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# Influential Factors on Braking Coefficients and Variability in Braking Force of Vehicle Service Brakes: A Neural Network Approach

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**Abstract:** Vehicles comprise several critical systems, including the braking, steering, transmission, and suspension systems, which operate in concert to ensure safe and efficient movement. Research has established that vehicle malfunctions, particularly in the braking system, contribute significantly to road accidents, with technical failures accounting for approximately 15% of crashes and brake system failures responsible for 17.4% of these incidents. In light of this, an investigation was conducted to identify the factors that influence the braking coefficient and the variability of braking force in vehicle service brakes. A total of 1,018 vehicles were involved in the study, with results indicating that variables such as vehicle production year, category, place of registration, engine power and displacement, gross and curb weight, and payload significantly affect the braking coefficient. Furthermore, the analysis revealed that factors such as vehicle production year, category, registration location, gross and curb weight, and payload are prominent in determining the braking force variability. Neural network analysis was employed to further assess these influential factors, highlighting that the year of manufacture, place of registration, and vehicle payload are particularly influential in predicting both compliance with minimum braking coefficient requirements and variations in braking force. The findings underscore the importance of these factors in the development of more precise models for vehicle brake performance, with potential implications for safety standards and regulatory frameworks.

**Keywords:** Braking coefficient; Braking forces; Influence factors; Neural networks; Vehicle performance; Brake system safety

## 1 Introduction

The vehicle consists of various systems designed to fulfill specific functions, ensuring proper and safe vehicle movement [1]. Since the vehicle is composed of different systems, some of them include the braking system, steering system, suspension system, and transmission system [2–4]. While earlier vehicle systems were mostly mechanical, modern developments have led to the majority of systems being electronic, operating on the principle of electronic control [5, 6]. Whether the system in the vehicle is mechanical or electronic, system malfunctions, failures, or defects can lead to road crashes [7]. According to [8], vehicles are responsible for 13% of all road crashes. Given that a vehicle comprises multiple systems, the failure of any one of these systems could be a potential cause. Research [9] indicates that technical malfunctions or poor technical condition of the vehicle are responsible for up to 15% of road crashes. Each element has its own reliability, and in study [10], the reliability probability of each system in the vehicle over one year was analyzed. Various studies have shown that the braking system significantly contributes to the occurrence of road crashes. Compared to other vehicle systems, brake system failure accounts for 12% of road crashes, following tires, which contribute 73% [11]. According to research [12], brake system failure contributes to 9% of road crashes as one of the causes. Additionally, when considering all types of system failures that lead to road crashes, brake system failure accounts for 17.4% of the causes [9]. Gorzelańczyk et al. [13], in their analysis of road crash causes, concluded that when a vehicle system fails, brake system failure contributed to 15.8% of crashes that occurred between 2001 and 2020. In research conducted by Aleksandrowicz [14], it was concluded that brake system failure contributed to 14.9% of road crashes where the vehicle was the cause of the crash. In Aleksandrowicz's [14] study, the causes of road crashes for different vehicle categories were analyzed, and the brake system was shown to be a significant cause of road crashes. The most relevant data was presented for M1 category vehicles, where brake system failure was identified as the cause of 65.5% of road crashes compared to other vehicle systems [15]. According to Santosa et al. [16], vehicles are the cause of 3.16% of all road crashes, with brake system failure contributing 26.64% within that percentage.

The braking system can fail or experience reduced efficiency for various reasons. Depending on the region where they are used and the vehicle category, disc brakes are increasingly used today, although drum brakes still have significant application [17–19]. Modern braking systems that rely on electronic control are becoming more popular, and the use of such systems is growing [20], but they still depend on disc brakes to perform the braking function. Electronic components in the braking system always include diagnostic systems, so when a malfunction is detected in the braking system, the diagnostic system alerts the driver with a warning light on the dashboard [21, 22]. When analyzing the process and dynamics of braking during brake activation, friction braking force and braking torque are generated, which lead to deceleration or a complete stop of the vehicle [23–25]. Both disc and drum brakes are friction brakes, considering that braking force and torque are generated due to the frictional interaction between friction elements [26, 27]. There are several reasons why friction brakes may fail or have reduced effectiveness. Thus, in the study by Ćatić et al. [28], the reasons for the reduced efficiency of drum brakes were analyzed, while in the study by Vasiljević et al. [29], brake failures of disc brakes were examined. Research indicates that a decrease in the efficiency of the braking system, whether disc or drum brakes, can occur due to various factors. One of the most common reasons for failure or reduced efficiency is the wear of friction pairs, that is, disc-brake pads or drum-brake shoes. Supporting this hypothesis is the research [30], which found that the use of new friction pairs leads to an increase in the efficiency of the braking system, while using new friction pairs and tires on the vehicle increases braking efficiency by up to 53%. In the study by Kowalski [30], it was concluded that the load and tire pressure affect the braking system's efficiency. According to research conducted in Ghana [31], brake system failure most commonly occurs due to low brake fluid pressure (in 40% of cases) or brake overheating (in 33% of cases). It was also found that the three most common reasons for reduced braking efficiency are air in the brake system (40%), vehicle overloading (23%), and poorly adjusted brakes (12%). According to the research [32] conducted in Ghana, which analyzed only minibuses, it was found that the most dominant reasons for brake failure were low brake fluid levels in the master cylinder (27.2%), brake overheating (22.5%), air in the brake system (13.4%), and grease or brake fluid on the brake linings (5.9%). In the study of drum brake failures [33], thirteen key reasons for the failure of this type of brake were identified. Some of the reasons include brake overheating, worn friction materials, braking technique, water in the brake fluid, and installation errors. The influence of braking force and braking characteristics also depends on the brake load. Thus, in the optimization of braking methods, the study [34] considered the braking force depending on the vehicle's axle load.

