried out on comparable groups of vehicles with different drive systems. Such analysis are based on the data collected from the secondhand market [11]. This is also the case in this article.

2. Methods

In the analysis, selected vehicle groups in the Netherlands, Germany, and Poland were taken into consideration and the numerical data were collected in the years 2016–2019 [15] based on the vehicles appearing in the secondhand market. The period of the pandemic (2020–2021) changed the behavior of vehicles' users, both in terms of individual mileage and the tendency to switch them. Thus, this period was removed from the research data conducted. Only a small number of HVs, chiefly made in 2010–2018, are present in the secondhand market. This stems from a small percentage of HVs in the total number of motor vehicles (Figure 1). As an example, the share of HVs in the sales of passenger cars in the EU markets in the years 2010–2015 increased from 0.6% to 3.7% (in the same period, it reached almost 1.6% in Germany and 5.4% in the Netherlands) [8, 33]. According to an analysis of the encouragements to buy HVs in the USA and EU, carried out in [1, 14, 30], the encouragements have been assessed as a short-term action. In Poland, only encouragements with local importance took place in the same time, but growing interest in purchasing the HVs can be observed (Figure 1).

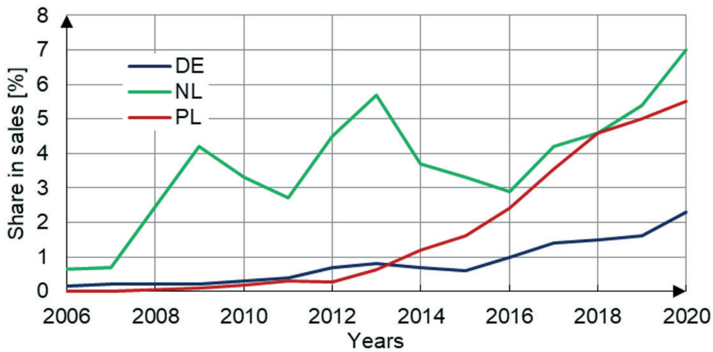

Fig. 1. Share of HVs in the total number of passenger cars sold [37–40]

In the market, Toyota hybrid vehicles predominate [8, 26]. Two HV models of that make were observed, i.e. Auris and Yaris, whose mileages were compared with those of the Auris and Yaris IC version cars. The said vehicles are categorized as small and medium-size multi-purpose motorcars (used as urban, family, and company cars). For the observation, they were divided into separate groups, i.e. Auris HV and IC as well as Yaris HV and IC. In individual groups, the cars' technical specifications are very close to each other (Table 1) and the vehicles are used for similar transportation tasks.

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Tab. 1. Technical specifications of the HV and IC version cars [7]

Parameter	Auris HSD	Auris 1.6	Yaris Hybrid	Yaris 1.33
Curb mass [kg]	1370	1230	1085	1015
Fuel consumption [L/100 km]	3.8	7.1	3.5	5.4
CO_2 emission [g/km]	81	153	79	123
(0–100) km/h acceleration time [s]	11.3	10.4	12.0	11.7

The data collection stage assured the records of 5,500 vehicles, including 2,600 HVs (Auris and Yaris in total). The dataset includes the following information: car make and model, mileage, as well as period and country of the car operation. As early as at the initial stage of data collection, the cars whose operation time was shorter than 3 months or whose average monthly mileage was shorter than 200 km/month were excluded from the analysis. The dataset is divided into groups that include vehicles of one manufacturer and model: Auris HVs and Auris IC, Yaris HVs and Yaris IC for each of the analyzed countries.

The following notation and definitions have been adopted, and the following calculation procedure have been applied.

1. The vehicles were divided into subgroups covering annual periods of operation, in which the time t_i belongs to the range $T_k<t_i\leq T_{k+1}$, where: k – consecutive car operation period, where $k = 1$ for cars operated from 3 to 12 months, $k = 2$ for cars operated from 13 to 24 months, $k = 3$ for cars operated from 25 to 36 months etc. The cars whose operation time belonged to the k^{th} car operation period were counted in the k^{th} subgroup. The time t_i is expressed in months and counted from the beginning of car operation.

2. The vehicle mileage L was treated as a random variable, and L_i^* is the ith value of the variable, i.e. the mileage of the i^{th} vehicle in time period t_i. For every car, its mileage value L_{ik}^* was normalized to the center t_k of the corresponding operation period as follows:

$$L_{ik} = L_{ik}^* \frac{t_k}{t_i} \tag{1}$$

3. Extimators were calculated: X, S, W – mean value, standard deviation, and relative coefficient of variation. For the k^{th} subgroup, consisting of n_k cars, the average mileage value was calculated:

$$X_k = \frac{1}{n_k} \sum_1^{n_k} L_{ik} \tag{2}$$

The coefficient of variation W_k for this subgroup was calculated as a quotient:

$$W_k = \frac{S_k}{X_k} \tag{3}$$

where S_k is the standard deviation of the mileage recorded in the k^{th} subgroup; n_k is the number of cars observed in their k^{th} operation period. If there were less than 30 vehicles in the k^{th} subgroup, it was combined with the next one.

