Article

Identification of the Right Moment for Motor Vehicle Replacement—Life-Cycle Analysis in Serbia and Montenegro

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Abstract: This paper deals with the issue of planning the end-of-life phase of motor vehicle life cycles in Serbia and Montenegro. This topic is trending around sustainability issues, given the very unfavorable age structure of vehicles and the increasing import of used cars, which intensifies the problem of the number of waste vehicles. On average, a motor vehicle is in active use for a period of 10 to 15 years. Individual phases of its life cycle are indicated differently, using multiple parameters. All phases are influenced by many factors, but this paper focuses on the phases of active use and the end of life of a motor vehicle. This paper investigates these two phases in terms of the influencing elements. The main aim of this study is to lay the foundations for making adequate decisions on how to handle end-of-life vehicles, from the perspective of their drivers. The study includes performing quantitative research analysis via the k-means clustering technique on a sample of 1240 drivers (private and commercial vehicles), in order to draw concrete conclusions through appropriate statistical analysis. The key findings suggest that different market, business, and environment indicators define the phases of active use and end of life, throughout the life cycle of a motor vehicle. Future research will expand the sample to surrounding countries.

Keywords: transport; motor vehicles; life cycle phase; sustainability

1. Introduction

Motor vehicles represent one of the most resource-intensive products available. Consequently, they cause environmental impacts throughout their entire life cycle, including a short period of being new, soon after purchase, followed by a multiyear operating period in which maintenance costs are low, when parts are wearing out through the phase of undisturbed exploitation, and finally, reaching its termination in the end-of-life phase [1]. On a yearly basis, several million vehicles are retired from service throughout the world [2,3],

typically because of major component failure or structural integrity loss due to wearing out, corrosion (physical decay), or traffic accidents.

While decisions for vehicle replacement are most often guided by the economic circumstances of the vehicle owner [4], the most efficient service life of a motor vehicle is also dictated by different business, economic and environmental factors for both commercial and passenger motor vehicles. For example, there is an environmental cost-benefit tradeoff between the purchase of a new, more energy-efficient, and less polluting motor vehicle versus continuing to use and maintain an older, less efficient, and more polluting vehicle [5,6]. All EU candidate countries (such as Serbia or Montenegro) are obliged to meet strict quality standards in the field of transport and environmental protection, thus forcing the drivers/owners of passenger and commercial vehicles to adjust to comply with regulations.

In previous research published by Arsić [7], it was concluded that there are no defined guidelines in such cases, or about when is the appropriate moment to opt for vehicle replacement. This research attempts initially to identify the right moment for motor vehicle replacement (as perceived by the drivers of motor vehicles), depending on the most important influencing factors, to effectively manage the sustainability of motor vehicles. This analysis primarily depends on automated, statistical learning; from the existing literature, it is still not clear what constitutes the key life-cycle phases in which drivers' decision-making regarding vehicle replacement comes into play. Existing life-cycle assessment studies mainly focus on comparative studies between electric or hydrogen versus conventional fuel-based vehicles, such as in the studies by Hawkins [8] or Candelaresi [9].

Previous work on the subject of drivers' rationales for vehicle replacement suggests several starting points; regarding the life-cycle segments of passenger vehicles, Kalmakov [10] analyzed the remaining useful time-period for the exploitation of a motor vehicle, while Marell [11] analyzed the direct and indirect effects of a private driver's decision to replace their passenger car. In multi-year-spanning research by Aizcorbe [12], the reported findings show that the cost of ownership and leasing is an essential factor in any vehicle replacement decision made by a domestic household. In the case of the life cycle of commercial vehicles, Redmer [13] analyzed the economic and budgetary constraints when identifying the most suitable moment for vehicle replacement, offering a mathematical model for adjusting between those limitations.

When analyzing various aspects of the usable lifespan of an individual motor vehicle, two main topics can be identified—the indicators for defining the key life-cycle phases of motor vehicles [14], and diversification between the active use and end-of-life phases of a motor vehicle's life cycle [15].

Two assumptions remain unclear after this analysis of the existing literature—the first one challenges the fact that the age of a vehicle is the key influence on the driver's decision on vehicle replacement, and the second reflects on how different business, market and environment indicators influence the driver's rationale for opting for a new vehicle (whether passenger or commercial).

This analysis was performed with the help of the k-means algorithm (similarly used in [16]), a clustering technique of unsupervised learning, on a sample of 1240 private and commercial drivers doing business in Serbia or Montenegro. The selection of drivers for the survey is based on the criterion of owning a vehicle that is at least 10 years old.

The main research questions can be defined as follows:

- *What are the main business, market and environment indicators of influence that define the active use and end-of-life phases in the life cycle of a motor vehicle?*
- *Is it possible to define the specific indicators of influence, depending on the type of vehicle?*

The authors conducted an assessment of the most important indicators with the help of external experts, followed by quantitative research and analysis, to be able to determine the answers to both research questions. This was executed through two research teams, the first located in Serbia and the second in Montenegro.

This paper is organized in the following manner. In Section 2, the authors will summarize the existing literature on the life-cycle phases of motor vehicle usage, as well as a definition of the indicators for distinguishing between active use and the end-of-life phase of its life cycle. In Section 3, the authors will explain the methodology, framework, sampled data processing. Section 4 displays findings of the quantitative research; and in Section 5, the authors will present the conclusions, a discussion with comparisons to other previous relevant papers, and announce future research.

2. Literature Review

Motor vehicles function throughout their lifespan in terms of the time period of their use, from the moment of purchase, followed by the exploitation period, maintenance, and obsolescence until the very end of their use [17].

Karagoz [18] reveals that the majority of research papers (62%) in top-tier journals dealing with the life cycle of motor vehicles have only been published in the last ten years, making this a topic of significant interest for any research dealing with sustainability. These papers are dealing mostly with environmental indicators [19] or technology (related to engine technology, such as was researched by Lane in [20]), influencing the life-cycle phases of motor vehicles, but this research attempts to broaden the scope of indicators, which will be defined through empirical research. Costa [21] reports that only one-third of research papers include a case study or empirical research.

After careful consideration, the most significant issues in motor vehicle management in Serbia and Montenegro regarding plans for end-of-life treatment are defined with a framework analysis (from the existing literature) and are displayed in Table 1 below.

Table 1. Framework analysis of conditions related to the management of end-of-life motor vehicles.