The functionality of the braking system, including braking force and the braking coefficient, is controlled using stationary and dynamic methods to assess deceleration or braking force on the wheels [35]. The most common method for analyzing the braking system is with dynamometer rollers, which were used in the study by Firdaus et al. [36] to analyze the efficiency of the braking system. In many countries, the functionality and braking force of the system are measured and tested using dynamometer rollers, which represent a form of laboratory testing. The measured values are compared with those legally prescribed as normative. This type of measurement is most often conducted at vehicle inspection stations [37, 38]. The testing of brake functionality, i.e., brake efficiency, at vehicle inspection stations in the Republic of Serbia, Croatia, and Montenegro is usually performed using dynamometer rollers under stationary conditions [39–41], except in special cases where measurements are carried out with devices that measure vehicle deceleration [42, 43], according to prescribed procedures [43–45]. Based on the measured values of braking force at vehicle inspection stations, as well as the analysis of braking diagrams and braking coefficients, it can be concluded whether the braking system is functioning properly and whether it meets the legally prescribed values for braking parameters [46]. The application of a dynamometer with rollers in the study [47] analyzed the impact of brake pad wear on braking forces and vehicle braking efficiency. It was concluded that the percentage of wear on brake pads affects the vehicle's braking parameters. On the other hand, in the research [48], the effect of vehicle load in the M1 category on braking forces and braking efficiency was researched using dynamometer rollers. In this case, it was determined that changes in vehicle load and center of gravity position affect the braking force and braking coefficient. Similarly, the impact of load on the braking of tractors and semi-trailers was analyzed, where it was found that load and center of gravity position influence the braking forces and efficiency [49].

The aim of this research is to analyze the factors that influence the braking coefficient and braking forces. In this case, a larger number of factors related to vehicle characteristics that have not been previously analyzed in terms of braking force and braking coefficient were examined. The analysis utilized data recorded during the technical inspection of vehicles at vehicle inspection stations. The data was collected in Montenegro, and the study included data recorded from 1,018 vehicles. The paper consists of five chapters, excluding the introduction. The second chapter explains the research methodology and sets the initial hypotheses. The third chapter presents the research results along with an analysis of the initial hypotheses. The fourth chapter provides a discussion, and the fifth chapter offers a comprehensive conclusion related to the factors affecting the braking coefficient and forces. Finally, the entire bibliography used in this research is presented.

## 2 Methodology

For the purposes of this paper, a study was conducted to examine the factors that influence the differences in braking forces and braking coefficients of the service brakes of the analyzed vehicles.

### 2.1 Conducting an Experiment

For the purposes of this research, data was collected from five selected locations where vehicle technical inspections are conducted in Montenegro. The experiment and data collection took place in September 2022. Data was gathered from regular technical inspections of vehicles across all categories. The collected data pertained to: vehicle category, year of manufacture, city where the vehicle is registered, vehicle power, engine displacement, gross and curb weight of the vehicle, differences in braking forces per axle, and the braking coefficient of the service brakes of the analyzed vehicles. The data entry from the reports of the regular technical inspections was performed using the MS Excel software package. After data entry, the data was examined and validated. Next, the statistical analysis of the obtained data was conducted in the software package IBM SPSS Statistics v.22 [50].

For the statistical analysis of the data, standard descriptive statistics methods were used (mean, median, standard deviation, minimum, maximum, Percentile 25, Percentile 50, Percentile 75), as well as statistical methods. The normality of distribution was tested by inspecting histograms and using the Kolmogorov-Smirnov test. Since the data for all measured variables were normally distributed, we used parametric methods. To assess the significance of differences, the one sample t-test and one-way ANOVA were employed [51]. Factors influencing the braking coefficient and differences in braking forces of the vehicle's service brakes were analyzed using a neural network.

The null hypothesis ($\mathrm{H}_0$) was: There is no statistically significant difference between the dependent variables (differences in braking forces observed by the axle of the vehicle and the braking coefficient of the service brakes of the analyzed vehicles) and the independent variables (vehicle category, year of manufacture, municipality where the vehicle is registered, vehicle power, vehicle displacement, gross and curb weight of the vehicle, vehicle payload). The alternative hypotheses ($\mathrm{H}_a$) were:

• Hypothesis 1 ($\mathrm{H}_1$). There are statistically significant differences in braking forces between the left and right wheels of the vehicle for each wheel;

• Hypothesis 2 ($\mathrm{H}_2$). There are statistically significant differences when analyzing the differences in braking forces, observed for all axles of the vehicle;

• Hypothesis 3 ($\mathrm{H}_3$). There are statistically significant differences in the braking coefficient of the service brakes of the analyzed vehicles;

• Hypothesis 4 ($\mathrm{H}_4$). There are statistically significant differences in braking forces and the braking coefficient of the vehicle's service brakes depending on the year of manufacture;

• Hypothesis 5 ($\mathrm{H}_5$). There are statistically significant differences in braking forces and the braking coefficient of the vehicle's service brakes depending on the category of the vehicle;

• Hypothesis 6 ($\mathrm{H}_6$). There are statistically significant differences in braking forces and the braking coefficient of the vehicle's service brakes depending on the vehicle's place of registration;

• Hypothesis 7 ($\mathrm{H}_7$). There are statistically significant differences in braking forces and the braking coefficient of the vehicle's service brakes depending on the power of the engine;

• Hypothesis 8 ($\mathrm{H}_8$). There are statistically significant differences in braking forces and the braking coefficient of the vehicle's service brakes depending on the engine displacement;

• Hypothesis 9 ($\mathrm{H}_9$). There are statistically significant differences in braking forces and the braking coefficient of the vehicle's service brakes depending on the gross weight of the vehicle;

• Hypothesis 10 ($\mathrm{H}_{10}$). There are statistically significant differences in braking forces and the braking coefficient of the vehicle's service brakes depending on the vehicle's curb weight;

• Hypothesis 11 ($\mathrm{H}_{11}$). There are statistically significant differences in braking forces and the braking coefficient of the vehicle's service brakes depending on the vehicle's load capacity.

The threshold for the statistical significance (a) was set to 5%. Consequently, if probability ($p$) is smaller or equal to 0.05, $\mathrm{H}_0$ is rejected, and $\mathrm{H}_a$ is accepted. On the contrary, if $p > 0.05$, $\mathrm{H}_0$ is not rejected. The Bonferroni post hoc test was used for the additional comparison between groups [52].

## 3 Results

In this section of the paper, the research results are presented, aiming to showcase the potential differences in braking forces and the braking coefficient of the service brakes of the analyzed vehicles.

### 3.1 Descriptive Statistics

The study involved 1,018 vehicles, with an average age of 17 years. The newest vehicle was manufactured in 2019, while the oldest was manufactured in 1975. The largest percentage of vehicles, 29.1%, were manufactured between 2005 and 2009, while 22.2% were manufactured between 2000 and 2004 (Figure 1).