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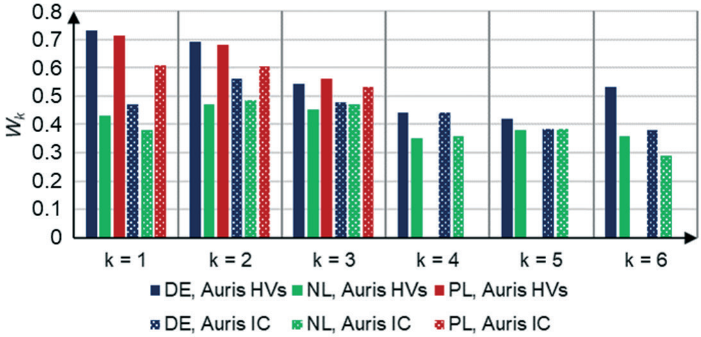

Fig. 2. Coefficient of variation W_k of mileage of the Auris HV and IC cars in successive car operation periods

The high W_k values that can be seen in Figure 2 indicate large scatter in the mileage values in the subgroups. Such a feature of the sets of mileage values is often observed; see e.g. [18, 25, 31]. The values of coefficient W may be reduced by rejecting the outlying (the smallest and largest) mileage values, but this would make it difficult to obtain information about the distribution of the HV and IC vehicles' mileage values. Therefore, the outliers have not been rejected and the data analysis has been based on distributions and frequency of occurrence of specific values of the HV and IC vehicles' mileage. The average value in the subgroup was used to calculate the monthly mileage in the k^{th} operation period:

$$PM_k = X_k/12 \tag{4}$$

4. <u>The percentage shares have been calculated.</u> The mileage values significantly differ between the subgroups, because the mileage values increase with vary intensity in vehicle operation years. Hence, they are hardly eligible for direct comparisons. Therefore, the mileage values L_{ik} were divided by their mean value in the k^{th} subgroup, according to equation:

$$P_{Lik} = \frac{L_{ik}}{X_k} 100\% \tag{5}$$

The values thus obtained represent the mileage values L_{ik} in percentage terms relative to the average mileage value X_k ("average-related mileage").

The average mileage values, calculated according to equation (2), have been used to show their changes with vehicle operation years. By analogy to equation (5), we have:

$$P_k = \frac{X_k}{X_1} 100\% \tag{6}$$

where X_1 is the average mileage value in the subgroup $k = 1$.

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In consideration of large scatter in the calculated average mileage values P_k and wide variation in the shares u_{kj} in successive vehicle operation years, an attempt was made to describe these changes with using non-linear trend models as a function $P_k=f(k)$. For these calculations, the regression method was used, combined with the selection of functions that ensure high values of the coefficient of determination R^2. Based on this criterion, a second-degree polynomial model was selected that produced values of the coefficient of determination within a range of 0.85–0.98. There were only several cases where a power function $y = ax^b$ had to be used as a model.

In the k^{th} subgroup we have n_k vehicles whose mileage L_{ik} have been normalizated according to equation (1) to the time t_k. The calculated values of the percentage share of P_{Lik} according to equation (5) were arranged in an increasing series

$$P_{Lk} = \{ P_{L1k}, P_{L2k}, \dots, P_{Lik}, \dots , \ P_{Lnk}\} \text{ where } P_{Lik} < \ P_{Li+1k} \tag{7}$$

An example of such a percentage mileage presentation calculated according to equation (5) and arranged according to series by (7), has been shown in Figure 3. The values, obtained for Auris cars of the HV subgroup operated in the Netherlands, have been arranged in the ascending order.

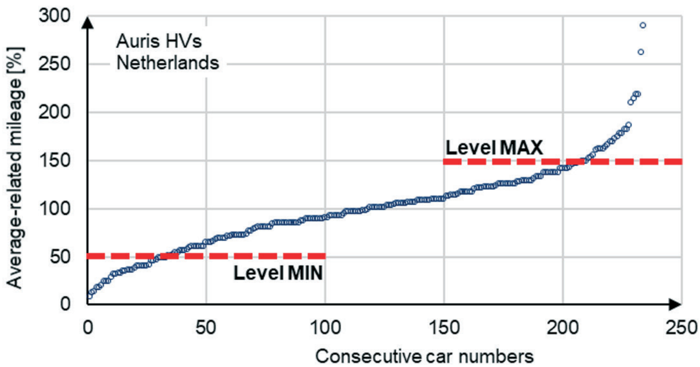

Fig. 3. Percentage values of the average-related mileage P_{Lik} of the Auris HV cars for the car operation period of 1–2 years (i.e. $k = 1$ and 2)

For a predominant number of cars, the mileage is close to the average value in the subgroup, i.e. it falls within the range of 50–150 % of the X_k values (the interval marked by dashed lines in Fig. 3).

The P_{Lik} values observed (f.e. in Figure 3) fall within the interval $P_L \in$ (5%; 250%). This wide range of values, after arranging according to equation (7), have been divided into m classes ΔP_L with a width of 25% or 50%. The ΔP_{Lj} classes include the number of n_{kj} cars whose mileage P_{Lik} expressed as a percentage belongs to the following ranges:

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$$\Delta P_{Lj} \in [(j-1)\Delta P_L, j\Delta P_L] \tag{8}$$

where $j = 1,2,\ldots,m$.

Percentage shares of the vehicles' number were also calculated:

$$u_{kj} = \frac{n_{kj}}{n_k} * 100\% \tag{9}$$

where u_{kj} is the percentage share of the HVs and IC vehicles whose mileage belongs to the j^{th} class in the k^{th} subgroup of the vehicle operation periods.

