Selection of vehicles for fleet of transport company on the basis of observation of their operational reliability

Tadeusz Dziubak[a], Tadeusz Wysocki[a], Sebastian Dziubak[a]

[a]Military University of Technology, Faculty of Mechanical Engineering, ul. Gen. Sylwestra Kaliskiego 2, 00-908 Warsaw, Poland

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Highlights

- A research method was proposed which aims to study the operational reliability of the vehicles.
- The operational reliability indices describing the failure frequency of the vehicles were used.
- An evaluation and comparison of the operational reliability of four makes of the vehicles operated was carried out.
- The reasonability to unify the fleet of the light commercial vehicles was confirmed.

Abstract

The exploitation reliability of the contemporary light commercial vehicles of four makes is subject to a quantitative analysis in the article. The issue concerning the quantitative evaluation of the operational reliability of the fleet of the commercial vehicles in the transport company and their selection for this fleet is not very numerously described in the literature. For the purposes of evaluating the operational reliability, results of monitoring failures of 115 vehicles during their several years of exploitation in the similar conditions in the urban area and its surroundings were used. A proposed test method uses the relative quantitative measures of the operational reliability indices targeted at the mileage of vehicles and frequency of the failures. The aforementioned enabled to identify the make of the vehicles, which during exploitation was characterized by the lowest failure frequency and thus reliability. This, in turn, allowed for a favorable selection of the vehicles within the next years of the operation of the company. The results of the study confirmed the possibility of using the proposed method to evaluate the operational reliability of the commercial vehicles in any transport company.

Keywords

exploitation, light commercial vehicles, exploitation reliability, indices of operational reliability evaluation.

1. Introduction

The selection of the vehicles for a fleet of the company should depend primarily on a profile of its economic activity and current transport needs. The transport fleet is of necessity in the economic activity where the sales and distribution of goods to the customer or the carriage of passengers is carried out. However, while selecting the vehicles, special attention should be paid not only to their technical parameters, including cargo parameters, but also to the efficiency and economy of the drive unit (engine power, fuel consumption, fulfilment of the Euro standards). An important performance parameter is also their failure frequency. The lower the failure frequency, the lower the costs of maintaining the fleet and the risk of failure to complete the task. Certainly, other criteria should be adopted in case of selecting, for example, passenger cars for the department of goods distribution in the undertaking, and others in the event of the commercial vehicles for the purposes of the goods distribution.

The planning and implementation of the exploitation process of the motor vehicles in a complex transport system requires the efficient use of the means of transport and constitutes one of the main manners of achieving a competitive advantage in the present-day market.

When a utility vehicle (commercial vehicle or light commercial vehicle) is selected by the entrepreneur, exploitation costs have a major impact, apart from the vehicle model, make and purchase price, as well as the exploitation decline in value.

Physical aging of the vehicle components resulting from the processes in the individual systems and matching elements, momentary overloads of these components and random events (e.g., collisions and road accidents) affect both the durability and reliability of the entire vehicle [37]. The evaluation of costs should take into account not only the predictable (planned) operating costs, but also the "incidental costs", which are strictly related to the operational reliability of the vehicles. Their importance is demonstrated by their significant impact on the guarantee and a completion of the transport service in a fashion manner. A failure frequency of the vehicles and the losses incurred due to it are in many cases the main factor for which the user loses confidence in a given make. Thus, the procedure for selecting vehicles by the user should consider an aspect of their technical failure frequency (operational reliability), including the type of failure, its frequency and repair costs.

There are researches in the source literature which present a reliability approach to the issues of the optimal selection of the means of transport to be used by a company for its transport operations [25], but

they are not numerous. Furthermore, the network analysis methods (CPM, PERT, GERT) often presented in the publications do not take this approach, as they are limited to the determination of the critical path for the planned transport of goods. In particular, as emphasized in [41], in an era of the strong market competition, the optimal selection of the means of transport for the undertaken transport task reduces the own costs of the company. This allows for a significant reduction in the price of the service and makes it easier to adjust the time and frequency of goods delivery to the customer expectations. However, in the procedure of optimal selection of the means of transport for the purposes of carrying out the undertaken transport task, it is proposed to take into account, inter alia, the criteria of availability, utilization of loading capacity and applicable legal restrictions, e.g., the EURO standards concerning the selected means of transport. The basis for such considerations can be found in the papers [42].

2. State of the art related to the research subject matter

In a system of exploitation, many different reliability indices are used in order to evaluate the efficiency of the use and handling of the vehicles, for example in respect of to the selected vehicle system [28, 32] or system component [33] in terms of the total reliability.