Legislative	State of Technology and Infrastructure	Economic and Market Trends	Environment Issues
National plan and strategy for the management of end-of-life motor vehicles (Petronijevic et al. [22]) Legal support in the area of motor vehicles management aligned with EU Directive (Official Gazette [23])	Low availability of waste treatment facilities on regional and national levels, for management of end-of-life motor vehicles (Stojanovic [24]; Hogg [25]; Von Schoenberg [26] Low level of investments for infrastructure development necessary for motor vehicle dismantling (Dencic Mihajlov [27]; Marstijepovic [28])	Data regarding the volume of motor vehicles across phases of the life cycle is unavailable (Sokic et al. [29]; Ratkovic [30]) Increased number of used vehicles (older than 10 years) imported from Western Europe to Serbia/Montenegro (Bjelotomic [31]) Inadequate and under-developed public awareness on the timeliness of motor vehicle replacement (European Investment bank report [32])	High levels of pollution caused by end-of-life motor vehicles (Dumitresca [33]) Reduced environmental impact through new engine technologies (Chanaron [34])

Now follows a subsection containing theoretical research regarding the definition of the life-cycle phases of a motor vehicle.

2.1. Indicators Defining the Life-Cycle Phases of Motor Vehicle Use

The life cycle of motor vehicles is beset with many challenges; therefore, the period of exploitation differs significantly. Hawkins [35] defined an average of 150,000 km as the projected lifetime of a conventional motor vehicle before the owner replaces it.

Environment factors, such as CO_2 emissions and their influence on the business operational performance of road transport companies (investigated by Sofijanic et al. [35]), are also causing quicker fleet renewal in the search for peak performance from commercial vehicles.

Following the need to define life-cycle phases where there exists a greater likelihood that a vehicle in use could be replaced, all the potential building blocks of a separate life-cycle phase have been classified using several sets of indicators:

- Motor vehicles in use are being replaced faster with the rise of models using new technologies, as analyzed by Bajpai [36] and Vanderseypen [37], who defined differences within the lifespan of a vehicle related to environment and technology; Drahokoupil [38], EC [39] and PwC [40] identified a business perspective influencing the driver's rationale;
- Changes of procedures in vehicle innovations and modifications, as researched by Helbig [41], as well as Schmidt [42], influencing the vehicle owner to consider vehicle replacement sooner;
- The declining trend of the purchase of used vehicles with older engine technology, influenced from the environmental (Schrotten [43]), business (McKinsey [44]), and marketing point of view (Hofstatter [45]).

It is also important to take into consideration the current situation involving the COVID-19 pandemic and its influence on market trends, affecting the driver's perceptions when it comes to prolonging the use of an existing motor vehicle instead of replacing it. Acea [46] asserts that during the pandemic period, the EU region recorded a decline in vehicle sales of 24% (passenger cars), 25% (trucks), and 18% (buses), while certain regions (outside the EU) including Serbia and Montenegro recorded an overall sales growth of 15% in the middle of the pandemic.

2.2. Separating Active Use from the End-of-Life Phase of a Life-Cycle

The phase of active use in the lifetime of a motor vehicle is depicted in terms of the sustainable performance of its operational capabilities, during which time the decision-makers (drivers of passenger cars or fleet managers, in the case of commercial vehicles) are still not considering vehicle replacement. In addition, that decision is under the significant influence of the constant emergence of new vehicle models (whether passenger or commercial). Motor vehicles are replaced because of two main influences—market trends and technology trends. Market trends are reflected through the change in demand for a certain type of motor vehicle, and emerging technology trends are depicted through the introduction of new types of engines, fuel technology, new functions, and functionalities. It can be concluded that individual decisions about motor vehicle replacement represent a tradeoff between different impacts, which supports a previous, older study performed by Gaines [47].

The phase of active use of a motor vehicle is followed by the end-of-life phase, where motor vehicles are approaching the moment of termination, creating 1% of all waste in Europe (Saidani [48]; Schmidt [49]). Yang [50] investigated the end-of-life phase of the life cycle in the case of commercial trucks and found that light-duty trucks enter the end-of-life phase when the recorded emissions of greenhouse gases drastically increase (compared to the average emissions during the whole life cycle). Pavlovic [51] investigated the paradigm of sustainable growth as a consequence of recycling end-of-life vehicles in Serbia, determining the business decision, government support, and volume (number) of end-of-life motor vehicles to be critical enablers of success.

From this research, it is not clear what factors facilitate the drivers' decision to replace a commercial vehicle. Karlewski [52] adds to this list of critical indicators by introducing social life cycle assessment, combining company data with social (external) data, i.e., the number of accidents, with government legislation regarding national roads and infrastructure forcing the buyer into the decision to replace a commercial vehicle. All of this can be observed as a list of external influences, or costs to the overall decision process before vehicle replacement occurs.

Cornago [53] analyzed transport-sector incentives for the replacement of older vehicles with new, electric vehicles (through the decarbonization initiative), so it can be

concluded that external incentives can also influence the vehicle owner to decide to retire an existing vehicle.

In the case of medium- and heavy-duty trucks, entering the last stage of its life cycle occurs when the total cost of ownership increases drastically (as also previously investigated by Furch [54]), because the likelihood of the sudden breakdown of a motor vehicle increases drastically when the owner is in the unfavorable position of no longer being able to sell his vehicle. Apart from environmental (emissions—Evtimov [55]) and economic (costs) factors (as in the research conducted by Earles and Halog [56]), Miotti [57] analyzed the dependency of fuel technology and the maintenance costs of engines as the main differentiator.

3. Methodology

3.1. Framework

Since the theoretical part of this research identified solid grounds for determining a proper answer to the defined research questions, the authors have defined a specific sustainability nexus (a framework for analyzing correlations and interdependencies). Therefore, it is possible to easily identify three groups of indicators:

- Environment (engine technology) and legislative indicators;
- Business/economic indicators and market sales trends of new/used motor vehicles;
- Societal indicators.