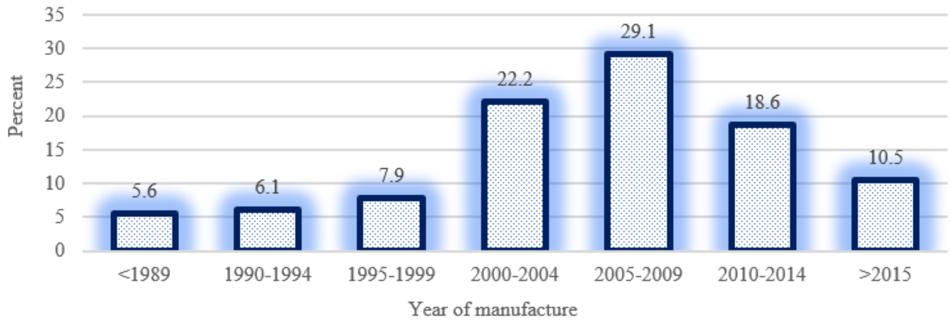


**Figure 1.** Distribution of vehicles by year of manufacture

The share of M1 category vehicles in the sample is 70%, N1 is 7.4%, N3 is 7.2%, N2 is 5.3%, L37 is 4.5%, O4 is 2.3%, and M2 is 1.2%, while all other categories in the sample make up 2.1%. When observed by municipality of vehicle registration, the largest percentage, as much as 42.8%, is from Podgorica, followed by 20.8% from Bar, 14% from Cetinje, 12.2% from Herceg Novi, 2.9% from Budva, 2.1% from Danilovgrad, and 5.2% from other municipalities (Figure 2).

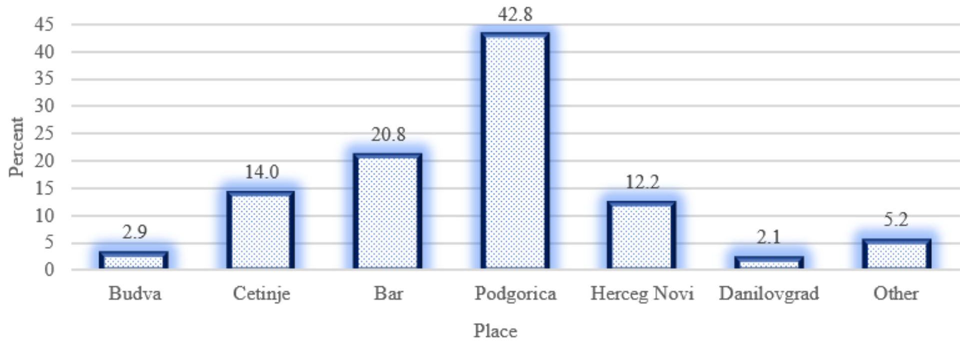


**Figure 2.** Distribution of vehicles by place of registration

Based on the analysis of the vehicle fleet distribution by fuel type, it can be concluded that in the analyzed sample, 72.2% of vehicles use diesel fuel as an energy source. Gasoline is used as fuel by 23.9% of the sample. There were no electric or hybrid vehicles in the analyzed sample (Figure 3).

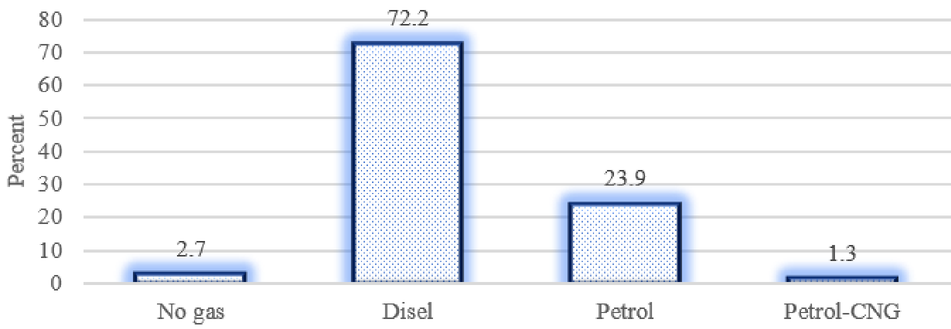


**Figure 3.** Distribution of vehicles by fuel type

The largest percentage of vehicles (31.8%) have an engine power in the range of 50–75 kW, followed by vehicles with an engine power of 75–100 kW (25.2%) (Figure 4).

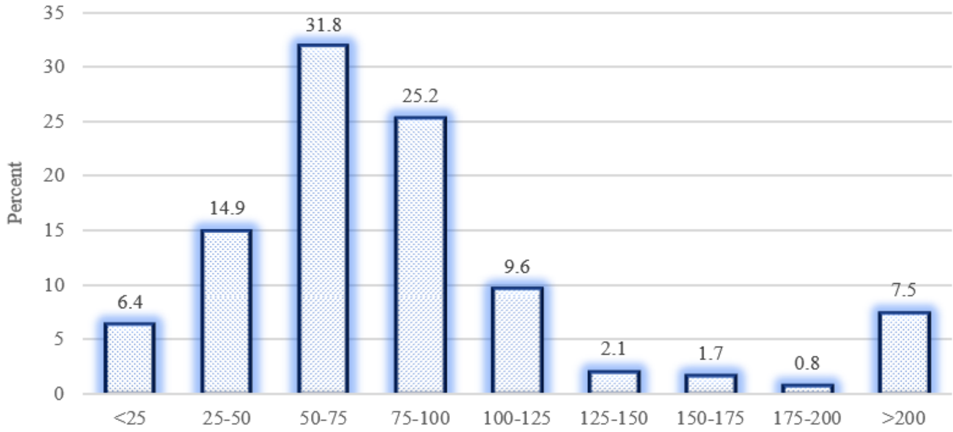


**Figure 4.** Distribution of vehicles by engine power (kW)

More than one-third (39.5%) of the analyzed vehicles are equipped with engines with a displacement between 1500 and 2000 $\mathrm{cm}^3$, followed by vehicles with engine displacements ranging from 1000 to 1500 $\mathrm{cm}^3$ (27.4%) (Figure 5).

