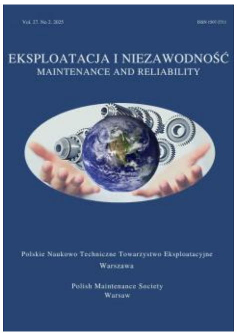

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Evaluating vehicle repair duration in relation to driving styles

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Highlights

- Mean time to repair (MTTR) is often used in vehicle maintenance models.
- The time a vehicle spends in repairs depends on driving styles.
- Driving style is evaluated based on average fuel consumption.
- The time the vehicles spend in repairs depends most on an aggressive driving style.

Abstract

One of the important factors affecting the technical condition of vehicles is driving style. This paper investigates the extent to which vehicle repair duration depends on different driving styles. Driving style was assessed based on average fuel consumption, which is an indicator of driving behavior. Three distinct driving styles were identified: mild, moderate, and aggressive, each characterized by different levels of average fuel consumption. The analyses were carried out on the basis of actual operating data of vehicles included in the fleet of one of the transport companies operating in the city of Lublin, Poland. The results of the study showed how vehicle repair time can be reduced by changing driving style from aggressive to mild, and can help answer the question of whether it is justified to increase drivers' competence in economical driving in order to improve vehicle reliability.

Keywords

vehicle repair time, driving style, fuel consumption, maintenance

1. Introduction

A vehicle malfunction and related downtime are disadvantageous both from the point of view of the transport company and its customers. In the case of the company, such a situation may be associated with the need to incur repair costs, loss of potential profit, or loss of confidence of customers who, due to the occurrence of delays in the execution of orders, may abandon the carrier's services [34].

Vehicle downtime can occur due to a number of factors, such as the driving style, vehicle operating conditions and the age of technical components [24]. Vehicle downtime is an important issue in operational risk management [22], a topic highlighted in the literature. In [21], a method for analyzing changes in risk corresponding to successive stages of a vehicle's mileage was presented, based on an assessment of losses associated with repair costs and losses due to loss of income during vehicle downtime. In [29], the impact of climatic seasonality and selected operational and technical factors on vehicle downtime was evaluated. The month of failure occurrence and type of failure were used as predictors. It was shown that among the studied downtime events included in the created model, events outside the company's control are dominant. In [30], it was shown that for the buses studied over 12 years, the availability factor is only slightly correlated with the age of the vehicle.

Vehicle failures are random in nature so the number of

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failures during operation can be treated as a random variable [32]. Similarly, the duration of vehicle repair is random [9]. Various reliability indices, such as mean time to repair (MTTR) and mean maintenance downtime (MMD) are used to describe vehicle downtime [32]. A mathematical model of mean downtime (MDT) was presented in [15]. Repair time issues were addressed in [13], among others, where classical minimum repair models with negligible repair time were presented and a generalized model with random repair time was proposed. In [25], the authors developed a mathematical model for scheduling vehicle maintenance to reduce repair waiting time that takes into account available resources and time to repair itself.

Maintenance of technical facilities is of particular importance at a time of increasing competition and higher demands on the quality, reliability and productivity of system tasks performed [23]. In [37] it was found that corrective maintenance does not affect the intensity of failures, while preventive maintenance has an impact on reducing the number of failures. In [38], a model for maintenance decisions was proposed that takes into account, i.a. the frequency of failures and the mean vehicle downtime. In [31], an algorithm for deciding how to perform maintenance through repair or replacement is described, based on time to repair and costs. The issues of system readiness were addressed in the article [10] in which the authors presented a model for vehicle maintenance, taking into account the influence of latent factors (affecting the reliability of technical systems) on the duration of various states.

The efficiency/maintenance of technical facilities is influenced by many factors, presented in the literature. An important component of the anthropotechnical system is the driver [17]. The article [19] stated that by changing their driving style, drivers can influence the technical condition of vehicles, given the same mileage and maintenance activities. In [14], it was shown that among driver behaviors, braking and acceleration had the greatest impact on tire wear, followed by turning maneuvers and driving speed. It was indicated that reducing rapid braking and acceleration had the potential to significantly decrease tire wear.