The analysis of two focused life-cycle phases (active use and decline) should be observed within the sustainability nexus (presented in Figure 1).
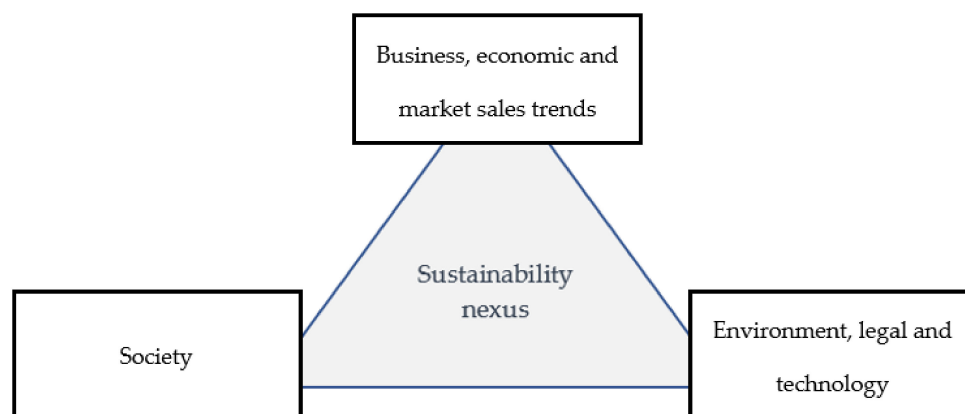
Figure 1. Sustainability nexus around motor vehicle life-cycle management.

From a variety of indicators established from the literature review, the authors approached the appropriate experts (with multiple years of experience) from the government agencies for traffic and motor vehicle safety (operating in both surveyed countries). After a discussion with these experts, the list of indicators defined through the literature review (in Section 2.1 of this manuscript) was shortened (the content of this discussion with the experts can be viewed in Appendix B). The next subchapter contains the final list of indicators, as formatted and approved by the experts, to be used in the quantitative part of this research.

Regarding quantitative research, firstly, the definition of research variables and the formulation of research goals and hypotheses were conducted to find the answers to the study's main research questions. Afterward, quantitative analysis was performed via applying the k-means clustering method of statistical learning, to be able to develop two key life-cycle phases—active use and decline.

Following deep post clustering analysis and the gathering of insights, it was possible to develop our findings and conclusions from the sampled data. The research hypotheses were tested for statistical significance via ANOVA tests, and, in terms of correlations, via the

appropriate regression tests. The research analysis is wrapped up with a discussion of the research findings and a summary of the results with those of other similar research papers.

3.2. Variables Definition and Hypothesis Formulation

Based on previous related research, discussed in Section 2 of this manuscript, the authors have formulated multiple indicators of influence on two key phases of a vehicle's life cycle, which could provide an answer to the main research questions.

Therefore, the list of indicators to be used in this research is defined in Table 2, as was also previously used by Capitano [58], as well as Hirz and Brunner [59]; the displayed indicators are part of the sustainability nexus identified in Figure 1.

Table 2. Indicators across the key life-cycle phases to be used in this research.

Key Indicators
Average age of motor vehicles (Vanderseypen [60])
Brand loyalty in relation to vehicle technology level (Power [61])
External costs influencing vehicle end-of-life management (Anderson [62])
Greenhouse gas emissions (Sopha [63], Gorner [64])
Maintenance cost in relation to operating costs (Spitzley [65])
Potential for vehicle recycling (Li [66])

Since there are no previously established boundaries or measured influences for all displayed indicators in the table, it is justifiable to conduct quantitative research to determine those boundaries. The survey questions suggest the level of influence of all mentioned indicators within the active-use and end-of-life phases of a motor vehicle's life cycle. In addition, the authors were influenced primarily by the experts in identifying when and in what circumstances drivers consider replacing their current vehicle.

All these indicators should be adequate for analyzing the sample cohort including the drivers of road vehicles in Serbia and Montenegro. The vehicles can be divided into two main types:

- Private vehicles (mostly passenger cars; see Appendix B for details);
- Commercial vehicles (cars, vans, trucks; see Appendix B for details).

In addition, the authors have formulated three research goals to be able to connect the published literature and the theoretical assumptions:

- To determine what defines the active use phase of a motor vehicle's life cycle, in terms of the different indicators of influence,
- To determine what defines the end-of-life phase of a motor vehicle's life cycle, in terms of the different indicators of influence,
- To determine whether it is possible to distinguish between life-cycle phases depending on the vehicle type (passenger or commercial vehicle).

Therefore, it is possible to determine the first, second, and third research hypotheses covering the research goals:

Hypothesis (H1). *It is possible to define the key indicators of distinctions between the active-use and end-of-life phase of a motor vehicle's life cycle.*

Hypothesis (H2). *It is possible to determine the indicators of the life-cycle phase of active use, specifically depending on its type (passenger vehicle or commercial vehicle).*

Hypothesis (H3). *It is possible to determine the indicators of the life-cycle phase of its end of life, specifically depending on its type (passenger vehicle or commercial vehicle).*

3.3. Methods Used for Quantitative Research

The research sample data has been processed using the Rapid Miner tool, v9.8 [67]. Clustering represents one of the most popular techniques in unsupervised (machine) learning, where data are grouped based on the similarity of the data points. The basic principle behind clustering is the assignment of a given set of observations into subgroups or clusters, such that the observations present in the same cluster possess a degree of similarity (see Grira [68]).

The analysis within this research manuscript aims to use clustering as a method of unsupervised learning since there is no external label attached to the object of research. Based on the answers from the sampled drivers, it is not possible to automatically determine what are the key factors that define the life-cycle phases of active use and end of life. The clustering algorithm must learn the features and patterns all by itself without any given input–output mapping. The algorithm is then able to extract inferences from the nature of data objects and then create distinct classes to group them appropriately.

The authors have followed the implementation instructions defined by Morissette [69] and Hastie [70]. Since the dataset cannot be considered as large, the Lloyd and Forgys algorithms were left out of the process; therefore, clustering was performed through the McQueen and Hartigan algorithms. In clustering machine learning, the algorithm divides the population into different groups, such that each data point is similar to the data points in the same group and dissimilar from the data points in the other groups. Based on similarity and dissimilarity, the algorithm then assigns an appropriate sub-group to the object. Generally, data should be organized into clusters, which have these properties:

- High level of intra-cluster similarity;
- Low level of inter-cluster similarity;
- Natural (visual, if possible) groupings among data points.