The authors of the paper [32], while using the reliability indices, concluded that the reliability of the individual structural systems of the two researched bus makes is different, in particular in terms of their mileage to first failure, whereby the system of the public transport buses that is characterized by the highest failure frequency turned out to be the engine itself. Whereas, the lowest risk of failure was determined in the power and braking systems. These results are inconsistent with the data obtained by the authors of the paper [28], who had evaluated a quantity of failures per public transport bus and per 10,000 km and the mileage between the failures and had stated that the braking system and external lighting, alarm system, tires and steering system had made the greatest impact (32-50%). The failure data of the individual systems were in consonance with the exponential distribution. The study is highly reliable as it had been conducted over a three-year period on a population of 160 public transport buses. The reliability curve shows that as an age of the vehicle increases, so does the failure frequency, and an established optimum useful life of the vehicle is 72 months. The aforementioned data is similar to the results of the comparative reliability studies of two selected makes of the commercial vehicles under the long-term rental conditions presented in the paper [36]. A description of reliability of the subassemblies and components was drawn up taking into account the mileage to first failure and the mean mileage between the repairs.

In these publications it was stated that the systems that feature the highest failure frequency of the studied vehicles in terms of the mileage to first failure were engine and powertrain, electrical, brake and exhaust systems. The aforementioned partially confirms the results of the analysis presented in [28]. Furthermore, it proves that one group of the vehicles is characterized by much higher reliability and lower exploitation costs than the vehicles of the second make, which coincides with a similar ascertainment presented in [32]. The similar findings were made by the authors of the paper [31], proving that the greatest repair costs are generated by failures to the suspension system and wheels and steering system, engine and powertrain and braking system. The analyzed systems of the vehicle were also mentioned by other authors [28, 32, 36] as the systems generating the highest quantity of failures and the highest repair costs. The above analyses fail to cover the repair time, which is also an important cost-generating factor, as apparently the minor failures may be the cause of the long-standing taking out of service of the vehicles. The problem of time in the reliability evaluation was presented by the authors of the paper [13], who used three reliability indices based on the averaged time in order evaluate the reliability of the main components of the electric vehicles: MTTF – mean time to failure, MTTR - mean time to repair

(downtime), MTBF - mean time between failures (cycle time that is a sum of operating time and downtime). Similarly defined reliability indices were presented by the authors of the paper [43] to evaluate the vehicle failure frequencies (Load-Haul-Dump) in an underground rock mine in Canada. They used the total time between failures, the time to repair (TTR), the time between failures (TBF) and, moreover, the machine downtime during a shift to evaluate the systems and components to which the generated breakdowns and failures were ascribed.

The author of the papers [39, 40] asserts that the aforementioned methods of the reliability description applied to the objects working to first failure, e.g., using only the reliability function R(t) or failure intensity λ(t) are insufficient. Reliability was presented by the author as a comprehensive property including: reliability, availability and maintainability (RAM). The RAM method is used in the varied industrial sectors, including aerospace, defense, energy, processing and transport [18, 34, 40]. For example, in the paper [18] the authors describe the possibilities of using the RAM model in the industrial practice to identify a critical equipment in terms of the frequent failures or high maintenance requirements. The paper [34] presents the use of the RAM analysis as a helpful tool in the design of systems, in the implementation of structural changes to achieve a minimum quantity of failures and increase the mean time between failures. The research [40] studies a relationship between the readiness, maintainability of the means of rail transport and the costs of unscheduled downtimes and vehicle maintenance. A model of the optimal implementation of the periodic inspections and repairs was conceptualized from a point of view of the costs, taking into account the current data on the vehicle failures.

The reliability indices are also used to analyze the exploitation costs of vehicles, while selecting a utility vehicle (commercial vehicle or light commercial vehicle) by the entrepreneur, have a major impact, apart from the model, vehicle make, purchase price and exploitation decline in value. In the vehicle exploitation, the planned costs of: repairs and technical maintenance, employees of maintenance and repair station personnel, parts and assemblies, fuel and oil, as well as other fluids and consumables [7, 10, 11] and the so-called "incidental costs": unplanned downtimes resulting from a potential loss of trust of the ordering party, the need to provide replacement vehicles [29], changes in the allocation of the vehicles to the specific operations [26].