Driving style generally refers to the way a driver drives and depends on the driver's physical as well as emotional conditions while driving. It is based on a combination of cognitive, emotional, sensory and motor factors that occur in space and time [3]. In earlier studies, driving styles were most often classified into three types: aggressive, moderate and mild/cautious. Aggressive style is usually associated with higher driving speed, rapid acceleration and braking, as well as higher turning speed compared to other driving styles. The mild style is usually associated with maintaining a greater distance from the preceding vehicle, longer braking and mild acceleration. The moderate style is relatively well suited to current road conditions [1,2].

Driving style can be evaluated based on the experiments conducted in driving simulators [6,7,36] or under real conditions using various sensors attached to the vehicle, such as accelerometers, GPS, 3D cameras, for example [20,26]. The paper [35] evaluated the behavior of vehicle drivers based on maximum values of lateral and longitudinal acceleration recorded during regular operation. The authors presented a method for preliminary classification of driving styles using acceleration values. This method makes it possible to identify the drivers who drive more aggressively than other drivers. It was also shown that the average maximum acceleration values used in the method are not significantly dependent on driver experience. In [2], driving styles are modeled using a hidden Markov model based on a driver's braking characteristics. In [26], driving style was classified based on analysis of OBD and GPS data. This paper focuses on the search for the measures of the car speed and acceleration signals as well as the measures determined from them that best describe driving style. In [16], a support vector machine (SVM)-based algorithm was used to identify driving style, which makes use of driving data, including speed, acceleration and degree of accelerator pedal opening. The article [11] presented a driving style classification method based on images from 6 vehicle-mounted cameras, which recorded images of the drivers' faces, pedal action, as well as the scene on the road in front and to the left and right of the vehicle. A method for analyzing driving styles based on the intensity of driving maneuvers was presented in [12]. The researchers also assessed driving style based on the driver's electrical brain activity [6,36].

An overview of strategies to reduce fuel consumption in cars is presented in [28]. The paper pointed out the significant impact of driver behavior on fuel consumption. In [27], fuel consumption was shown to differ significantly for the three driving styles studied. The paper [5] focused on the analysis of energy efficiency and dynamics during car acceleration, including the determination of the relationship between vehicle acceleration and fuel consumption. In the case of the vehicle studied, it was determined that excessive acceleration or excessive pedal position above 40% resulted in sub-optimal operation in terms of energy expenditure. The article [33] studied the effect of driving style and traffic conditions on exhaust emissions and fuel consumption during vehicle operation under real-world conditions. It was shown that fuel consumption is generally dependent on driving style. In [18] it was indicated that driving style is directly related to fuel consumption. In particular, adopting an efficient driving style can achieve fuel savings of up to 20%. An aggressive driving style always results in higher energy consumption and CO_2 emissions, while smooth driving provides greater energy efficiency and reduced emissions.

In summary, in the cited literature, researchers have pointed out that the time to repair is random. Vehicle service models often use mean time to repair (MTTR), which is one of the reliability indicators. There are studies that evaluate the impact of climatic seasonality, or operational and technical factors, such as vehicle age, on the frequency of failures. Existing studies have shown that the driving style of drivers also has a significant impact on the occurrence of vehicle failures. Numerous papers have shown that an aggressive driving style leads to increased fuel consumption as well as faster wear and tear of vehicle parts, but the relationship between driving style and the vehicle repair time remains poorly studied. The research presented in this article aimed to bridge this gap by providing analysis on assessing the impact of driving style, on the vehicle repair time. The assessment can help determine whether it is reasonable to improve drivers' competence in economical driving in order to improve vehicle reliability.

2. Material and methods

2.1. Material

The data that were used to perform statistical analyses were obtained from one of the transport companies operating in the city of Lublin, Poland. They concerned the operation of two makes of vehicles over a period of three consecutive years. During this period, each of the vehicles was driven by many drivers. In the paper, the names of these makes were coded using letter designations. The first make was designated as model X, the second as model Y (see Table 1). At the start of the study, all vehicles had mileage close to 0 km. All of the vehicles studied performed the same transportation tasks, within the cities of Lublin, and carried only light loads [34].

Tab. 1. Data of studied vehicles.