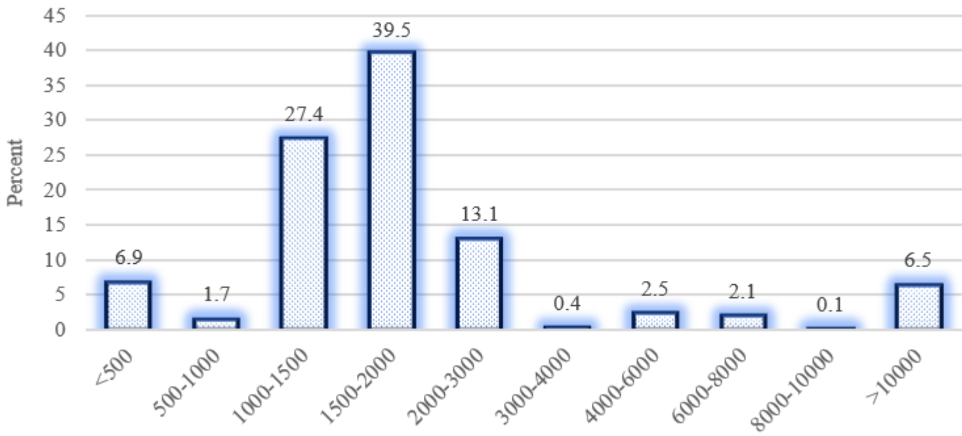


**Figure 5.** Distribution of vehicles according to engine displacement ($\mathrm{cm}^3$)

The largest number of vehicles, accounting for 63.9% of the analyzed sample, have a gross weight in the range of 1000 to 2000 kg. This is followed by vehicles with a gross weight in the range of 2000 to 3000 kg, which make up 10.2% of the sample (Figure 6).

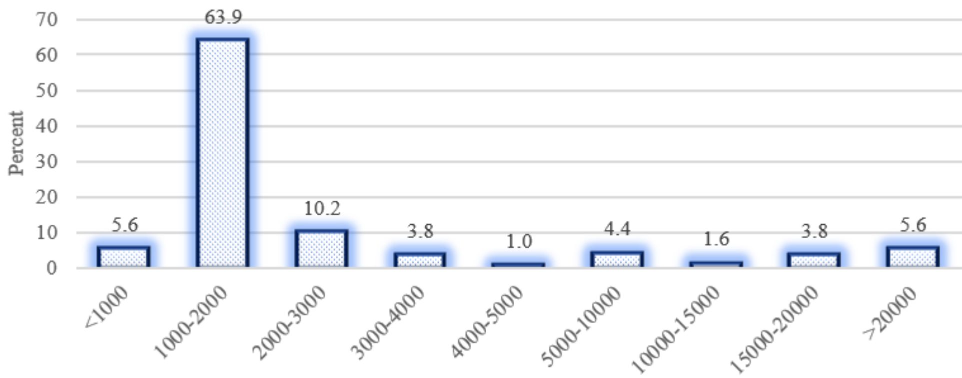


**Figure 6.** Distribution of vehicles based on gross weight of the vehicle (cal.) (kg)

In the study, 50% of the vehicles, or 509 vehicles, had a curb weight in the range of 1000–1500 kg (Figure 7).

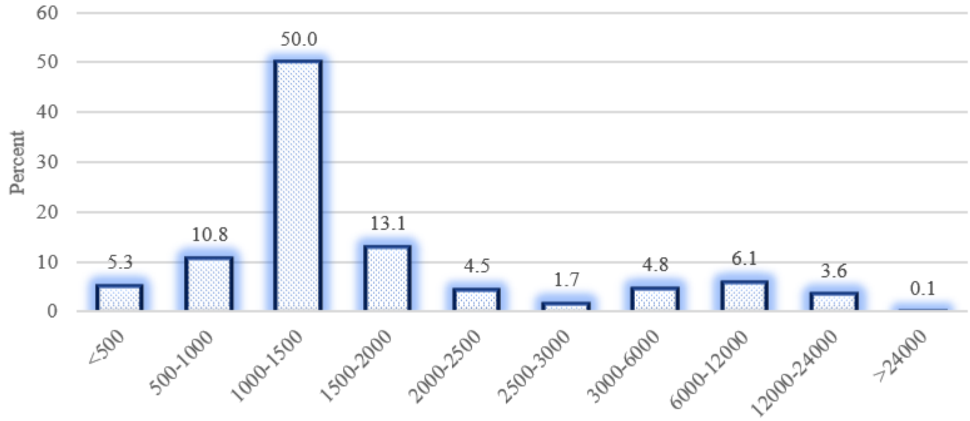


**Figure 7.** Distribution of vehicles based on curb weight of the vehicle (kg)

The data on the vehicle's payload capacity is present in 21.8% of the analyzed vehicles. The largest number of vehicles (31.53%) have a payload capacity ranging from 1000 to 5000 kg (Figure 8).

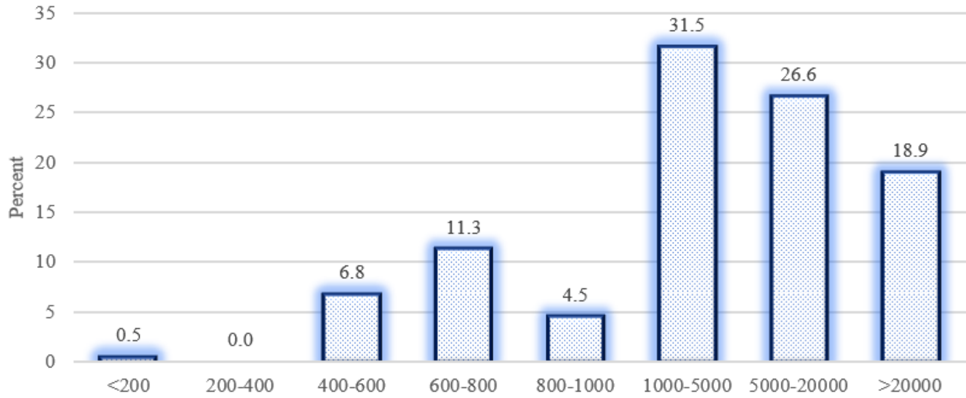


**Figure 8.** Distribution of vehicles according to vehicle's payload capacity (kg)

### 3.2 Braking Forces on the Vehicle's Service Brakes

The arithmetic means of the braking forces on the left and right wheels, analyzed by axles, indicate that the left wheel on the first, second, and third axles has a lower braking force, while for vehicles with a fourth axle, the left wheel exhibits a higher braking force (Figure 9 and Table 1).