Another condition, brought up in the source literature, related to the selection of the vehicles in a company that has been gaining in importance and popularity within the recent years, is the environmental safety of the transport fleet, which is determined by the various factors, such as, for example: vehicles in a bad technical condition and emitting an increased amount of toxic compounds into the atmosphere [3, 9], an implementation of technologies (catalytic reactor, DPF and electronic injection, EGR system) reducing an impact of toxic exhaust gases on the environment [27], properly selected engine oil of low viscosity, which increases engine efficiency and simultaneously reduces a fuel consumption [14] and an oil contamination with fuel which may condense on the walls of the cylinder liner and flow into the oil sump reducing oil viscosity and carbon black resulting from an operation of the EGR system [1, 22]. As a result of this phenomenon, the chemical and physical properties of the engine oil deteriorate, which may result in the accelerated wear of the engine parts and its higher failure frequency. The elongated maintenance intervals in respect of the internal combustion engines extended by the manufacturers, aimed at reducing the vehicle exploitation costs and the environmental impact of the used oil are conductive to this process. At the present moment, a low fuel consumption and a compliance with the exhaust emission standards is a key exploitation factor in the vehicle selection for the company fleet.

Many national and international publications describe a problem of optimizing an allocation of the vehicles to their tasks. This solution should take into account the time of the individual tasks as this time

determines the risk of the vehicle failure. A typical multi-vehicle task allocation scenario consists in a deployment of the fleet of vehicles to visit a group of the target locations while minimizing the certain objectives such as: the total cost of traveling of the vehicles with a limited loading capacity to deliver the order to the several customers and return to the depot [5], the fuel consumption costs, cargo storage costs, cargo purchase costs and lead times depending on a cargo weight and a vehicle loading capacity [20], the maintenance costs including preventive maintenance of the heavy vehicles travelling long distances in the rather difficult road conditions [23], the costs and lead times of the cargo carriage including technical and economic factors [41], the total cost per unit of a fuel consumption fulfilling the requirements of three interdependent factors: transport, maintenance and environment [44], the total travel time of a fleet of the distributed vehicles that has to visit multiple destinations while encountering obstacles [3], the time of assigning planes to apron parking lots upon their landing [15], the total distance travelled by the robots [50], the maximum time for the robots to perform their tasks [12] or finding a maximum quantity of persons assigned to the vehicles in the flooded areas [51], the costs of a non-compliance with the service schedule [45], the time of waste collection, the duration of route allocation and the use of the resources [21]. The solution to the transport task may be to calculate the optimal route taking into account the exploitation parameters [47].

However, most of these researches focus primarily on how to effectively assign tasks to the vehicles, assuming that these vehicles can move freely between any two chosen locations where there is no external interference.

According to the author of the paper [35], the modern-day vehicles, which are equipped with on-board telematic systems connecting electronic devices between them, also have a specific exploitation potential, which can be used to improve a value of the specific reliability and exploitation indices of the vehicles. Transport telematics is the application of information, telecommunication, automatic, measurement and transport management technologies to achieve the best possible results in the trafficability performance. Telematics systems include the Internet, mobile networks, radio communication systems, geographical and road databases, satellite navigation systems, weather and traffic monitoring devices, radars and street cameras.

An improvement in the vehicle reliability and exploitation indices can be achieved by the use of the wireless technologies used in the vehicle-to-vehicle or vehicle-to-infrastructure communication. For example, in [2] a model was developed for the purpose of evaluating an impact of the "vehicle-to-vehicle" (V2V) and the "vehicle-to-infrastructure" (V2I) technology for the travel time and its reliability and for the scenario of a motorway work zone, which causes an increase in the travel time, queuing length and fuel consumption. The authors of the paper [19] presented the thesis that "vehicle-to-vehicle" communication (V2V) while using the short-range communication technology (DSRC) can help dramatically reduce a quantity of the vehicle collisions. Whereas, the paper [49] discusses the VANETs system, which is part of the intelligent transport system (ITS), using the "vehicle-to-vehicle" (V2V) and "vehicle-infrastructure" (V2I) communication to obtain information on the traffic and vehicle condition so that the road accidents can be prevented. The basic problems of the cooperating vehicle-infrastructure system (CVIS) were analyzed in the paper [52]. It discusses how the vehicle and network communication influences the benefits received from the common calculations in the CVIS and what should be an optimal cooperation in terms of reliability. Thus, the vehicles equipped with such technologies are better perceived by the purchaser and will be more willingly proposed to equip the fleet of the company.