Model code	Maximum gross weight [kg]	Engine capacity [dm^3]	Fuel type	The number of vehicles studied
X	3500	2.2	diesel	43
Y	2150	1.9	diesel	14

The data included the information on which driver drove the vehicle on a given day, what distance the vehicle covered on that day, and how much fuel was consumed to travel that distance. The aforementioned transport company has its own service base where vehicles are serviced. From this workshop, data was collected on the duration of repairs for all the surveyed vehicles.

2.2. Driving style classification

The literature cited in the introduction presents a number of methods used to assess driving style. It was shown that fuel consumption is closely correlated with driving style. Drivers with a mild driving style achieve the lowest fuel consumption. They are characterized by smooth acceleration, avoidance of abrupt maneuvers, and anticipation of road conditions, which minimizes the need for frequent braking and acceleration. Drivers with a moderate driving style have average fuel consumption. Their driving style is more balanced, with moderate intensity in acceleration and braking. They are neither extremely fuel-efficient nor aggressively driving. Drivers with an aggressive driving style consume the most fuel. They are characterized by rapid acceleration, frequent braking, and dynamic driving, which leads to higher engine strain and increased fuel consumption. Therefore, the driving style of drivers was evaluated based on the criterion of average daily fuel consumption expressed in dm^3/100 km. The average fuel consumption was calculated using the following formula:

$$FC = \frac{C \cdot 100}{l} \quad \left[\frac{dm^3}{100\,km}\right] \tag{1}$$

where: FC – average daily fuel consumption, C – daily fuel consumption [dm^3], l – daily mileage [km].

Next, for all the average daily fuel consumption values calculated using formula (1) for the examined vehicles of a given model during the analyzed three-year period, the normality of the distribution was checked using the Shapiro-Wilk test. Since the values did not follow a normal distribution for both examined vehicle models, it was not possible to divide them, for example, based on the mean and standard deviation. Therefore, it was decided to categorize them into three groups based on quantiles (first and second terciles). These groups will henceforth be referred to as fuel consumption classes: 'low,' 'medium,' and 'high,' which correspond to 'mild,' 'moderate,' and 'aggressive' driving styles, respectively.

2.3. Evaluation of the impact of driving style on vehicle repair time

To investigate whether there is a relationship between driving style and the vehicle repair time, the procedure described below was carried out. To begin with, for all the studied vehicles of a given model, the shares of mileage driven with fuel consumption specific to each fuel consumption class, i.e., with a particular driving style, were calculated in relation to the total mileage of each.

$$\theta_i^c = \frac{L_i^c}{L_i^t} \tag{2}$$

where: θ_i^c – share of the *i*-th vehicle mileage driven with particular fuel consumption class (driving style), $i \in \{1, 2, \dots, n\}$, n – the number of examined vehicles, $c \in \{L, M, H\}$; L_i^c– mileage of the *i*-th vehicle with a particular fuel consumption class [km]; L_i^t – total mileage of the *i*-th vehicle [km]; where the symbol L denotes low, M - moderate, and H - high fuel consumption class.

They also calculated how many working days each of the studied vehicles spent in repair per 10,000 kilometers driven. For this purpose, the following relationship was used:

$$D_i^r = \frac{\sum_{j=1}^{k} d_{ij}^r \cdot 10000}{L_i^t} \left[\frac{days}{10000\ km}\right], \tag{3}$$

where: D_i^r – number of working days the *i*-th examined vehicle spent in repairs per 10,000 kilometers; d_{ij}^r – number of working days for the *j*-th repair of the *i*-th examined vehicle, $1 \leq j \leq$ k, k - number of repairs; L_i^t – total mileage of the *i*-th vehicle [km].

Then, to determine whether there is a statistically significant correlation between the shares of vehicle mileage performed with each driving style ($\theta_i^L, \theta_i^M, \theta_i^H$), and the vehicle repair time (D_i^r), a Spearman rank-sum test was performed. The test assumed a significance level of α=0.05.