Naturally, we have:

$$\sum_{j=1}^{j=m} n_{kj} = n_k \tag{10}$$

where m is the number of such classes.

5. The number of vehicles that perform the smallest and the largest mileage has been established; for this purpose, the following threshold values have been adopted $L_{ik} \le 0.25X_k$ or $0.50X_k$ and $L_{ik} \ge 1.5X_k$ or $2.0X_k$. The use of the above-mentioned threshold values allowed the values of P_{Lik} belonging to the (0–25)% or (0–50)% class, i.e. for $j = 1$, were marked as MIN. Values belonging to the class over 150% or over 200%, i.e. for j = m–1 or j = m, are marked as MAX, respectively. According to the marks mentioned above, the numbers of the vehicles with mileages from MIN or MAX classes, were also marked as follows: $n_{kj} \rightarrow n_{k\ MIN1}$ or $n_{k\ MIN2}$ for $j = 1$ for class (0–25)% or (0–50)% and $n_{kj} \rightarrow n_{k\ MAX1}$ or $n_{k\ MAX1}$ for j = m–1 or j = m for classes over 150% and over 200%.

These values were used to calculate the percentages $u_{k\ MIN1}$ and $u_{k\ MIN2}$ as well as $u_{k\ MAX1}$ and $u_{k\ MAX2}$ according to equation (9).

6. The empirical distribution function F was calculated. The empirical distribution in this study is treated as a function based on n_k values of P_{Lik}, which are a percentage-related mileage of the car in k^{th} period of operation.

$$F(P_{Lrk}) = \frac{\#(P_{Lik} \le P_{Lrk})}{n_k} 100\% \text{ where } r = 1, 2, \ldots, n_k \tag{11}$$

3. Results

In this work, the methods described above were employed, the calculations were carried out, and the results obtained for individual countries have been presented as follows:

- Table 2 shows the monthly mileage values PM_k in k^{th} period of car operation.
- Figure 4 shows percentage changes in the P_k average mileage values vs years of car operation, calculated according to equation (6).

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- The histograms in Figures 5–10 and the values in Tables 3–4 show the u_{kj} values, calculated according to equation (8) as the percentage share of number the HVs and IC vehicles whose mileage fell within specific ΔP_L classes; the percentage shares have been shown for class widths 25% or 50%.

- The graphs in Figures 11–13 allow a comparison of the empirical distribution of the mileage value of HVs and IC vehicles.

- The functions that approximate the P_k values and the share of cars with mileages belonging to the classes $u_{k\ MIN}$ and $u_{k\ MAX}$ depending on the years of operation of the HVs and IC vehicles have been shown in Figure 14.

Table 2. Average values of the monthly mileage PMk of the HVs and IC vehicles (average monthly mileage in the kth car operation period), expressed in kilometres

Auris	NL; HVs	NL; IC	DE; HVs	DE; IC	PL; HVs	PL; IC
$k=1$	2 060	1 790	1 260	1 470	1 700	1 720
$k=2$	2 380	1 590	1 250	1 040	2 100	1 870
$k=3$	2 280	1 430	1 280	1 110	1 800	2 060
$k=4$	1 900	1 060	1 200	1 090	2 130	1 300
$k=5$	1 540	1 160	1 100	1 020	–	–
$k=6$	1 390	1 140	960	950	–	–
Yaris	**NL; HVs**	**NL; IC**	**DE; HVs**	**DE; IC**	**PL; HVs**	**PL, IC**
$k=1$	1 590	1 600	850	900	1 270	1 390
$k=2$	1 760	1 110	1 160	900	1 140	1 240
$k=3$	1 340	1 090	1 150	1 030	1 670	1 580
$k=4$	1 350	1 070	1 000	1 080	1 800	1 530
$k=5$	–	1 100	–	1 020	–	1 320
$k=6$	–	1 100	–	990	–	1 530

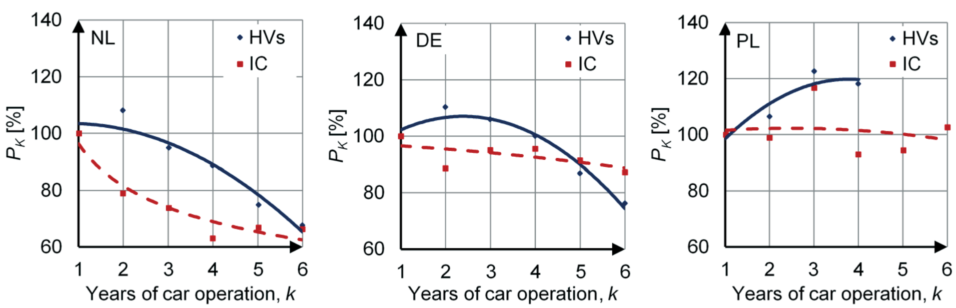

Fig. 4. Percentage changes in average vehicle mileage values vs years of vehicle operation, in the Netherlands (NL), Germany (DE), and Poland (PL) (average for Auris and Yaris cars groups)

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The analysis of the average monthly mileage values PM_k given in Table 2 has revealed different mileage build-up processes that take place in the HV and IC vehicle groups. In most of the vehicle groups (defined by various countries and years of vehicle operation), the mileages travelled by HVs exceeded those done by IC vehicles. The excess values, averaged for the first four years of vehicle operation, were:

- in the Netherlands, 32% for the Auris cars and 19% for the Yaris cars;
- in Germany, 6% for Auris and 5% for Yaris;
- in Poland, 8% for Auris and 5% for Yaris.