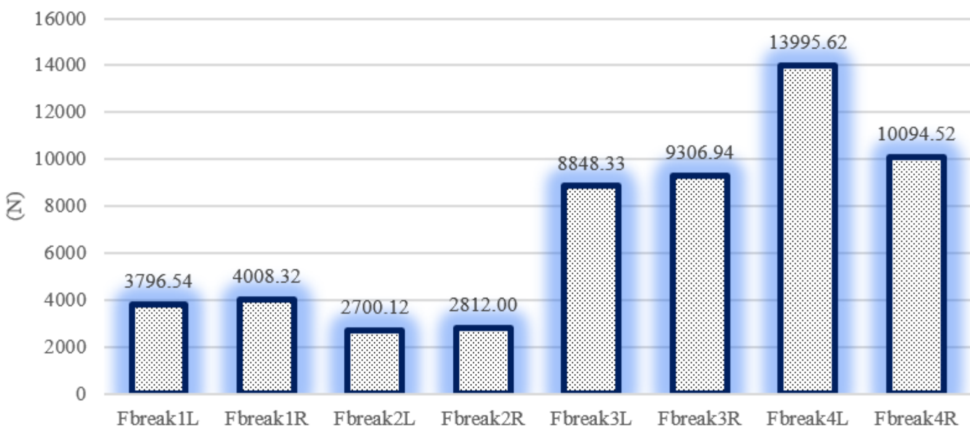


**Figure 9.** Arithmetic mean of the braking forces on the left and right wheels, analyzed by axles for all vehicles (kg)

**Table 1.** Descriptive statistics of the braking force on the service brakes of vehicles

| Statistics | Fbreak1L | Fbreak1R | Fbreak2L | Fbreak2R | Fbreak3L | Fbreak3R | Fbreak4L | Fbreak4R |
|---|---|---|---|---|---|---|---|---|
| Mean | 3796.54 | 4008.32 | 2700.12 | 2812.00 | 8848.33 | 9306.94 | 13995.62 | 10094.52 |
| Median | 2618.50 | 2607.00 | 1629.00 | 1682.50 | 8947.00 | 8655.50 | 10897.00 | 10013.00 |
| Str. Deviation | 3744.36 | 5933.75 | 3053.86 | 3305.15 | 4075.49 | 5473.10 | 17300.86 | 3055.61 |
| Minimum | 346.00 | 646.00 | 338.00 | 308.00 | 3113.00 | 497.00 | 3993.00 | 4868.00 |
| Maximum | 23364.00 | 146940.00 | 27171.00 | 29880.00 | 22778.00 | 29880.00 | 87981.00 | 15785.00 |
| $P_{25}$ | 2111.25 | 2159.50 | 1291.00 | 1311.00 | 5642.50 | 5987.00 | 8662.50 | 8066.50 |
| $P_{50}$ | 2618.50 | 2607.00 | 1629.00 | 1682.50 | 8947.00 | 8655.50 | 10897.00 | 10013.00 |
| $P_{75}$ | 3352.75 | 3377.50 | 2354.00 | 2403.75 | 11049.50 | 11110.50 | 11821.50 | 11927.00 |

The results show statistically significant differences in the analysis of the measured braking forces on the left and right wheels of the vehicle for each of the vehicle wheels, as determined by the one-sample test. There are no statistically significant differences in the measured braking forces on the left and right wheels of the vehicle on the same axle, as determined by the paired samples t-test.

The difference in braking forces on the first axle for the service brakes was analyzed on a sample of 961 vehicles, with the range of values being between Xmin = 0.0% and Xmax = 96.19%. The difference in braking forces on the second axle was analyzed for 960 vehicles, with the range of analyzed values between Xmin = 0.0% and Xmax = 96%. The difference in braking forces for the third axle was analyzed for 52 vehicles, with the interval ranging from Xmin = 0.17% to Xmax = 95.05%, while the analysis for the fourth axle was represented by 21 vehicles, with values ranging from Xmin = 0.26% to Xmax = 88.51%. Considering that the permissible difference in braking forces on the same axle of the vehicle in the country where the research was conducted is a maximum of 25%, the results indicate that 98.3% of vehicles meet this condition for the first axle, 94.8% for the second axle, 82.7% for the third axle, and 85.7% for the fourth axle. Thus, based on these results, it can be concluded that the largest percentage of vehicles do not meet the condition regarding the difference in braking forces on the third axle in 17.3% of the analyzed cases, as well as on the fourth axle in 14.3% of the analyzed cases (Figure 10).

The results show statistically significant differences in the analysis of the differences in braking forces for all vehicles in the sample for the first ($F = 28.094; p < 0.001$), second ($F = 27.307; p < 0.001$), third ($F = 6.766; p < 0.001$), and fourth ($F = 2.980; p = 0.007$) axles, as determined by applying the one-sample test.

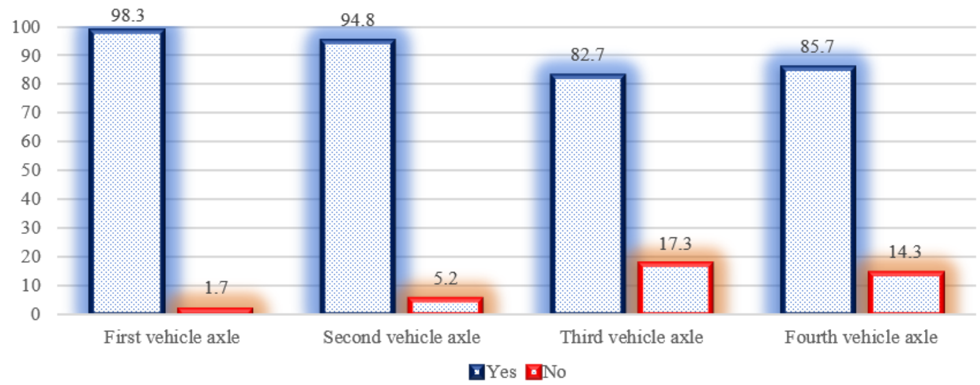


**Figure 10.** Fulfillment of the conditions related to the difference in braking forces on the same axle of the vehicle

### 3.3 Braking Coefficient on the Service Brakes of Vehicles

The arithmetic mean of the braking coefficient results on the service brakes of the vehicles is 61.69%. In the country where the research was conducted, the allowed braking coefficient must be over 40% for category L, 50% for category M, 45% for category N, 43% for category O, and more than 25% for category T. Considering the allowed braking coefficient for all vehicle categories (Table 2), the results indicate that 96.4% of vehicles meet the defined minimum percentage requirements for the braking coefficient. The results show statistically significant differences in the analysis of the braking coefficient on the service brakes of the analyzed vehicles, as determined by the application of the one-sample test ($F = 181.740; p < 0.001$).