On the basis of the above-described evaluation of the impact of driving styles on the vehicle repair time, it was shown that the higher the proportion of vehicle runs made with an aggressive driving style, the longer the vehicle repair time. Therefore, in the next step, it was estimated by how much the repair time could potentially be reduced by decreasing the share of mileage driven with an aggressive driving style For this purpose, the total repair time for all examined vehicles of a given model was calculated as follows:

$$d_r = \frac{\overline{D^r} \cdot \overline{L} \cdot n}{10000}\ [days], \tag{4}$$

where the value $\overline{D^r} = \frac{1}{n}\sum_{i=1}^{n} D_i^r$ denotes average number of working days all examined vehicles spent in repairs per 10,000 kilometers; $\overline{L}$ – average mileage of all examined vehicles.

Since different vehicles in the study period were operated for a varying number of days, the results of further calculations were converted to 1 year of operation, assuming that there are 250 working days per year during which vehicles are operated. Thus, the average operating period expressed in years was determined from the following relationship:

$$\overline{T} = \frac{\overline{d_o}}{250}\ [year], \tag{5}$$

where: $\overline{d_o}$ – the average number of days of vehicle operation.

Subsequently, the average number of days that one vehicle of a given model spends in repair per year was calculated:

$$\overline{d_{r/year}} = \frac{d_r}{\overline{T} \cdot n} \left[\frac{days}{year}\right]. \tag{6}$$

Finally, from the set of all examined vehicles of a given model, for selected values V ∈ [0.1, 1], a subset of vehicles S ∈ $\{i\colon \theta_i^H \leq V,\ 1 \leq i \leq n\}$ was chosen, where the share of mileage driven with an aggressive driving style did not exceed the specified V. For this subset, new values of $\overline{D^r}, d_r,$ and $\overline{d_{r/year}}$ were calculated using formulas (4) and (6). This procedure was repeated until the share of mileage driven with an aggressive driving style θ^H, reached approximately 10%.

3. Results

Figure 1.a and 2.a show density plots of average daily fuel consumption for model X and model Y vehicles, respectively. The Shapiro-Wilk tests showed that, for both examined vehicle models, the values of average daily fuel consumption do not

follow a normal distribution. Therefore, it was decided to categorize these values into three groups (consumption classes) based on terciles (T1 and T2), for which a normal distribution is not required. As a result of the categorization based on terciles, the range of fuel consumption values for each fuel consumption class for the model X and Y vehicles tested are shown in Figures 1.b and 2.b, respectively.

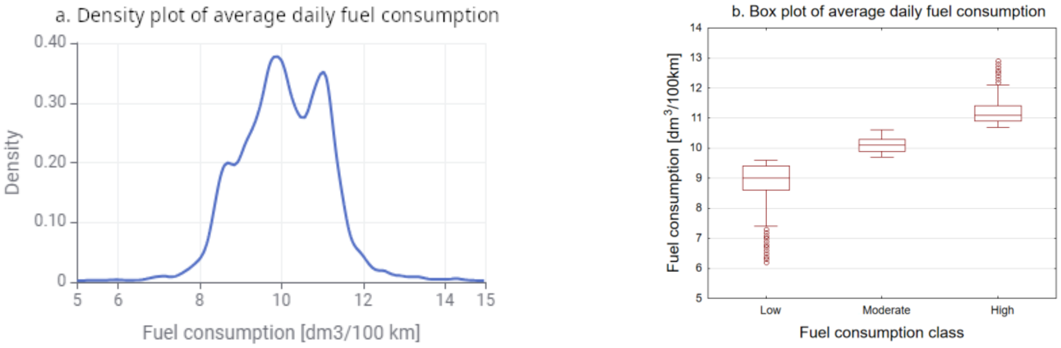

Fig. 1. a. Density plot of average daily fuel consumption for model X vehicles; b. The range of fuel consumption values in dm^3 per 100 kilometers for each of the three fuel consumption classes for model X vehicles

The lower and upper whiskers of the box plot represent the minimum and maximum values within the non-outlier range, respectively. The boxes of the plot represent the first and third quartiles. The middle line represents the median. Points located outside the whiskers represent selected outlier and extreme fuel consumption values.