Changes in the excess values in the following years of vehicle operation were not regular (see Table 2 and Figure 4). A definite drop in these differences could be seen in the Netherlands and Germany from the third vehicle operation year on. As an example (see Table 2), the difference recorded during the third and fourth vehicle operation year was (840–860) km/month for Auris and (250–280) km/month for Yaris in the Netherlands, as against mere (120–180) km/month in Germany, and rapidly dropped in the next years. In the Polish market, this excess varied (Table 2), with the upward trend being predominant; after 3–4 years, it reached values similar to those observed in the Netherlands for Auris and Yaris.

Figure 14 shows the functions that approximate changes in the average monthly mileage values of HVs (heavy line) and IC cars (dashed line). Based on these functions and the values specified in Table 2, the following may be formulated as the predominating observations.

- With the widely known tendency for the IC cars' monthly mileage to decrease in successive vehicle operation years, the P_k mileage value in the HVs group (with the Auris and Yaris cars being taken together) for the first two years of vehicle operation rose by 10% in Germany but in the Netherlands the increase is less.
- After the initial period of growth in P_k, these values in the HVs group declined in the next vehicle operation years and the P_k drop rate was from 7% (DE) to 8% (NL) a year.
- In the IC group, a continuous decline in the P_k values was observed in successive vehicle operation years. After the third vehicle operation year, however, the average rate of this decline was lower than that in the HVs group and ranged from 2% (DE) to 6% (NL) a year.
- In Poland, where the number of HVs in the market was definitely lower, the period of growth in the P_k as shown in Figure 4 lasted for up to four years (at the end of this period, a stabilization in the P_k value was observed). For the said period, the P_k mileage remained on an almost constant level in the IC group.
- The excess of HVs' mileage over the mileage of IC cars was much less for Yaris than it was for Auris (a replacement of Yaris IC with Yaris HV produces very small fuel economies).

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Table 3. Percentage share u_{kj} of the Auris cars, reaching MIN or MAX mileage in the k^{th} class

	k = 1–2	k = 3–4	k = 5–6	k = 1–2	k = 3–4	k = 5–6
u_{kj}		HVs; NL			IC; NL	
$u_{k\,MIN\,1}$	3.85	1.18	1.89	1.20	0.00	0.00
$u_{k\,MIN\,2}$	14.10	8.82	8.49	18.92	9.75	2.78
$u_{k\,MAX\,1}$	10.25	11.76	10.37	20.00	14.63	8.33
$u_{k\,MAX\,2}$	2.56	1.18	0.94	0.50	2.44	2.78
		HVs; DE			IC; DE	
$u_{k\,MIN\,1}$	4.87	1.57	1.68	3.56	1.82	0.87
$u_{k\,MIN\,2}$	29.20	11.28	12.45	15.56	11.52	6.38
$u_{k\,MAX\,1}$	21.23	12.22	10.10	14.67	15.15	9.28
$u_{k\,MAX\,2}$	7.52	5.33	3.37	4.00	2.12	1.16
		HVs; PL			IC; PL	
$u_{k\,MIN\,1}$	6.59	5.88	–	9.55	3.13	–
$u_{k\,MIN\,2}$	25.27	17.65	–	25.91	18.75	–
$u_{k\,MAX\,1}$	18.32	21.57	–	18.64	18.75	–
$u_{k\,MAX\,2}$	9.16	5.88	–	4.55	7.29	–

Note: the sign „–„ means too few cars in the j^{th} and k^{th} subgroup.

Table 4. Percentage share u_{kj} of the Yaris cars, reaching MIN or MAX mileage in the k^{th} class

	k = 1–2	k = 3–4	k = 5–6	k = 1–2	k = 3–4	k = 5–6
u_{kj}		HVs; NL			IC; NL	
$u_{k\,MIN\,1}$	5.02	4.46	–	3.49	2.31	2.94
$u_{k\,MIN\,2}$	17.35	15.92	–	16.86	15.03	9.41
$u_{k\,MAX\,1}$	13.24	13.38	–	15.70	15.03	9.41
$u_{k\,MAX\,2}$	5.02	3.82	–	6.40	1.73	2.94
		HVs; DE			IC; DE	
$u_{k\,MIN\,1}$	6.25	6.40	–	8.37	0.53	3.80
$u_{k\,MIN\,2}$	29.69	15.70	–	26.11	12.11	14.56
$u_{k\,MAX\,1}$	22.92	16.86	–	19.21	14.21	13.92
$u_{k\,MAX\,2}$	6.25	3.49	–	8.87	5.26	3.16
		HVs; PL			IC; PL	
$u_{k\,MIN\,1}$	6.82	4.35	–	10.05	9.88	1.49
$u_{k\,MIN\,2}$	25.00	26.09	–	26.98	22.22	13.43
$u_{k\,MAX\,1}$	15.91	21.74	–	22.22	20.99	16.42
$u_{k\,MAX\,2}$	5.68	8.70	–	7.94	6.17	5.97