The studies on evaluating the exploitation reliability of both intercity and urban rail transport contained in the available literature are aimed at: a reduction of the exploitation costs and an improvement of the maintenance efficiency, a flexible management of exploitation and ensuring safety of the urban railway system [6], a development of a model of the railway vehicle maintenance strategy based on the

reliability indices - mean time to first failure, mean time between failures, mean time to recovery [16], an elaboration of a model for the short-term prediction of train failures taking into account the intensity of failures and a configuration of the spare parts [24].

It should be highlighted that the source literature does not often include the comprehensive studies describing the methods of the optimal selection of rolling stock (means of transport) in the transport company considering their operational reliability.

Therefore, there is a need to apply the comprehensive methods that enable to select the means of transport in the transport company in the optimal manner, taking into account their operational reliability. In the available literature, such researches are not easily available, hence there is a need to supplement this knowledge in terms of the reliability-based approach to solving the problem of selecting and optimizing the structure of the means of road transport in the company.

The commercial vehicles are essential for an existence of the transport company on the market. Therefore, the fleet should consist of the vehicles with the lowest failure frequency, which has a positive impact on their operational reliability.

The commercial vehicle is an intricate technical system which exploitation reliability is defined as a characteristic of its ability to be used or handled under the certain operating conditions. The evaluation of the operational reliability of the commercial vehicle is enabled by the various measures, including quantitative measures in the form of the varied numerical indices of the statistical nature. The availability of information on a course of the performance of the commercial vehicle in a concerned transport company is a key condition for the daily use of such indices [6].

The analysis carried out on the problem of the exploitation reliability of the vehicles shows that they usually involve a minimization of the costs linked to their use and operation, and ensuring the maximum reliability of the transport system. The impact of the vehicle use on the natural environment and the resulting safety and reliability aspect is also subject to the analyses. From the standpoint of authors of many studies an improvement of the reliability and exploitation indices of the vehicles can be achieved using the wireless technologies used in the vehicle communication and the telematic equipment of the on-board systems. The evaluation of the exploitation intensity of the vehicle is conducted while considering, inter alia, the mileage value, engine capacity, vehicle age, repair costs, revenues, technical readiness and intensity of the vehicle operation. It is not very often that the studies analyze and provide models for evaluating the operational reliability of the commercial vehicles in the transport company. This evaluation is of particular importance when selecting vehicles for the company.

This publication is an attempt to present the model that enables a manufacturer of the means of road transport, in particular light commercial vehicles, to select a vehicle manufacturer for the transport company while regarding its operational reliability.

3. General systematics of the exploitation reliability of the vehicle

The exploitation of a vehicle comprises a set of the intentional, interconnected organizational and technical operations from the moment the vehicle is taken into operation in order to use it optimally and according to its intended use until its totaling.

The optimal use of the vehicle is conditioned by many of its properties, among which the exploitation reliability expressed as a set of properties that describe the readiness for use and correctness of operation, durability, repairability and maintainability of the vehicle is of great importance. It is a measure of an ability of the vehicle to perform its functions efficiently, if needed and for a duration of the required time or mileage and under the specific environmental conditions.

In the exploitation practice, the readiness for use of the vehicle is treated as a fraction of a period of its usability, during which the vehicle performs or is able to perform its utility functions.

The correctness of operation is characterized by an ability of the vehicle to perform its work without any failure, and its durability - to maintain its usability until the vehicle reaches the limit state which means that it is technically impossible or economically inexpedient to continue its exploitation. The repairability, on the other hand, should be understood as a characteristic of the vehicle, which means its adaptation to the recovery of its condition by removing malfunctions or failures through maintenance and repair. The maintainability is a property of the vehicle which consists in maintaining the determined values of its exploitation parameters during its non-use [17].

The exploitation reliability of each vehicle is subject to the continuous and unfavorable changes due to an occurrence of operational wear and tear phenomenon. Having a knowledge of this reliability largely enables efficient and effective management in the company.

For the purposes of evaluating the exploitation reliability of the vehicles in the company the specifications, known as the reliability indices, which enable to conduct a quantitative evaluation of the impact of the varied factors occurring within the process of exploitation of the individual groups of the vehicles on their reliability and the obtained operational effects [46, 48]. Furthermore, the reliability indices facilitate a correct organization of the use and maintenance processes, including planning of the spare parts procurement within the company.

It can be assumed that the specific exploitation performance of the vehicle that determine its exploitation reliability are, first of all, as follows:
- correctness of operation, characterized by its ability to perform work failure-free,
- repairability, characterized by its ability to recover its usability.