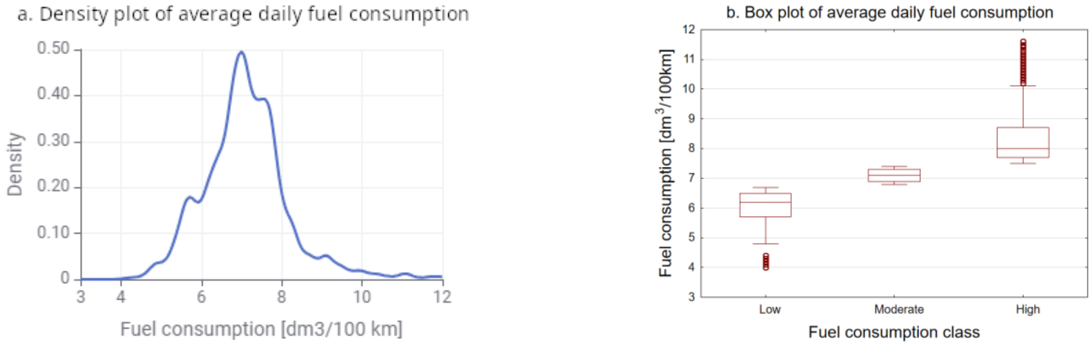

Fig. 2. a. Density plot of average daily fuel consumption for model Y vehicles; b. The range of fuel consumption values in dm^3 per 100 kilometers for each of the three fuel consumption classes for model Y vehicles.

For model X vehicles, the values of the D_i^r parameter ranged from 0.13 to 3.47 days per 10,000 kilometers driven.

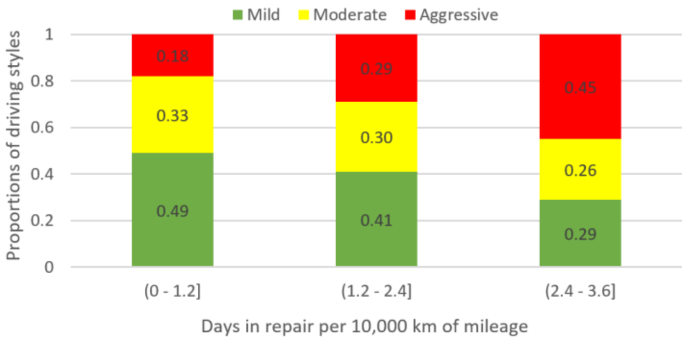

Fig. 3. Average proportions of vehicle mileage driven in each of the three driving styles relative to the time the vehicle spends in repair, for model X vehicles.

These values were divided into three ranges, and for each range, the average share of mileage driven with a particular driving style was calculated. The average shares of mileage driven with a specific driving style, relative to the vehicle repair time per 10,000 kilometers driven, for model X vehicles are illustrated in Figure 3 using a bar chart.

For model Y vehicles, the values of the D_i^r parameter ranged from 0.26 to 5.54 days per 10,000 mileage. These values were also divided into three ranges, and for each range, the average share of mileage driven with a particular driving style was calculated. The average shares of mileage driven with a specific driving style, relative to the vehicle repair time per 10,000 kilometers driven, for model Y vehicles are illustrated in Figure 4.

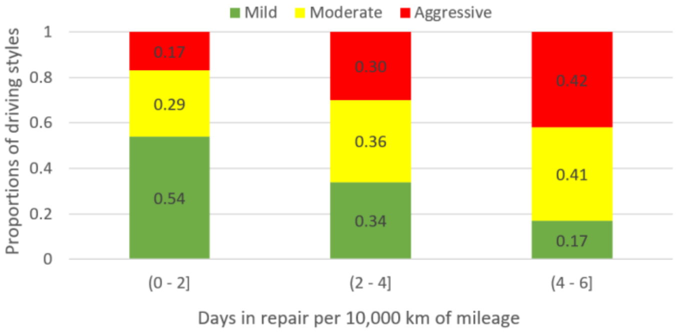

Fig. 4. Average proportions of vehicle mileage driven in each of the three driving styles relative to the time the vehicle spends in repair, for model Y vehicles.

The results of the Spearman's rank correlation analysis performed for model X vehicles are shown in Table 2. Comparing the results of the p-value with the adopted significance level of α=0.05, it can be concluded that a statistically significant correlation between driving style and the vehicle repair time occurs only for the aggressive driving style.