**Table 2.** Descriptive statistics of the braking coefficient on the service brakes of the vehicles

| Statistics | Brake Coefficient |
|---|---|
| Mean | 61.69 |
| Median | 60.83 |
| Str. Deviation | 10.83 |
| Minimum | 0.00 |
| Maximum | 98.94 |
| $P_{25}$ | 55.76 |
| $P_{50}$ | 60.83 |
| $P_{75}$ | 67.25 |

### 3.4 Analysis of Influencing Factors on the Braking Coefficient and Differences in Braking Force on the Service Brakes of the Vehicles

The one-way ANOVA was used to analyze the influencing factors (year of manufacture, vehicle category, place of registration, engine power, engine displacement, gross weight, curb weight, and vehicle load capacity) on the braking coefficient and differences in braking force on the service brakes of the vehicles (Table 3).

**Table 3.** The results of the conducted research are presented through the accepted hypotheses, considering the influencing factors on the braking coefficient and braking force differences in the service brakes of the vehicles

| Influential Factors | Braking Coefficient | Braking Force Difference (Axle of the Vehicle) | | | |
|---|---|---|---|---|---|
| | | I axle | II axle | III axle | IV axle |
| Year of manufacture | $H_4$ | $H_0$ | $H_4$ | $H_0$ | $H_0$ |
| Vehicle category | $H_5$ | $H_5$ | $H_5$ | $H_0$ | $H_0$ |
| Place of registration | $H_6$ | $H_6$ | $H_6$ | $H_6$ | $H_6$ |
| Engine power | $H_0$ | $H_7$ | $H_7$ | $H_7$ | $H_0$ |
| Engine displacement | $H_0$ | $H_8$ | $H_8$ | $H_0$ | $H_0$ |
| Gross weight | $H_9$ | $H_9$ | $H_9$ | $H_0$ | $H_0$ |
| Curb weight | $H_{10}$ | $H_{10}$ | $H_{10}$ | $H_0$ | $H_0$ |
| Vehicle payload | $H_{11}$ | $H_{11}$ | $H_{11}$ | $H_0$ | $H_0$ |

The results of the one-way ANOVA show that there are statistically significant differences regarding the influence of year of manufacture, vehicle category, place of registration, gross weight, curb weight, and vehicle load capacity on the braking coefficient of the service brakes. Statistically significant differences were also observed in the influence of vehicle category, place of registration, engine power, engine displacement, gross weight, curb weight, and vehicle load capacity on the braking force difference on the first axle (Table 3 and Table 4).

The results indicate that there are statistically significant differences between all analyzed influencing factors and the braking force difference on the second axle. The braking force differences on the third axle are influenced by the place of vehicle registration and engine power, while the braking force differences on the fourth axle are influenced by the place of vehicle registration (Table 3 and Table 4).

### 3.5 Factors Influencing the Fulfillment of Technical Conditions for Vehicle Compliance

Factors influencing the fulfillment of technical conditions for vehicle compliance by analyzing the braking coefficient and differences in braking force of the service brakes of vehicles were analyzed using the Matlab software package. The dataset used in the network consisted of training data (61.9%) and testing data (38.1%).

Each element for training the multi-layer neural network model consisted of [53]:

$$q_k = \left(p^{(k)} \cdot t^{(k)}\right) \tag{1}$$

where, $q_k$ means the elements for training neural network models. $p^{(k)}$ means the input data for training neural network models. $t^{(k)}$ means the output data for training neural network models.

**Table 4.** Statistical significance of the results observed by influential factors on the braking coefficient and differences in braking force of the service brakes of vehicles

| Influential Factors | Braking coefficient | | Braking Force Difference (Axle of the Vehicle) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | I axle | | II axle | | III axle | | IV axle | |
| | F | P | F | P | F | P | F | P | F | P |
| Year of manufacture | 5.202 | 0.001 | | | 11.393 | 0.001 | | | | |
| Vehicle category | 19.985 | 0.001 | 6.803 | 0.001 | 5.229 | 0.001 | | | | |
| Place of registration | 33.419 | 0.001 | 3.535 | 0.002 | 10.325 | 0.001 | 4.121 | 0.011 | 6.406 | 0.020 |
| Engine power | | | 5.81 | 0.001 | 3.400 | 0.001 | 5.330 | 0.025 | | |
| Engine displacement | | | 6.688 | 0.001 | 2.503 | 0.008 | | | | |
| Gross weight | 5.412 | 0.001 | 7.283 | 0.001 | 4.595 | 0.001 | | | | |
| Curb weight | 5.236 | 0.001 | 12.676 | 0.001 | 7.503 | 0.001 | | | | |
| Vehicle payload | 8.060 | 0.001 | 5.960 | 0.001 | 3.790 | 0.001 | | | | |

The input data for each element for training the multi-layer neural network model was represented as a vector and consisted of 8 data points (Table 5):

$$p^{(k)} = \cdot \left[p_1^{(k)} \cdot p_2^{(k)} \cdot p_3^{(k)} \cdot p_4^{(k)} p_5^{(k)} \cdot p_6^{(k)} \cdot p_7^{(k)} \cdot p_8^{(k)}\right]^T \tag{2}$$

where:

$p^{(k)}$— Input data for each element for training multi-layer neural network model.
$p_1^{(k)}$— Input data for "vehicle category" for the kth specimen.
$p_2^{(k)}$— Input data for "year of manufacturing" for the kth specimen.
$p_3^{(k)}$— Input data for "place of registration" for the kth specimen.
$p_4^{(k)}$— Input data for "engine power" for the kth specimen.
$p_5^{(k)}$— Input data for " engine displacement" for the kth specimen.
$p_6^{(k)}$— Input data for "gross weight" for the kth specimen.
$p_7^{(k)}$— Input data for "curb weight" for the kth specimen.
$p_8^{(k)}$— Input data for "vehicle payload" for the kth specimen.

The input variables were assigned specific nominal values using a nominal scale. Table 3 shows the distribution of values for each characteristic used as input data.