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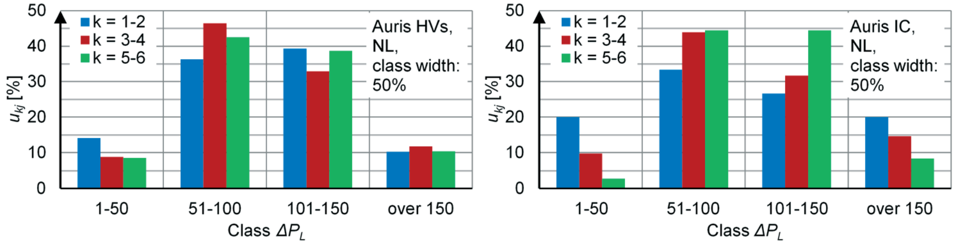

Fig. 5. Percentage share u_{kj} of the Auris HV and IC cars in individual mileage classes ΔP_{Lj}, in the Netherlands (NL)

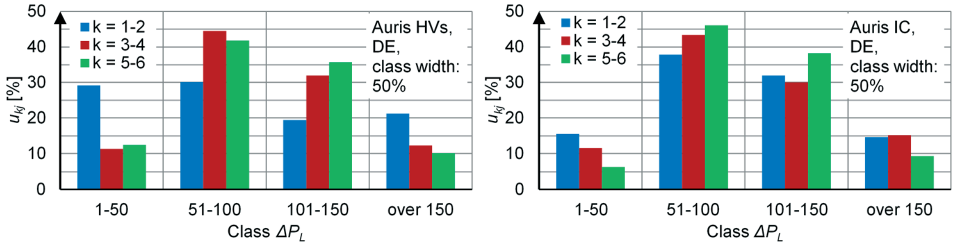

Fig. 6. Percentage share u_{kj} of the Auris HV and IC cars in individual mileage classes ΔP_{Lj}, in Germany (DE)

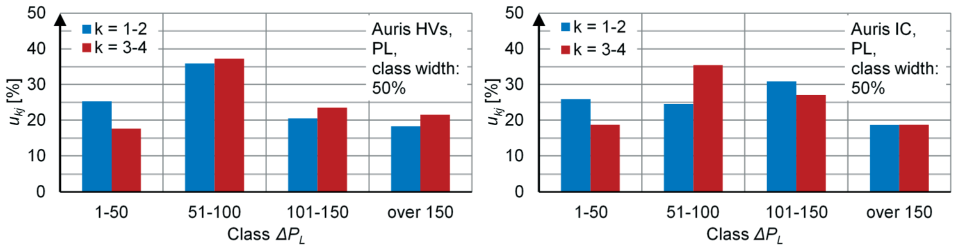

Fig. 7. Percentage share u_{kj} of the Auris HV and IC cars in individual mileage classes ΔP_{Lj}, in Poland (PL)

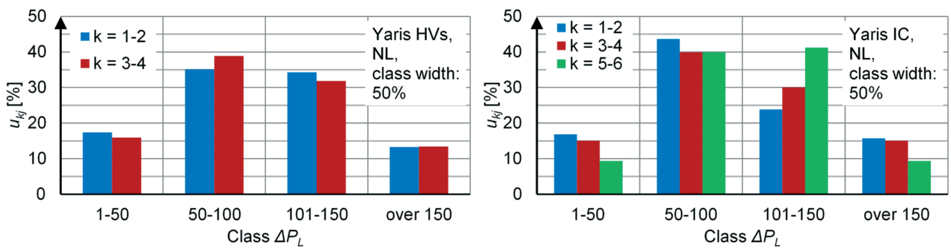

Fig. 8. Percentage share u_{kj} of the Yaris HV and IC cars in individual mileage classes ΔP_{Lj}, in the Netherlands (NL)

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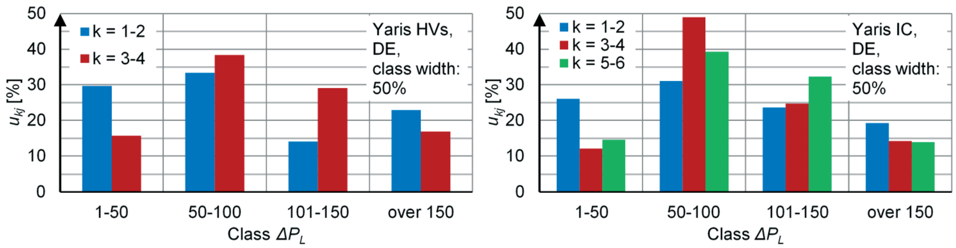

Fig. 9. Percentage share u_{kj} of the Yaris HV and IC cars in individual mileage classes ΔP_{Lj}, in Germany (DE)

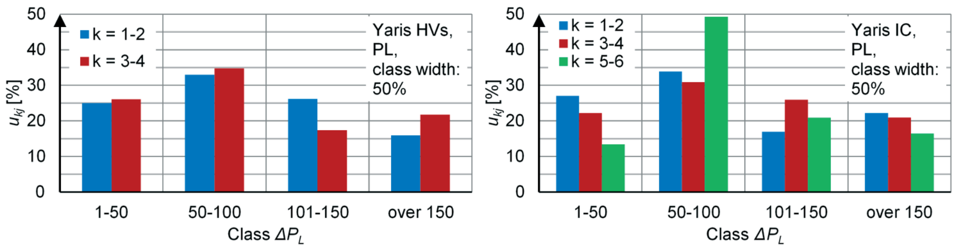

Fig. 10. Percentage share u_{kj} of the Yaris HV and IC cars in individual mileage classes ΔP_{Lj}, in Poland (PL)

The histograms in Figures 5–10 represent the distribution of vehicles between individual ΔP_{Lj} classes. This distribution has been presented in percentage terms according to equations (6) and (8). The number of the vehicles with mileages much longer or shorter than the average, is one of the measures that describe the vehicle operation mode. In this aspect, the following has been found:

- In the MIN classes, significant drop is predominantly observed in the share of the HV and IC vehicles with growing number of vehicle operation years;
- In the MAX classes, the great number of the HVs can be seen whose mileages are significant greater than average (see Tables 3 and 4).