Tab. 2. The obtained parameter values of the correlation analysis between the proportions of vehicle mileage driven with each of the three driving styles and the time the vehicle spends in repair for model X vehicles.

Proportions of mileage within a specific driving style	Correlation value	p value	Degrees of freedom
Mild	-0.25	0.10	41
Moderate	-0.20	0.19	41
Aggressive	0.37	0.02	41

For model Y vehicles, there is a statistically significant correlation between driving style and vehicle repair time for mild and aggressive driving styles (Table 3). However, if the proportion of mileage driven with an aggressive driving style is higher, the proportion of mileage driven with a mild driving style is simultaneously lower (see Figure 4), so only the aggressive driving style was focused on in further analysis.

Tab. 3. The obtained parameter values of the correlation analysis between the proportions of vehicle mileage driven with each of the three driving styles and the time the vehicle spends in repair for model Y vehicles.

Proportions of mileage within a specific driving style	Correlation value	p value	Degrees of freedom
Mild	-0.55	0.04	12
Moderate	0.37	0.20	12
Aggressive	0.66	0.01	12

Figure 5 shows the values of the $\overline{d_{r/year}}$ parameter calculated as described in Chapter 2.3. In the graph below, it can be seen that for both vehicle models studied, the vehicle repair time increases with the proportion of mileage driven with an aggressive driving style.

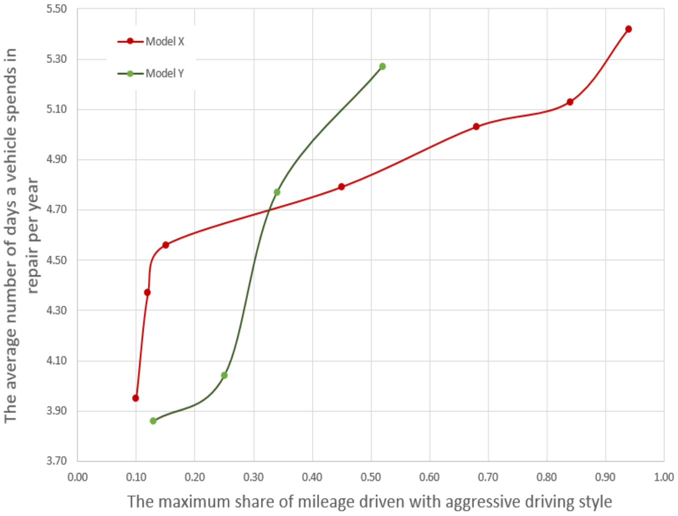

Fig. 5. The average number of days a vehicle spends in repair per year depends on the maximum share of mileage driven with aggressive driving style for vehicles of models X and Y.

Tables 4 and 5 show the total number of days in repair per year for 43 model X cars and 14 model Y cars, respectively, according to the maximum proportion of mileage driven with an aggressive driving style. The tables also show the number of potentially gained days relative to the current state in which mileage driven with an aggressive driving style was not minimized in any way.

Tab. 4. Estimated calculation results for model X vehicles.

Max share of mileage with aggressive driving style V	$\overline{d_{r/year}}$	Total number of days in repair per year per 43 vehicles	Number of potential days gained	Decrease vs. current status [%]
0.94	5.42	233	-	-
0.84	5.13	221	12	5
0.68	5.03	216	17	7
0.45	4.79	206	27	12
0.15	4.56	196	37	16
0.12	4.37	188	45	19
0.10	3.95	170	63	27

Tab. 5. Estimated calculation results for model Y vehicles.

Max share of mileage with aggressive driving style V	$\overline{d_{r/year}}$	Total number of days in repair per year per 14 vehicles	Number of potential days gained	Decrease vs. current status [%]
0.52	5.27	74	-	-
0.34	4.77	67	7	9
0.25	4.04	57	17	23
0.13	3.86	54	20	27

4. Discussion

Analysis of the data showed that the model X vehicles driven by drivers with aggressive driving styles consumed an average of 14% more fuel compared to the vehicles driven by drivers with moderate driving styles and 29% more compared to the vehicles driven by drivers with mild driving styles. The model Y vehicles driven by drivers with aggressive driving styles consumed an average of 25% more fuel compared to the vehicles driven by drivers with moderate driving styles and 46% more compared to the vehicles driven by drivers with mild driving styles.