**Table 5.** Characteristics of input variables

| Characteristics | Values |
|---|---|
| Vehicle category | $1 = \mathrm{L}_{11}; 2 = \mathrm{L3}; 3 = \mathrm{M}_1; 4 = \mathrm{M2}; 5 = \mathrm{M}_3; 6 = \mathrm{N}_1; 7 = \mathrm{N}_2; 8 = \mathrm{N}_3; 9 = \mathrm{O}_1; 10 = \mathrm{O}_2; 11 = \mathrm{O}_3; 12 = \mathrm{O}_4$ |
| Year of manufacturing | $1 =< 1989; 2 = 1990-1994; 3 = 1995-1999; 4 = 2000-2004; 5 = 2005-2009; 6 = 2010-2014; 7 => 2015$ |
| Place of registration | 1= Budva; 2= Bar; 3= Cetinje; 4= Danilovgrad; 5= Herceg Novi; 6= Podgorica; 7= Other municipalities |
| Engine power | $1 =< 25; 2 = 26-50; 3 = 51-75; 4 = 76-100; 5 = 101-125; 6 = 126-150; 7 = 151-175; 8 = 176-200; 9 => 200$ |
| Engine displacement | $1 =< 500; 2 = 500-1000; 3 = 1000-1500; 4 = 1500-2000; 5 = 2000-3000; 6 = 3000-4000; 7 = 4000-6000; 8 = 6000-8000; 9 = 8000-10000; 10 => 10000$ |
| Gross weight | $1 =< 1000; 2 = 1000-2000; 3 = 2000-3000; 4 = 3000-4000; 5 = 4000-5000; 6 = 5000-10000; 7 = 10000-15000; 8 = 15000-20000; 9 => 20000$ |
| Curb weight | $1 =< 500; 2 = 500-1000; 3 = 1000-1500; 4 = 1500-2000; 5 = 2000-2500; 6 = 2500-3000; 7 = 3000-6000; 8 = 6000-12000; 9 = 12000-24000; 10 => 24000$ |
| Vehicle payload | $1 =< 200; 2 = 200-400; 3 = 400-600; 4 = 600-800; 5 = 800-1000; 6 = 1000-5000; 7 = 5000-20000; 8 => 20000$ |

The output data for training the multi-layer neural network model consisted of five data (Table 6):

$$t^{(k)} = \left[t_1^{(k)} \cdot t_2^{(k)} t_3^{(k)} \cdot t_4^{(k)} t_5^{(k)}\right]^T \tag{3}$$

where:

$t^{(k)}$— Output data for training neural network models.

$t_1^{(k)}$— Output data related to predicting the fulfillment of the minimum defined percentage of brake coefficient.

$t_2^{(k)}$— Output data related to predicting the fulfillment of the percentage of brake force differences for the first axle of the vehicle.

$t_3^{(k)}$— Output data related to predicting the fulfillment of the percentage of brake force differences for the second axle of the vehicle.

$t_4^{(k)}$— Output data related to predicting the fulfillment of the percentage of brake force differences for the third axle of the vehicle.

$t_5^{(k)}$— Output data related to predicting the fulfillment of the percentage of brake force differences for the fourth axle of the vehicle.

**Table 6.** Characteristics of output variables

| Characteristics | Values |
|---|---|
| Prediction of meeting the minimum defined percentage of brake coefficient | 1 = Yes; 2 = No. |
| Prediction of meeting the percentage of brake force differences for the first axle of the vehicle | 1 = Yes; 2 = No. |
| Prediction of meeting the percentage of brake force differences for the second axle of the vehicle | 1 = Yes; 2 = No. |
| Prediction of meeting the percentage of brake force differences for the third axle of the vehicle | 1 = Yes; 2 = No. |
| Prediction of meeting the percentage of brake force differences for the fourth axle of the vehicle | 1 = Yes; 2 = No. |

Based on the analysis of different activation functions and the number of hidden layers, the network that produced the best results in predicting the satisfaction of the minimum defined percentage of brake coefficient and the percentage of brake force differences for the first, second, third, and fourth axles was a multilayer feedforward neural network. It consisted of an input layer, two hidden layers, and an output layer. The hidden layer of the neural network was composed of two hidden layers, with the first hidden layer having 6 neurons and the second hidden layer having 5 neurons. In this model, the hyperbolic tangent function was applied.

The results of the conducted research indicate that the year of vehicle manufacturing, the place of vehicle registration, and the vehicle's payload are factors that have a significant impact on predicting the satisfaction of the minimum defined percentage of the brake coefficient and the percentage of brake force differences for the first, second, third, and fourth axles (Figure 11).

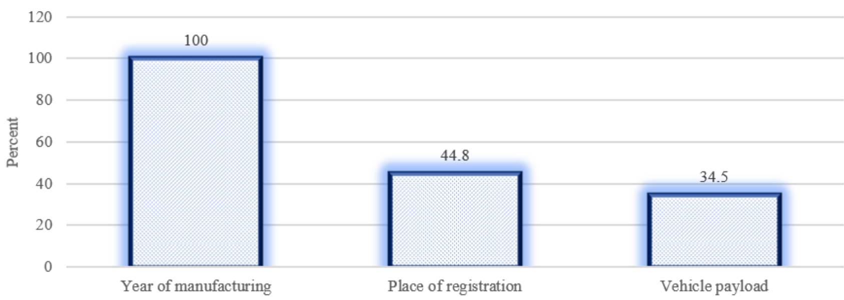


**Figure 11.** Factors influencing the prediction of meeting the minimum defined percentages of the braking coefficient and brake force differences for the service brakes of vehicles

## 4 Discussion

An analysis of the results shows that 96.4% of vehicles meet the minimum defined requirements for the braking coefficient, indicating a high level of compliance with legal standards. However, a detailed analysis reveals variations linked to specific factors such as the year of manufacture, place of registration, vehicle payload and curb weight, as well as engine displacement and power.

The influence of vehicle manufacturing year shows that older vehicles have statistically significantly poorer braking performance, suggesting that older vehicles may not be adequately maintained or may use outdated braking technology. This aligns with the expectation that older vehicles become less reliable in terms of technical condition and performance, especially when it comes to critical systems like brakes.

The place of vehicle registration also has a significant impact on the braking coefficient and differences in braking forces. This variation can be explained by different vehicle maintenance conditions in various regions, as well as differences in technical inspections and controls conducted in urban and rural areas. For example, in urban areas where technical inspections are stricter, vehicles may have better technical condition.

The vehicle's payload and curb weight have proven to be important factors in predicting compliance with the minimum criteria for the braking coefficient and differences in braking forces. These results show that vehicles with higher load capacity and weight exhibit greater differences in braking forces, which may be due to varying loads and the dynamic characteristics of these vehicles in motion. Greater weight requires stronger braking systems, and vehicles not equipped for this type of load may show larger differences in braking forces.

The analysis of the impact of engine power and displacement did not show statistically significant differences in the braking coefficient but determined a significant effect on the difference in braking forces on the first and second axles. This suggests that engine power and displacement have a greater influence on the braking dynamics of vehicles on the front axles, where the impact of engine power is likely to be more pronounced.