Thus, with the years of operation increasing, the number of cars in the MIN classes decreases, but remains high in the MAX classes. On the whole, the share of the cars with mileages significantly differing from the average decreasing from 24% to 21% in the HVs group in the Netherlands and from 50% to 23% in Germany, as recorded during four years of operation of the Auris cars (Table 3). In Poland, the trend observed in the HVs group was similar: this share varied from 44% to 39% in the same period. The share of the IC vehicles with mileages being outside of the range (50–150)% of X_k dropped during the first four years of vehicle operation from 39% to 24% in the Netherlands and from 30% to 27% in Germany. In Poland, this drop was from 45% to 38% for the same period.

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A similar downward trend in the share of vehicles with mileages significantly differing from the average (in the MIN and MAX classes taken together) was observed with growing number of vehicle operation years for the Yaris cars (Table 4). For this car model, the figures recorded during the first four HVs operation years slightly exceeded those for the Auris cars. In the Yaris group, they decreased from 31% to 29% in the Netherlands and from 52% to 33% in Germany. In Poland, these figures for the Yaris HVs were even higher, as they changed from 41% to 48%. Interestingly, a growth in the shares of vehicles with mileages belong to MIN and MAX classes was observed in this case.

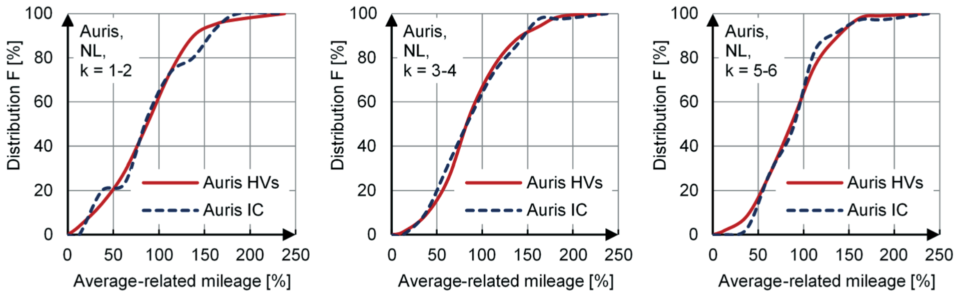

Fig. 11. The empirical distribution function F in the distribution of the Auris HV and IC cars depending on their mileage, specified in average-related percentage terms (P_{Lrk}); the Netherlands (NL)

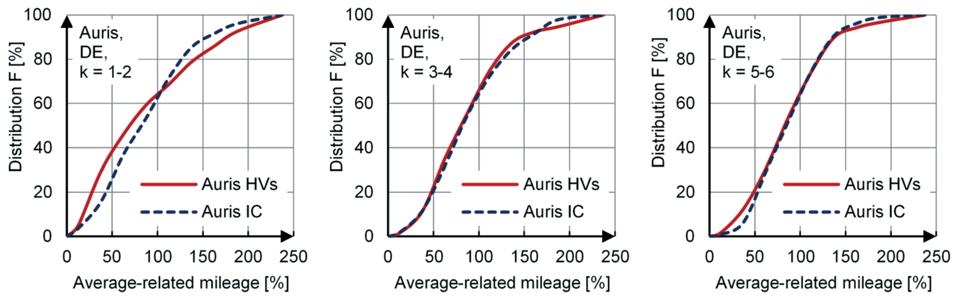

Fig. 12. The empirical distribution function F in in the distribution of the Auris HV and IC cars depending on their mileage, specified in average-related percentage terms (P_{Lrk}); Germany (DE)

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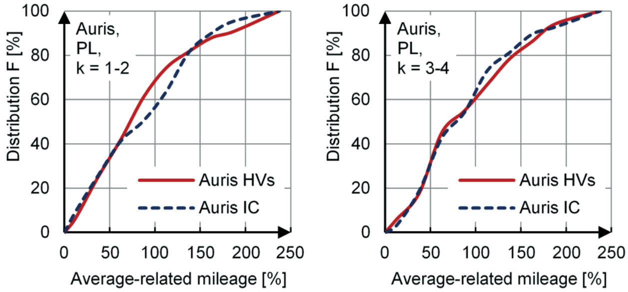

Fig. 13. The empirical distribution function F in in the distribution of the Auris HV and IC cars depending on their mileage, specified in average-related percentage terms (P_{Lrk}); Poland (PL)

Figures 11–13 show the relation between empirical distribution function F of vehicles' mileage P_{Lrk} in the HV and IC vehicle groups, with the Auris cars taken as an example. In this relation, the quantities are presented in percentage terms, according to equations (6) and (8). The juxtaposition of distribution function curves in the graphs also confirms the differences occurring in the distributions of the HV and IC car mileage values. As an example, the presence of HVs whose mileages significantly exceeded those of IC cars can be clearly seen for the initial period of operation of Auris cars in the Netherlands (Figure 11). However, the differences between the mileage distributions between the HVs and IC cars within the range of mileage values in classes MIN and MAX gradually decreased in the subsequent vehicle operation years (Figure 11).