The aforementioned properties of the vehicle are verifiable and measurable during its exploitation. While determining their characteristics, the conditions under which the vehicle was used or operated are taken into account. Thus, reliability in the broader sense, i.e., the exploitation reliability or, in a narrower sense, the operational reliability of the selected vehicle or a specific group of the vehicles in the company can be determined.

The operational reliability of the commercial vehicle is nothing else than its property - its ability to be used under the certain operating conditions and for a certain period of time or a certain service live. The operational reliability of the vehicle expresses a confidence of the decision-maker, dispatcher or driver that the vehicle will be fit to commence a transport task and will maintain this usability to complete that task(s). The level of this confidence may depend on a type of the task, requirements of the decision maker, conditions of completion and other factors [17].

The reliability theory makes extensive use of statistical calculation methods, and a global or a targeted operational reliability of the concerned make of the commercial vehicle can be determined as a value of a specific quantitative measure of a statistical nature or a group of these measures.

In addition to the operational reliability of a technical system, other types of the technical system, such as maintenance or economic reliability, are distinguished in the source literature.

The maintenance reliability expresses a confidence of the decision-maker and/or operator that an object (component, device, system) can be operated (recovered) under the certain conditions and over a certain time. On the other hand, the economic reliability - that an object will perform a specific exploitation (operational) task at an economic profit.

This trust may be based on the experience gained from observing the functioning of a certain population of the objects of the same type, carried out under the same or similar operating conditions, frequently also on a theoretical analysis and a simulation of the exploitation processes [17].

4. Evaluation criteria of the operational reliability of the vehicle

The studying and evaluation of the operational reliability of the commercial vehicles plays an important role in conveying information to the entity that operates them. Each entity that commissions in-service testing expects different information on the condition of its own fleet, so for each entity the reliability testing is usually targeted on the specific characteristics of its vehicles and is usually conducted under a different focus using the different reliability measures and indices or characteristics.

In this paper, the multi-criteria in-service reliability study of four groups (makes) of the commercial vehicles in the transport company existing on the modern market used three basic measures (quantitative indices), which are used in the literature to evaluate motor vehicles, rail vehicles, electric vehicles [17].

- mean mileage do to first failure $L_{u,k}$ of the vehicles in the studied "k" group,
- mean failure intensity $\lambda_{u,k}(l)$ of the vehicles in the studied "k" group,
- mean mileage between failures (breakdowns) $L_{m,k}$ in the studied "k" group.

The studies concerned a determination of the operational reliability of these groups (makes) of the vehicles targeted on the frequency of an occurrence of failures (breakdowns) preventing periodically (temporarily) the use of these vehicles by the concerned company.

The indices of the operational reliability of the concerned transport means used in the course of the study are presented below:

1) Mean mileage $L_{u,k}$ to first failure "u" of the vehicles in the studied „k" vehicle group/make is defined by the relation:

$$L_{u,k} = \frac{1}{N(0)}\left(L_1 + L_2 + \ldots + L_{N(0)}\right) = \frac{1}{N(0)}\sum_{i=1}^{N(0)} L_i \quad [\text{km}], \quad (1)$$

where: $N(0)$ – quantity of the vehicles studied in the concerned vehicle group/make, L_i – mileage to first failure of i – th vehicle in the concerned group (make).

2) Mean failure intensity $\lambda_{u,k}(l)$ of the vehicles in the studied "k" vehicle group/make for their assumed mileage/service life l (l = 75,000 km) is defined by the relation:

$$\lambda_{u,k}(l) = \frac{n(l)}{N(0)*L}\left[\frac{failures}{km}\right] = \frac{l*n(l)}{N(0)*L}\left[\frac{failures}{75,000km}\right], \quad (2)$$

where: $n(l)$ – quantity of failures (breakdowns) of the individual vehicles for the assumed mileage/service life l, L – total mileage of the studied "k" vehicle group (make) to their first and subsequent failures for the assumed service life/mileage l = 75,000 km.

3) Mean mileage $L_{m,k}$ between failures "m" (breakdowns) in the studied „k" vehicle group (make) is defined by the equation:

$$L_{m,k} = \frac{1}{\sum_{j=1}^{N(0)}\left(\sum_{i=1}^{n_j}n_{ij}-1\right)}\sum_{j=1}^{N(0)}\sum_{i=2}^{n_j}l_{ij} = \frac{1}{\sum_{j=1}^{N(0)}\left(n_j-1\right)}\sum_{j=1}^{N(0)}\sum_{i=2}^{n_j}l_{ij} \ [\text{km}],$$

$$(3)$$

where: n_{ij} – i-th failure in the j - th vehicle, l_{ij} – mileage between i - th, and preceding $(i$-1$)$ failure of j – th vehicle, n_j – j - th vehicle in the studied group of the vehicles, $N(0)$ – a quantity of the vehicles studied in the concerned "k" vehicle group/make.