All findings from quantitative research shall be tested with appropriate regression tests. For measuring the performance of the clustering algorithm, the most obvious measurement is via the sum of squared errors (SSE) (see Franti [71]), an adjusted Rand index (see Santos [72]), and the variation of information (Meila [73]) and normalized mutual information (Celebi [74]).

$$\text{SSE} = \sum_{i=1}^{N} ||x_i - c_j||^2$$

Then:

$$\text{ARI} = \frac{(\textit{Rand Index} - \textit{Expected Rand Index})}{(\textit{max}(\textit{Rand Index}) - \textit{Expected Rand Index})}$$

The adjusted Rand index should have a value of close to 0.0 for random labeling, independently of the number of clusters and samples, and of exactly 1.0 when the clusters are identical:

$$\textit{VI}(X;Y) = -\sum_{i,j} r_{ij}\left(log\left(\frac{r_{ij}}{p_i}\right) + log\left(\frac{r_{ij}}{q_j}\right)\right)$$

$$\textit{NMI}(Y,C) = \frac{2\,X\,I(Y;C)}{(H(Y) + H(C))}$$

where *Y* represents the class labels, *C* represents the cluster labels, *H* represents entropy, and *I(Y; C)* represents mutual information between *Y* and *C*.

There follows a presentation of the research sample; it has been processed to perform a quantitative analysis of the displayed indicators and to define the cluster values for both life-cycle phases. Similar attempts have previously been made by Redmer [75], who defined an iNLP (integer nonlinear programming) model to assess the efficient replacement of commercial vehicles.

4. Results

4.1. Research Sample

The research sample (as shown in Table 3) consists of 1240 respondents and it includes the drivers/owners of motor vehicles that are at least 10 years old, including mostly 10–15-year-old vehicles (40% in Serbia and 47% in Montenegro), with the largest share being private cars and commercial trucks (about two-thirds of the sampled drivers in both countries). The authors tried to ensure the representativeness of the sample in terms of regional presence (drivers from all regions in Serbia and Montenegro were represented, with similar proportions). Additional characteristics of the sampled drivers (such as gender, age group, type of vehicle, etc.) have been displayed in Table A4, in Appendix B of this study. All dimensions, such as gender, age group, vehicle type, and engine type, have been subject to basic statistical tests to check for variability, in order to avoid bias (because of potential noise in the data derived from a certain group of the sample). The results of these tests confirm that the sample distribution includes a sufficient level of variability (all results from the statistical tests can also be seen in Appendix B).

Table 3. Sampled owners of motor vehicles in Serbia and Montenegro.

		Percentage of Sample	
Data	**Response**	**Serbia**	**Montenegro**
Age of motor vehicle	10–15 years	40%	53%
	16–25 years	38%	27%
	26+ years	22%	20%
Type of motor vehicle	Commercial van	24%	32%
	Commercial car	10%	11%
	Commercial truck	30%	28%
	Passenger car	30%	22%
	Bus	6%	7%

Around 10,000 potential respondents (drivers of passenger or commercial vehicles) were contacted twice through e-mail during October and November 2021, and all replies were gathered automatically through an online survey tool. All the contacted respondents who do not own/drive a motor vehicle of any sort were not allowed to proceed with giving answers in the survey. There were no missing data for the survey answers since it was not possible to submit the response without having filled in all the necessary fields.

The calculation of descriptive statistics was performed using Stata v16. The research questionnaire and the possible answers are displayed in Appendix A. The share of surveyed drivers from Serbia and Montenegro can be seen in Table 3.

### 4.2. Research Results and Findings

Defining the active use and end-of-life phases of a motor vehicle's life cycle includes obtaining empirical values (boundaries) for those indicators defined in the previous subsection and in Table 2, which are incorporated into the clustering process. By providing the characteristics of each cluster, both life-cycle phases can be clearly described, and this can serve as a starting point for determining the right moment for motor vehicle replacement. The results are displayed in Table 4.

In addition, a brief, simplified graphic display of each indicator has been introduced in Figure 2, to provide a visualization of the clustering results, when compared with age and total maintenance costs (C1 and C3 display clusters defining the active-use phase of the life cycle, in the case of passenger vehicles and commercial vehicles, respectively, C2 and C4 display clusters defining the end-of-life phase of the life cycle, in the case of passenger and commercial vehicles, respectively).

Table 4. Post-clustering ranges of research variables (key indicators for defining life-cycle phases).

Key Indicators	Intra-Cluster Ranges of Variables			
	Active Use Phase		End of Life Phase	
	Passenger Vehicle	Commercial Vehicle	Passenger Vehicle	Commercial Vehicle
Average age of motor vehicles	10–14 years old	9–11 years old	At least 14 years old	At least 12 years old
Number of travelled km	Below 200,000 km	Below 300,000 km	Above 200,000 km	Above 300,000 km
Estimated loyalty to the brand of vehicle	High to very high	Very low to low	Medium to low	Medium to low
External costs	Low to medium	Medium to high	Medium to high	High to very high
Estimation of harmful gas emissions	Low to medium	Medium to high	High to very high	Medium to high
Maintenance cost in relation to operating cost	Low to medium	Low to medium	Medium to high	High to very high
Possibility of recycling the vehicle	Medium to very high	Medium to low	Very low to medium	Very low to low
Estimated period for replacement/dismantling of vehicle	3–5 years	1–2 years	1–2 years	0–1 year
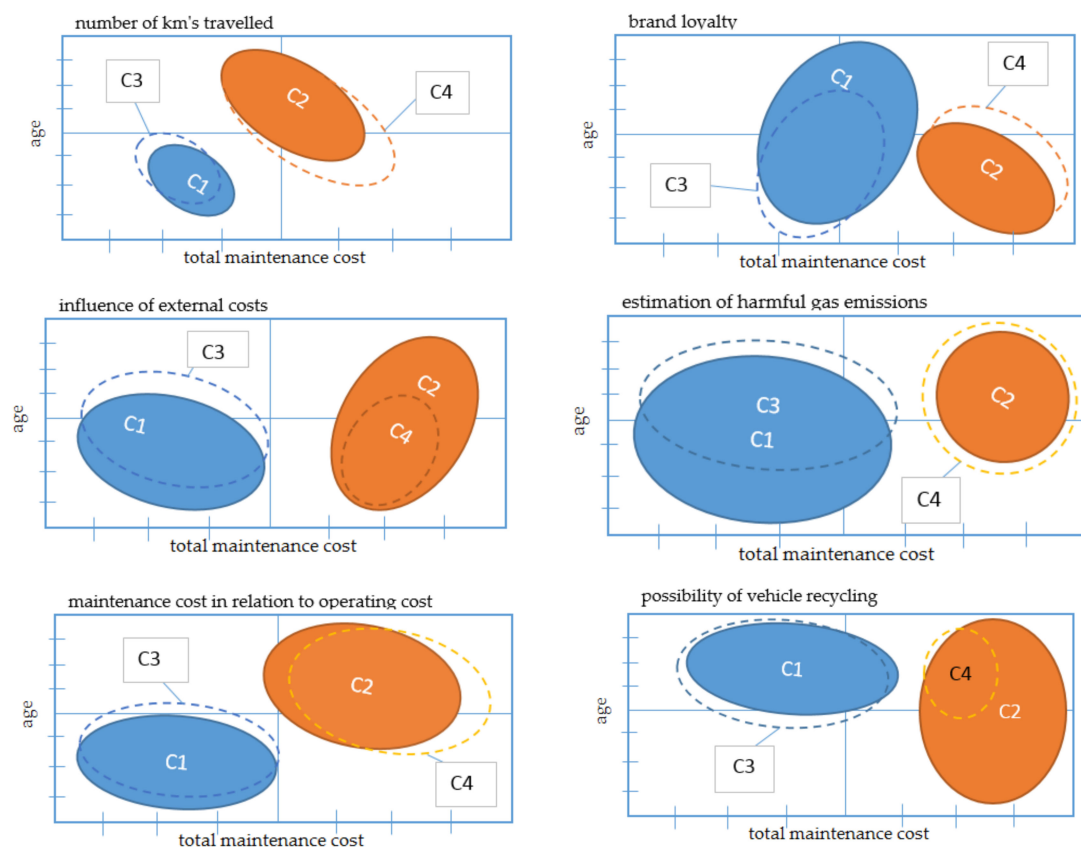
Figure 2. Visualization of clustering results between the two observed life-cycle phases (the placement of C1, C2, C3, C4 is used to determine the position of the cluster centroid).