In Figure 14, three curves have been plotted in each graph, which should be interpreted as follows:

- The curve plotted as heavy line shows percentage changes in the average mileage in subgroups, according to equation (7).

- The curve plotted as fine solid line, represents

$$P_k + u_{kMAX1} \tag{12}$$

- The curve plotted as fine dashed line represents

$$P_k - u_{kMIN2} \tag{13}$$

The distances between the heavy line and the fine lines show changes in the percentage shares of the cars that do extreme mileages.

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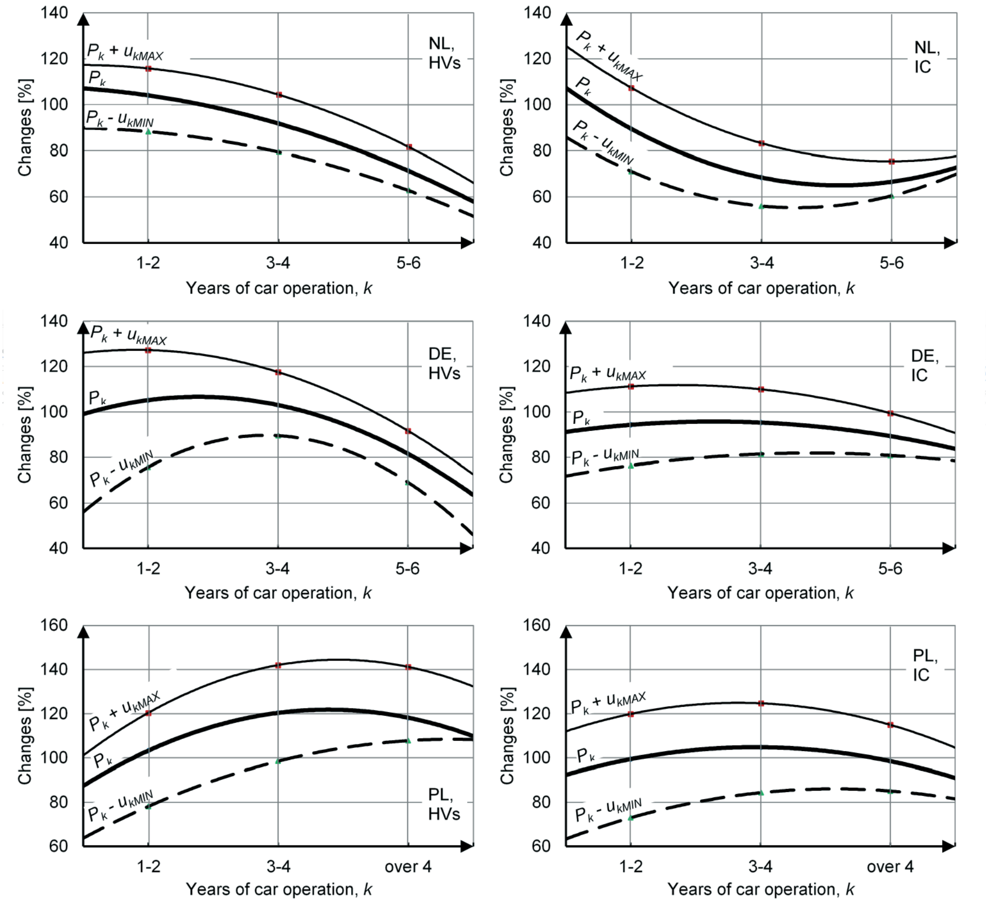

Fig. 14. Functions that approximate the average values of the car mileage (P_k) and of the smallest and largest mileage values (u_{kMIN2}, u_{kMAX1}) depending on the years of operation of the HVs and IC vehicles

The positions of curves in Figure 14 draw attention to the forming of the share of mileage values from class MAX in the HVs group (Auris and Yaris). This share (measured by the u_{kMAX} value) is represented in Figure 14 by the distance between the heavy line (the P_k curve) and the fine solid line (the P_k+u_{kMAX} curve). The position of the P_k+u_{kMAX} curve relative to P_k shows changes in the percentage of the cars whose mileages exceed 150% of X_k and provides grounds for the following findings:

- In all the groups, the number of the HVs whose mileages exceeded 150% of the average mileage was high in the initial vehicle operation period; as an example, there were (10–12)% of such HVs users in the Netherlands and their number did not drop as quickly with vehicle operation years as it did in the case of IC car users.

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- In Germany, u_{kMAX} was observed to drop from 21% to 10% in the HVs group and from 15% to 9% in the IC group (Table 3); in both of the above countries, this drop took place during the period of five to six years from the start of vehicle operation.

- In Poland, the u_{kMAX} value in the HVs group did not decline; in contrast, a drop in this share was observed after the third year of operation of the IC cars, with the rate of this drop being 2% a year.