Multivariate analysis conducted using neural networks indicates key factors affecting the fulfillment of technical compliance conditions for vehicles, with year of manufacture, place of registration, and vehicle payload identified as the most significant predictors. These results suggest a need for additional regulations and adjustments to technical inspections, particularly for older vehicles and those with higher load capacities, to ensure the safety of all road users.

## 5 Conclusions

Based on the data collected and analyzed in the conducted research, the following conclusions can be drawn:

• The arithmetic means of the braking forces on the left and right wheels, observed by axle, indicate that the left wheel on the first, second, and third axles has a lower braking force, while for vehicles with a fourth axle, the left wheel exhibits a higher braking force;

• A statistically significant difference was observed in the analysis of the measured braking forces on the left and right wheels of the vehicles for each wheel;

• The results show statistically significant differences in the analysis of the differences in braking forces, observed for all vehicles in the sample, for the first ($\mathrm{F} = 28.094; p < 0.001$), second ($\mathrm{F} = 27.307; p < 0.001$), third ($\mathrm{F} = 6.766; p < 0.001$), and fourth ($\mathrm{F} = 2.980; p = 0.007$) axles;

• The arithmetic mean of the braking coefficient results for vehicles with service brakes is $61.69\%$;

• The results indicate statistically significant differences in the analysis of the braking coefficient on the service brakes of the analyzed vehicles ($\mathrm{F} = 181.740; p < 0.001$);

• There are statistically significant differences regarding the impact of the vehicle's year of manufacture on the braking coefficient ($\mathrm{F} = 5.202; p < 0.001$) of the vehicle's service brakes, as well as on the difference in braking force of the service brake for the second ($\mathrm{F} = 11.393; p < 0.001$) axle of the analyzed vehicles;

• There are statistically significant differences regarding the impact of the vehicle category on the braking coefficient ($\mathrm{F} = 19.985; p < 0.001$) of the vehicle's service brakes, as well as on the differences in braking force of the service brake for the first ($\mathrm{F} = 6.803; p < 0.001$) and second ($\mathrm{F} = 5.229; p < 0.001$) axles of the analyzed vehicles;

• There are statistically significant differences in the impact of the vehicle's place of registration on the braking coefficient ($\mathrm{F} = 33.419; p < 0.001$) of the vehicle's service brakes, as well as on the differences in braking force of the service brake for the first ($\mathrm{F} = 3.535; p = 0.002$), second ($\mathrm{F} = 10.325; p < 0.001$), third ($\mathrm{F} = 4.121; p = 0.011$), and fourth ($\mathrm{F} = 6.406; p = 0.020$) axles of the analyzed vehicles;

• There are statistically significant differences regarding the impact of the engine power on the difference in braking force of the vehicle's service brake for the first ($\mathrm{F} = 5.810; p < 0.001$), second ($\mathrm{F} = 3.400; p = 0.001$), and third ($\mathrm{F} = 5.330; p = 0.025$) axles of the analyzed vehicles. There are no statistically significant differences regarding the impact of the engine power on the braking coefficient of the vehicle's service brake;

• There are statistically significant differences regarding the impact of the engine displacement on the difference in braking force of the vehicle's service brake for the first ($\mathrm{F} = 6.688; p < 0.001$) and second ($\mathrm{F} = 2.503; p = 0.008$) axles of the analyzed vehicles. There are no statistically significant differences regarding the impact of the engine displacement on the braking coefficient of the vehicle's service brake;

• There are statistically significant differences regarding the impact of the gross weight of the vehicle on the difference in braking force of the vehicle's service brake for the first ($\mathrm{F} = 7.283; p < 0.001$) and second

($\mathrm{F} = 4.595; p < 0.001$) axles of the analyzed vehicles, as well as on the braking coefficient of the vehicle's service brake ($\mathrm{F} = 5.412; p < 0.001$);

• There are statistically significant differences regarding the impact of the vehicle's curb weight on the difference in braking force of the vehicle's service brake for the first ($\mathrm{F} = 12.676; p < 0.001$) and second ($\mathrm{F} = 7.503; p < 0.001$) axles of the analyzed vehicles, as well as on the braking coefficient of the vehicle's service brake ($\mathrm{F} = 5.236; p < 0.001$);

• There are statistically significant differences regarding the impact of the vehicle's payload on the difference in braking force of the vehicle's service brake for the first ($\mathrm{F} = 5.960; p < 0.001$) and second ($\mathrm{F} = 3.790; p < 0.001$) axles of the analyzed vehicles, as well as on the braking coefficient of the vehicle's service brake ($\mathrm{F} = 8.060; p < 0.001$);

• The results of the conducted research indicate that the year of vehicle manufacturing, the place of vehicle registration, and the vehicle's payload are factors that significantly influence the prediction of meeting the minimally defined percentages of the braking coefficient and the percentage of difference in braking force for the first, second, third, and fourth axles.

The application of the obtained results in practice is reflected in the improvement of the vehicle technical inspection process, particularly in terms of compliance with legislative standards regarding differences in braking forces by axle and minimum values of the braking coefficient. These results can assist traffic engineers and regulatory authorities in identifying key factors affecting vehicle technical correctness, such as the year of manufacture, place of registration, and vehicle payload. This enables the formulation of targeted recommendations for improving technical inspections and reducing the number of technically defective vehicles on the road.

The limitations of the study pertain to the representativeness of the sample, as the research covers vehicles from a limited geographical area and specific categories of vehicles. This may complicate the generalization of the results to a broader population framework. Additionally, the neural network used for performance prediction could yield better results with more extensive parameter tuning and a greater number of input variables.

Further research should focus on expanding the sample of vehicles from different geographical regions and categories to obtain more comprehensive data. Additionally, the application of other machine learning models for predicting vehicle technical performance could be considered. Future studies should also include additional variables such as road conditions and weather conditions to better understand the factors affecting road safety.

### Author Contributions

Conceptualization, T.I. and S.V.; methodology, T.I.; software, S.S.; validation, A.T.; formal analysis, T.I.; investigation, T.I.; resources, S.V.; data curation, S.S.; writing—original draft preparation, T.I.; writing—review and editing, A.T.; visualization, S.S.; supervision, S.V.; project administration, S.S.; funding acquisition, S.S. All authors have read and agreed to the published version of the manuscript.

### Data Availability

The data used to support the research findings are available from the corresponding author upon request.

### Conflicts of Interest

The authors declare that they have no conflicts of interest.

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