From Table 5 and Figure 2, the main findings are as follows:

- In terms of the age of the motor vehicle, the inter-cluster border is around 14 years in the case of passenger vehicles and around 12 years in the case of commercial vehicles;
- In terms of the number of kilometers traveled, the inter-cluster border is around 200,000 km in the case of passenger vehicles and around 300,000 km in the case of commercial vehicles;
- Regarding the active-use phase—as total maintenance costs grow, the estimated loyalty to the brand of the vehicle is constant, external costs are increasing, the estimate of harmful gas emissions is increasing, and the potential for recycling the vehicle is a constant, as the vehicle is getting older;
- Regarding the end-of-life phase—as the estimate of total maintenance costs grows and surpasses the operational costs, loyalty to the brand decreases significantly, external costs (influence of the environmental impact, etc.) grow significantly, harmful gas emissions are much higher (particularly in the case of passenger vehicles), and finally, the recycling potential drops significantly;
- Regarding the type of vehicle, for the end-of-life phase of commercial vehicles, maintenance costs in relation to operating costs differ most significantly compared to passenger vehicles; therefore, this can be observed as a unique indicator of the end-of-life phase of the life cycle in the case of commercial vehicles. The same pattern can be observed with passenger vehicles in the end-of-life phase when it comes to the estimation of harmful gas emissions.

Table 5. Comparison of k-means clustering results and the subsequent performance metrics.

No. of Clusters	C1—Active-Use Phase of Life Cycle C2—End-of-Life Phase of Life Cycle			
	SSE	ARI	VI	NMI
K = 2	1911	0.36	0.87	0.43
K = 3	1083	0.28	0.66	0.55
K = 4	933	0.27	0.59	0.72
K = 5	941	0.27	0.57	0.76
K = 6	944	0.31	0.55	0.80
K = 7	975	0.30	0.52	0.81
K = 8	972	0.31	0.51	0.84

Table 5 displays the results of applying different performance metrics after k-means clustering (defined in Section 3.3). Both life-cycle phases, for each sampled country, divided by vehicle type, are included when k equals 8.

From Table 5, it can be concluded that the optimal results of the clustering process are achieved when k = 4, taking into account all four clustering performance measures (when k = 4, SSE, ARI, and VI have the minimum recorded values, and NMI has the maximum recorded value, compared with k = 2 or 3).

It is obvious from Figure 3 that clusters (based on the data from two countries) are overlapping when it comes to the active-use phase of the life cycle of a motor vehicle, and that clusters defining the end-of-life phase of the life cycle are clearly distinct and divided. Figure 4 displays a silhouette measurement of cluster validity, in the case of 2, 4, and 8 clusters (each life-cycle phase (2) is observed as one cluster in each country (2), divided by vehicle type (2)).
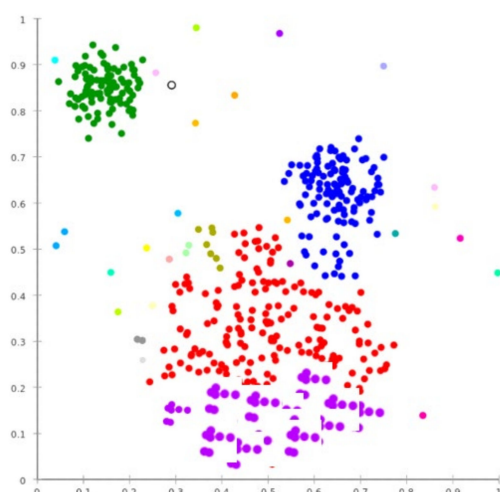
Figure 3. Results of k-means (k = 4) clustering on 1240 data points—samples from Serbia (green—end-of-life phase, red—active-use phase) and Montenegro (blue—end-of-life phase, purple—active-use phase).

No. of clusters	Spherical shape	Non-spherical shape	Spherical overlap shape
k = 2			
k = 4			
k = 8			

Figure 4. Silhouette measure of clustering when k = 2, k = 4, and k = 8.

It can be concluded from Figure 4 that the cohesion is not disturbed (coefficients are the same, around 0.8) when applying k = 4 instead of k = 2 since the silhouette represents a measure of how similar an object is to its own cluster (cohesion) compared to other clusters (separation).

However, when applying k = 8 instead of k = 4, cohesion is disturbed, and the cluster-related coefficients do not remain the same. Therefore, for the purposes of research, k equals 4. The authors applied this measure instead of the standard elbow method.