4. Discussion

4.1. Monthly and annual mileage

Multiannual observations of the intensity of use of IC cars [6, 21, 34] show a decrease in their mileage travelled in successive vehicle operation years. Conversely, a growth in the mileage values in the initial vehicle operation period was observed in the group of HV purchasers. This may be interpreted as an indication that the buyers were satisfied with using such vehicles and that the ecological and economic motivation was convincing [12]. An analysis of changes in the HVs' mileage values in Poland may confirm (at an assumption made as specified above) considerable satisfaction from purchasing HVs. However, the special satisfaction disappeared during the 3rd–4th vehicle operation year. If the P_k growth effect in Germany and the Netherlands is interpreted in a similar way, it should be noticed that this period lasted for up to two years only. There is a lack of a long-lasting effect because the dynamic performance characteristics of HVs of the group under analysis are inferior to those of IC cars (see Table 1).

The average annual mileage Xk in the first two years of operation (for k = 1–2) of HVs in the analyzed countries ranges from 15 500 km (Yaris) to 21 500 km (Auris) and increases slightly (Figure 4) with the operation time. In the following years ($k > 2$) the annual mileage values decrease by (7–8)% annually. In the same period of car operation time in the USA, the average annual mileage of HVs is 24 000 km and it decreases by (5–11)% in subsequent years [24]. The rate of decline in the annual mileage of HVs is greater than in the IC group in both the USA [16, 24] and the EU countries.

4.2. Occurrence of the largest and smallest mileage values

The result of changes in the share of vehicles with mileages belong to MIN and $_{MAX}$ classes results in the concentration of mileage values around the average value of the mileage with vehicle operation years. As an example, this concentration reached values of 76% to 79% for HVs and of 73% to 76% for IC cars during four years of operation of Auris cars in the Netherlands and Germany. In Poland in the same period, this concentration was lower by 11% to 18% than that observed in the Netherlands and Germany. In the operation of Yaris cars, a trend similar to that observed for Auris can be seen, but the concentration in most of the vehicle subgroups under analysis was lower by 6% to 10%.

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For example, there was a group of HVs users in the Netherlands whose vehicles covered very high mileages; the number of such users was not decreasing as quickly as it did in the case of IC car users (Tables 3 and 4, Figures 5 and 8). A similar situation took place in Germany, where considerable drop in the u_{kMAX} value was observed in the group of IC cars (from 15% to 9%). The drop in this share observed in Poland showed that the changes in intensity of vehicle use considerably differed from those taking place in the Netherlands and Germany.

Interest may be aroused by the percentage of the vehicles whose mileages fell within the class u_{kMAX2}, observed in Tables 3 and 4. In the Netherlands, 2.56% of HVs were counted in this class during the first two years of operation of such cars (Table 3). In the Auris IC cars group under comparison, the vehicles doing so high mileages made only a quarter of the above figure. A significant number of HVs in the class u_{kMAX2} was also recorded in Germany. In the initial vehicle operation period, 7.52% of HVs and 4% of IC cars were counted in this class. At the same time, the number of HVs in this class rapidly dropped with vehicle operation years in both of these countries.

The use of HVs is profitable for buyers who realize large annual mileages [27, 35], hence HVs are recommended for taxi drivers [13]. The calculations performed in this study show that only a small part of HVs buyers do so. Additionally, the operation time of HVs is often shorter than IC [11].

5. Conclusions

The intensity of use of hybrid vehicles (HVs) in several countries (the Netherlands, Germany, and Poland) was observed. The analysis has been based on results of surveying the mileage of motorcars whose technical specifications were very close to each other (Table 1). The results of calculations and analyses made it possible to define and adopt a few measures, suitable for describing the initial period of HVs operation. The attention was focused on the average monthly mileage value (P_k) and on the shares (u_{kMIN}, u_{kMAX}) of vehicles with the smallest and largest mileage values in comparable subgroups of HVs and IC vehicles (solely driven by internal combustion engines). Both of these measures were defined in percentage terms, in accordance with equations (5) and (7).

The calculations carried out have indicated that the choice between the HV and IC drive system has an impact on the intensity of vehicle use. Differences in this intensity occur in the initial vehicle operation period. In the Netherlands and Germany, this period lasts for about two years, as against three to four years observed in Poland. Low vehicle operation costs have an impact on higher intensity of use of HVs compared with IC cars (which is reflected in higher monthly mileages). However, other factors (e.g. worse dynamic performance characteristics of HVs) cause the excess of HVs mileage over the mileage of IC cars to decline quite rapidly with vehicle operation years. In Poland, an upward trend can be seen in these excess values for three to four years; afterwards, this excess value gets stabilized.

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The results obtained may confirm in a special way the satisfaction of HVs buyers, which is reflected by the following:

- the mileages covered by HVs exceed those of IC cars;
- there is a high number of the HVs that do high mileages; e.g. in Germany, more than 7% of the cars of this group cover mileages exceeding 200% of the average while the observed number of the IC vehicles with mileages like those is a quarter as big.

Unfortunately, the above are short-lasting effects. In such an approach, the calculation results confirm the conclusions drawn from the research on the market of HVs buyers; according to [2, 17], the said conclusions indicate a lack of long-lasting satisfaction from the use of HVs and are rather focused on short-lasting acceptance of the good points of such vehicles. In Poland, the satisfaction from the use of HVs holds in Poland much longer than this can be seen in the Netherlands and Germany. This may have an economic aspect stemming from the low vehicle operation costs, which are of considerable practical importance at the low GDP per capita value (in 2018, the GDP was USD 53,024 in Germany, USD 48,196 in the Netherlands, and mere USD 15,424 in Poland [36]).

At the current stage of using HVs, the changes observed cannot be deemed a confirmation of creating a new model of operation of motor vehicles with an alternative drive system.

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