Statistical studies showed that in their current state, model X vehicles spent an average of 5.42 days in repair per year. Estimation studies have shown that if mileage driven with an aggressive driving style were reduced to a maximum of 10%, this time could be shortened to 3.95 days/year for model X vehicles, a decrease of about 27%. Model Y vehicles, in their current state, spent an average of 5.27 days/year, and if mileage driven with an aggressive driving style were reduced to a maximum of 13% then the time could be shortened to 3.95 days/year, a decrease of about 27%. Thus, for the two vehicle models studied, the reduction in repair time (expressed as a percentage) by reducing mileage driven with an aggressive driving style is similar; nevertheless, it should be kept in mind that there were only 14 model Y vehicles studied.

The obtained study results are in accordance with previous findings, which have shown that an aggressive driving style leads to higher fuel consumption and faster wear of vehicle components.

Possible causes are more frequent acceleration and braking, which increase the load on the engine and other vehicle components. On the other hand, the added value of the research conducted is to provide a quantitative assessment of the relationship between driving styles and vehicle repair time, which was not included in previous studies.

The performed analyses do not take into account the duration of the repair expressed in man-hours. Hence, regardless of whether, for example, 2h or 8h was spent on the repair, the repair time in such a case was treated as 1 day. The reasons for long repair times, i.e. those that lasted several working days, were also not taken into account, whether they were due to the complexity of the repair itself or, for example, waiting for spare parts.

Although the cited literature shows that driving style has a significant impact on fuel consumption, the limitations of the studies conducted mainly include factors affecting fuel consumption that are beyond the control of the driver. Other researchers point to factors that affect fuel consumption, such as road conditions [33], or the number of stops per unit of route over which the driver has no control [4], which were not included in the analyses conducted. However, some of these aspects in the case studied have an insignificant impact on average fuel consumption. In [8], it was found that currently available driving cycles, such as the Worldwide harmonized Light vehicles Test Cycle (WLTC) cannot be used to estimate the actual fuel consumption of vehicles in a given region, because they do not take into account the local driving pattern. In contrast, the fuel consumption for a defined local driving cycle is similar to the average fuel consumption of all vehicles using the same technology traveling in the region. Since the vehicles under study traveled through the same city, and therefore in a region with similar road conditions, the average fuel consumption of the vehicles under study should be similar. It was also pointed out in [37] that the incidence of failures is influenced by the type and intensity of preventive maintenance performed on the vehicles, but the vehicles studied were serviced at the same company's service station, hence they were all serviced in a similar manner.

5. Conclusions

The research conducted bridges the indicated research gap by providing a quantitative assessment of the relationship between driving styles and vehicle repair time, thus contributing to a better understanding of the relationship between driver behavior and maintenance time. The Spearman rank-sum test performed showed that for both vehicle models studied, there is a statistically significant correlation, between the driving style, assessed via average fuel consumption, and the vehicle repair time, with the greatest impact on prolonging vehicle repair time corresponding to the mileage driven with an aggressive driving style.

Estimation studies have shown that vehicle repair time could be reduced by as much as 27% if mileage driven with an aggressive driving style were reduced to a maximum of 10% for model X vehicles and 13% for model Y vehicles. However, even a relatively small reduction in the share of mileage driven with an aggressive driving style, on a fleet-wide basis, can make a significant difference in reducing the time repair time and represents a tangible benefit to the company.

Changing to a milder driving style can therefore lead to a reduction in the time vehicles are out of service as well as significant savings in fuel consumption, hence the rationale for improving drivers' competence in economic driving. These lessons can have important implications for fleet managers, helping them to develop better vehicle operating strategies to maximize vehicle availability and minimize operating costs.

This paper describes the general relationship between driving styles and vehicle repair time from the day it is accepted for repair to the day the repair is completed. In further research, the authors would like to determine how driving styles affect the wear and tear of individual vehicle systems, the labor intensity of repairs, or the cost of repairs, as well as in classifying driving styles, it is planned to use vehicle location data from GPS to determine the actual road conditions under which a vehicle travels.

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