Next, we present the conducted tests to determine the significance level of the sample data and to confirm all research hypotheses.

4.3. Testing of Research Hypotheses

In order to confirm/reject all defined research hypotheses, firstly, it is necessary to determine the overall statistical significance of the research samples and sub-samples, through appropriate variance tests. Secondly, it is necessary to analyze the impact of different independent variables within two clusters (determining the active-use and end-of-life phases of the motor vehicle life cycle), distinguished according to the opinions garnered from drivers in Serbia and Montenegro, as well as by vehicle type (passenger or commercial vehicle).

4.3.1. Statistical Significance of the Research Sample

Different indicators were used for identifying both life-cycle phases of interest, so it is legitimate not only to analyze differences in the values of research variables for drivers from both surveyed countries but also to analyze the statistically significant differences between drivers who are in different countries. Samples differ by size and variability significantly, so it is possible to learn from both markets (Serbia and Montenegro).

Further analysis of the variables is carried out with the help of statistical indicators, which are appropriate assumptions whose accuracy they test:

- ANOVA test—to determine if there is any statistically significant difference within and between defined groups;
- F test and p-value.

ANOVA tests were conducted to compare the business, market, economic, and environmental indicators defining both life-cycle phases, within and between sampled groups, based on survey answers, to determine whether clustering sampled drivers (concerning passenger vehicles or commercial vehicles) into two life-cycle phases is a good model for division at all. The results can be seen in Table 6.

Table 6. ANOVA tests for both research hypotheses.

Variable	Segment of Sample	Sub-Sample	ANOVA (Sources of Variability Within and between Groups)				F Test p-Value
			Sum of Squares		Mean of Squares		
			Between Groups	Within Groups	Between Groups	Within Groups	
C1—Active-use phase	Passenger vehicles	Serbia	226,153	14,356	12,786	9657	F 11.64 p-value < 0.01
		Montenegro	192,786	12,455	11,655	9157	F 12.08 p-value < 0.01
C3—Active-use phase	Commercial vehicles	Serbia	186,533	22,391	18,954	8987	F 9.12 p-value < 0.01
		Montenegro	176,353	21,082	17,898	9165	F 10.09 p-value < 0.01
C2—End-of=life phase	Passenger vehicles	Serbia	84,566	8245	18,966	7155	F 13.33 p-value < 0.01
		Montenegro	79,633	7654	17,654	7537	F 11.91 p-value < 0.01
C4- End of life phase	Commercial vehicles	Serbia	53,662	14325	18,356	6778	F 8.36 p-value < 0.01
		Montenegro	52,356	11,765	16,859	7511	F 9,.18 p-value < 0.01

Table 6 clearly shows that the groups within and between are sufficiently representative to be tested for correlations. With the help of the sampled drivers in Serbia and Montenegro, a great deal of variability was described within independent variables (based on the values of the sum of squares and mean of squares, which are significantly larger than zero). Clusters 1 and 3 for defining the active-use phase of the life cycle have the highest score for ANOVA (the biggest difference of variability, depending on the fact of whether the sampled drivers come from Serbia or Montenegro). In the case of clusters 2 and 4, defining the end-of-life phase of the life cycle, there is enough difference in variability in both sampled countries and types of considered vehicles to be able to confirm the statistical significance of the defined results.

Based on all the above, it can be objectively considered that all three hypotheses are confirmed; that is, the tested independent variables confirm the presence of statistical significance after the definition of two clusters through k-means clustering. That is, it can be stated with 95% certainty that the analysis suggests that finding the moment for motor vehicle replacement lies between the active-use and end-of-life phases of its life cycle, depicting key influences within both identified life-cycle phases.

Undoubtedly, after analyzing all test results, it can be concluded that there is a significant relationship between the variables (the adjusted R^2 is very close to "1", the F statistics value is much larger than "1", RSE is slightly above standard deviation level, and the *p*-value is smaller than 0.05) it can be concluded that there is a statistically significant correlation between different indicators, between drivers clustered in two different life-cycle phases, on a general basis (without differentiating between types of vehicle). All tests were conducted on predefined values within the experimental region (based on values of variables within the sample).

4.3.2. Regression Tests within A Cluster (Phase of Life Cycle)

To be able to properly test all research hypotheses, it is necessary to conduct appropriate regression tests within separate clusters. To confirm each hypothesis, it is necessary to analyze the impact of each independent variable characterizing the different phases of the life cycle of a motor vehicle. The regression analysis is conducted by determining the level of regression between cluster centroids (dependent variables) and separate indicators (independent variables), with the help of several statistical indicators:

- Regression coefficients (slope) for specific independent variables (indicators);
- The *p*-value and comparison based on a confidence interval of 0.05;
- Student's *t*-test.

The results of the regression tests can be observed in the Appendix part A of the manuscript.

Regarding the regression test results between independent variables and the cluster centroids C1 and C2, it can be seen that there does exist a significant level of regression. In addition, strong regression can be identified for cluster centroid C4. However, in the case of cluster centroid C3, there is a weak regression in terms of the regression coefficient and Student's *t*-test of significance. It can be concluded that hypotheses H1 and H3 can be confirmed, but hypothesis H2 is not supported by the results of the quantitative research. In other words, it was not possible to differentiate between two types of vehicles (passenger, commercial) when it comes to the active-use phase of the life cycle of a motor vehicle.

The adjusted R^2 parameter is above 0.8 in all cases and it was not displayed in the table. Statistical parameters that also follow the regression coefficients (*p*-value and Student's *t*-test) show that adequate independent variables were used in the analysis (there are no cases where the *p*-value exceeds 0.05 and the *t*-test is always at a non-zero level) so it can be concluded that the test results are statistically significant at the 95% level.

5. Discussion and Conclusions

5.1. Comparison of Key Research Findings

This research enabled the introduction of different factors influencing the active use and end of life phases of motor vehicles' life cycles. Since the characteristics of both life-

cycle phases were developed through k-means clustering, it is important to discuss the results alongside previous findings reported by other authors.

Firstly, apart from taking into consideration the most obvious indicator (the age of a motor vehicle) for the definition of a life-cycle phase, it is possible to conclude the following:

- In terms of the active-use phase of the life cycle, since maintenance costs are perceived to be growing (to the point of being perceived as not acceptable in terms of sustainability), as the number of kilometers traveled reaches 200,000 km, this phase is also characterized by low to medium external costs, harmful gas emissions, the market appeal is still more important than technology, and the potential for recycling is medium to very high—during this phase, the majority of the resources can be reused;
- In terms of the active-use phase, there were no statistically important differences between the types of motor vehicles, regarding the level of influence of the quantified indicators;
- In terms of the end-of-life phase of the life cycle, maintenance costs are no longer sustainable after passing the 200,000 km mark, external costs are higher than ever, the estimated harmful gas emissions are higher than ever and the influence of brand loyalty is dropping significantly. The potential for reuse of the vehicle parts through recycling is minimal, and the end of life is approaching wherein the vehicle shall be put out of order through waste management;
- in terms of a cluster containing commercial vehicles in the end-of-life phase of their life cycle, a specific level of influence was identified of the maintenance cost indicator in relation to regular operating costs, which was quantified as high to very high.

When comparing the results of this empirical research to the previous findings of other authors, it is possible to identify and summarize the following:

- Avesani [75] analyzed life-cycle sustainability by considering corporate, social, and eco-friendly parameters/indicators. This paper expands on it by introducing market trends (the estimated loyalty of drivers to a specific vehicle brand, thus expanding the usage of the existing vehicle) and some environmental indicators (the estimated level of harmful gas emissions, the possibility of recycling their current vehicle). In addition, this study presents a preliminary effort to distinguish between the active-use and end-of-life phases of a motor vehicle's life cycle;
- Traverso [76] and Young [77] analyzed life-cycle phases from a sustainability point of view, concluding that social impact is having a greater than ever influence on the exploitation period of a product. This research expands along those lines, identifying the specific level of influence of external costs according to the cost of ownership, as is particularly important in the case of households owning a passenger vehicle, taking into account the share of the vehicle cost of ownership in terms of the overall costs of the entire household;
- In a study by Jasinski [78], the full cost of ownership of motor vehicles was developed, involving relevant experts with 20+ years of experience in the automotive industry, and searching a total of 4000+ papers. This research confirms their findings by analyzing the dependency of age and total maintenance costs across different indicators of influence, expanding the research to two new markets of Europe—Serbia and Montenegro;
- Conclusions from this study are in opposition to the findings made by Kagawa [79], who concluded that the drivers' decision to prolong their vehicle's life cycle (instead of replacing it with a new one), caused a decrease in the overall CO_2 emissions on a national level since the average number of vehicles in use is thus lower.

Finally, this study can be a useful addition to a previous study by Yang [80], who analyzed the life cycles of motor vehicles through input-output analysis, wherein clustering analysis enabled an initial definition of boundaries between the two life-cycle phases. An additional aspect of this research is the differentiation between the active-use and decline life-cycle phases, depending on vehicle type (passenger or commercial).

5.2. Limitations

The main limitations of this paper are that the level of environmental influence is unknown and the overall inclusion of these parameters is impossible within the proposed model. The second and even bigger problem is the fact that the survey consists of drivers' opinions gathered only for the purposes of this research, making it harder for researchers from Serbia and Montenegro to perform multiannual trend analysis.

5.3. Future Research

This research on the life-cycle assessment of motor vehicles can be expanded to include the owners of electric cars, as previously performed by Del Pero [81], and/or to the owners of hybrid cars, as in the case of research conducted in Lithuania by Petrauskiene [82]. However, the market share of electric vehicles is still low in the Balkans region, and it is mostly an issue in the case of bus transport (where it could be useful to survey the drivers of commercial vehicles in more detail).

In addition, the authors plan to expand this research to all countries in the region (Bosnia and Herzegovina, Albania, North Macedonia, etc.) to enable further testing of the clusters initially defined within this research.

5.4. Practical Implications

This research study enables readers from the academic field, as well as different stakeholders from an economic or government background, to clearly distinguish between the active-use and end-of-life phases of the life cycle of a motor vehicle. The proposed methodology can be used for decision support when considering vehicle replacement. All factors representing the main characteristics of vehicles in the active-use phase of the life cycle are important to take into consideration since the total costs of keeping the existing motor vehicle in use are perceived as being sustainable at that moment. However, this research serves as a starting point for future research into vehicle replacement decisions. Expansion of this research could find the answers to new questions that arose from this research, such as: "Why do many drivers still use their car, although they think that the external costs and the maintenance costs are high?", or "Does the rationale for vehicle replacement from an individual perspective differ from that of society?"

The process of identifying key life-cycle phases where decision-makers should execute vehicle replacement was achieved through clustering as a form of unsupervised learning, and through hypothesis-testing. The greatest influence on end-of-life phases is detected with vehicles of a certain age and mileage, as well as with vehicles that are deteriorating, stressing that vehicle replacement should occur before reaching these conditions.

The authors believe that this research can contribute to aiding decision-makers involved in transport activity, the definition or modification of government regulations, the creation of new eco-friendly investments in the automotive industry, or to anyone in a private household who is in need of data-driven advice when considering motor vehicle replacement. In addition, this research is complementary for international academic readers by offering a new perspective (considering Serbia and Montenegro as EU candidate countries already dealing with EU regulations and sustainability challenges).

Appendix A

Table A1. Research questions.

Research Question	Possible Answers (Only One Response Is Possible)				
RQ1: What is the average age of your motor vehicle? (If age is below 10, the survey ends)	Enter the age of your vehicle (minimum 10 or larger)				
RQ2: What type of motor vehicle are you driving?	Commercial van	Commercial truck	Commercial car	Passenger car	bus
RQ3: Number of km traveled with your vehicle?	Below 100,000 km	100–150,000 km	150–250,000 km	250–350,000 km	More than 350,000 km
RQ4: How would you define the level of loyalty to your vehicle's brand?	Very low	Low	Medium	High	Very high
RQ5: How would you rate the level of influence of external costs (social, environmental, legal) to the cost of ownership of your vehicle?	Very low	Low	Medium	High	Very high
RQ6: How would you rate the harmful gas emissions of your vehicle to the environment?	Very low	Low	Medium	High	Very high
RQ7: How do you rate the maintenance cost (repairs) in relation to the operating costs (regular, everyday) associated with your vehicle?	Very low	Low	Medium	High	Very high
RQ8: How would you rate the possibility of recycling your vehicle in the following period?	Very low	Low	Medium	High	Very high
RQ9: At what point would you consider replacing your current vehicle (or fleet of vehicles)?	Enter time period (number of years) after which you would consider vehicle replacement (1,2, etc)				

Table A2. Hypothesis regression tests for all dependent variables (cluster centroids C1, C2, C3, C4).

Independent Variable	Cluster Centroid *	Regression Coefficient (Slope)	*p*-Value	*t*-Test
Average age of motor vehicles	C1	0.54	<0.01	1.98
	C2	0.33	<0.01	0.96
	C3	0.65	<0.01	1.34
	C4	1.28	<0.01	1.13

Table A2. *Cont.*

Independent Variable	Cluster Centroid *	Regression Coefficient (Slope)	*p*-Value	*t*-Test
Number of traveled kilometers	C1	1.95	<0.01	2.08
	C2	1.56	<0.01	1.91
	C3	075	<0.01	1.44
	C4	3.91	<0.01	1.16
Estimated loyalty to the brand of vehicle	C1	1.21	<0.01	1.58
	C2	1.55	<0.01	1.33
	C3	0.54	<0.01	1.87
	C4	0.87	<0.01	1.25
External costs	C1	1.29	<0.01	1.22
	C2	1.63	<0.01	1.48
	C3	1.01	<0.01	1.89
	C4	1.97	<0.01	1.99
Estimation of harmful gas emissions	C1	0.91	<0.01	1.92
	C2	0.88	<0.01	1.54
	C3	0.22	<0.01	1.76
	C4	0.39	<0.01	1.65
Maintenance cost in relation to operating cost	C1	1.01	<0.01	1.77
	C2	0.93	<0.01	1.87
	C3	0.83	<0.01	1.53
	C4	4.13	<0.01	1.99
Possibility of recycling the vehicle	C1	0.88	<0.01	2.01
	C2	0.11	<0.01	1.42
	C3	0.62	<0.01	1.55
	C4	0.09	<0.01	2.11
Estimated period for replacement/dismantling of vehicle	C1	0.05	<0.01	1.64
	C2	1.88	<0.01	1.45
	C3	0.53	<0.01	1.81
	C4	2.56	<0.01	2.30

* C1—centroid for the cluster defining the active-use phase of passenger vehicles' life cycles; C2—centroid for the cluster defining the active-use phase of commercial vehicles' life cycles; C3—centroid for the cluster defining the end-of-life phase of passenger vehicles' life cycles; C4—centroid for the cluster defining the end-of-life phase of commercial vehicles' life cycles.

Appendix B

Table A3. Results of the discussion with experts.

Indicators Defined after Literature Review	Indicators Marked as Key after Discussion with Experts
Average age of motor vehicles	
Brand loyalty in relation to vehicle technology level	
External costs influencing vehicle end of life management	Marked as important for further analysis
Greenhouse gas emissions	
Maintenance cost in relation to operating costs	
Potential for vehicle recycling	
Remaining useful time for exploitation of vehicle engine	
Leasing as a form of ownership over a vehicle	
Engine technology	
Country is a candidate for EU membership	
Shortage of regional/national infrastructure for disposal of end-of-life vehicles	Marked by experts as not important for further analysis
Financial/banking incentives for vehicle replacement	
Legal support aligned with EU Directives	
Number of imported new vehicles	
Number of runtime failures	
Risk level for other participants in traffic	
Existence of mass transport systems	
Fleet renewal	

Table A4. Distribution of sampled drivers across different characteristics.

Characteristics		Serbia	Montenegro	Standard Deviation	Pearson Kendall Tau b Correlation Coefficient *								
					RQ1	RQ2	RQ3	RQ4	RQ5	RQ6	RQ7	RQ8	RQ9
Gender	Male	70%	74%	1.92	0.76	0.93	0.19	0.29	0.34	0.67	0.56	0.21	0.24
	Female	30%	26%	1.95	0.75	0.64	0.21	0.18	0.29	0.45	0.27	0.11	0.18
Age group	18–30	11%	20%	1.03	0.81	0.14	0.11	0.15	0.09	0.14	0.05	0.11	0.09
	31–50	42%	32%	1.13	0.74	0.26	0.25	0.26	0.35	0.26	0.35	0.11	0.33
	51–70	40%	34%	1.11	0.74	0.24	0.23	0.22	0.39	0.28	0.43	0.12	0.35
	71+	7%	4%	1.99	0.92	0.05	0.04	0.09	0.21	0.03	0.36	0.03	0.37
Region	Metropolitan	38%	26%	1.43	0.69	0.16	0.45	0.11	0.65	0.66	0.32	0.24	0.45
	Urban (other cities except the capital)	34%	39%	1.85	0.70	0.17	0.48	0.15	0.62	0.58	0.30	0.26	0.43
	Rural	28%	35%	2.01	0.84	0.26	0.43	0.02	0.36	0.24	0.24	0.14	0.48
Passenger vehicle type	Small car	29%	9%	1.94	0.65	0.22	0.23	0.02	0.11	0.27	0.21	0.11	0.51
	Family car	54%	63%	1.44	0.63	0.34	0.66	0.11	0.12	0.43	0.22	0.22	0.65
	Sports car	5%	2%	1.65	0.67	0.12	0.24	0.35	0.55	0.78	0.15	0.09	0.45
	SUV/Jeep	12%	26%	1.54	0.58	0.25	0.25	0.39	0.23	0.95	0.16	0.03	0.40
Engine type	Diesel	45%	62%	1.86	0.57	0.51	0.32	0.01	0.55	0.89	0.02	0.25	0.11
	Unleaded	55%	38%	1.54	0.58	0.49	0.31	0.01	0.46	0.56	0.04	0.22	0.09
Type of commercial vehicle	Bus	17%	21%	2.34	0.48	0.44	0.77	0.01	0.08	0.88	0.06	0.07	0.11
	Small transport vehicle	18%	19%	2.11	0.49	0.22	0.75	0.02	0.07	0.54	0.11	0.11	0.12
	Light commercial vehicle	40%	35%	1.54	0.33	0.24	0.76	0.03	0.04	0.78	0.12	0.16	0.14
	Medium commercial vehicle	10%	9%	1.32	0.49	0.26	0.78	0.01	0.16	0.69	0.14	0.24	0.12
	Heavy-duty vehicle	15%	16%	1.12	0.63	0.21	0.90	0.01	0.01	0.66	0.28	0.21	0.08

* Pearson correlation coefficient between the sample characteristics and the response to a survey question.

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