It should be emphasized the above listed utility reliability indices have different physical quantities, which would significantly impede their use and comparison during a targeted analysis of this reliability for the studied groups (makes) of the light commercial vehicles.

In order to enable a mutual comparison, the indices (1, 2, 3) adopted for the analysis were subjected to a standard normalization procedure, depriving them, inter alia, of a physical quantity and standardizing their order of values to the range [0; 1].

The standardized index of mean mileage to first failure $L_{u,knorm}$ of the concerned "k" vehicle group/make was calculated according to the following relationship:

$$L_{u,knorm} = \frac{L_{u,k} - L_{u,min}}{L_{u,max} - L_{u,min}}, \qquad (4)$$

where: $L_{u,k}$ – mean mileage to first failure of the concerned "k" vehicle group (make), $L_{u,min}$ – minimum mileage to the first failure of the vehicle required in the company was of 50,000 km, $L_{u,max}$ – maximum value of mean mileage to first failure among the A, B, C and D vehicle makes considered within the study.

The quantitative condition for the data adopted for the calculations:

$$L_{u,min} \le L_{u,k},$$

what means that a minimum mileage to the first failure of the vehicles required in the company with regard to the possessed fleet may not exceed a monitored/disclosed mean value for this mileage.

The standardized index of mean failure intensity $\lambda_{k,norm}(75,000)$ at the beginning of exploitation for the mileage adopted in the company $l = 75,000$ km was calculated with the use of the following relationship:

$$\lambda_{u,knorm}(75,000) = 1 - \frac{\lambda_{u,k}(75,000) - \lambda_{u,n}}{\lambda_{u,max} - \lambda_{u,min}}, \qquad (5)$$

where: $\lambda_{u,k}(75,000)$ – mean failure intensity of the vehicles of the concerned make, $\lambda_{u,min}$ – minimum value of mean failure intensity for the studied vehicle makes, $\lambda_{u,max}$ – mean failure intensity of the vehicles required in the company should not exceed 0.5 failure/75,000km.

The quantitative condition for the data adopted for the calculations:

$$\lambda_{u,max} > \lambda_{u,min},$$

what means that a permissible, required by the company, mean failure intensity of the vehicles with regard to the possessed fleet cannot be less than monitored/disclosed value of the intensity.

The standardized index of mean mileage between failures $L_{m,knorm}$ for the vehicles of the studied make was calculated from the following relationship:

$$L_{m,knorm} = \frac{L_{m,k} - L_{m,min}}{L_{m,max} - L_{m,min}}, \qquad (6)$$

where: $L_{m,k}$ – mean mileage between failures/breakdowns of the studied vehicle make, $L_{m,min}$ – minimum mileage between failures required in the company was of 10,000 km, $L_{m,max}$ – maximum value of mean mileage between failures among the considered vehicle makes.

The quantitative condition for the data adopted for the calculations:

$$L_{m,min} \le L_{m,k},$$

what means that a minimum mileage between failures required in the company with regard to the possessed fleet cannot exceed a monitored/disclosed mean value for this mileage.

5. Algorithm for the evaluation of the operational reliability of the vehicles in the transport company

Unquestionably, an effective methodology for studying the reliability of the commercial vehicles in the transport company is the key to their utility evaluation and, following an appropriate decision on the selection (choice) of the most reliable vehicle makes for the fleet already in possessed.

For the need of the undertaken evaluation, an algorithm for evaluating the operational reliability of the commercial vehicles had been developed in the form of a diagram, which was then used for such an evaluation of the commercial vehicles in the transport company existing on the Polish market (Fig. 1). The study covered four makes (groups) of the light commercial vehicles – delivery vans. In each group there were vehicles of the same homologation category N1 used since their manufacture for several years under the similar conditions in the concerned transport company. The quantity of the vehicles in the individual groups (makes) varied. The monitoring in this study covered the years (2010-2015) of the use of these vehicles

The versatility of the above diagram consists, inter alia, in the fact that the mathematical models (indices) of the operational reliability of the individual means of transport used in any study, according to the range of information (data) available, and depending on a course of their exploitation – use, can be always freely changed. According to the following algorithm, the operational reliability indices were calculated for the studied vehicle makes in the concerned transport company.
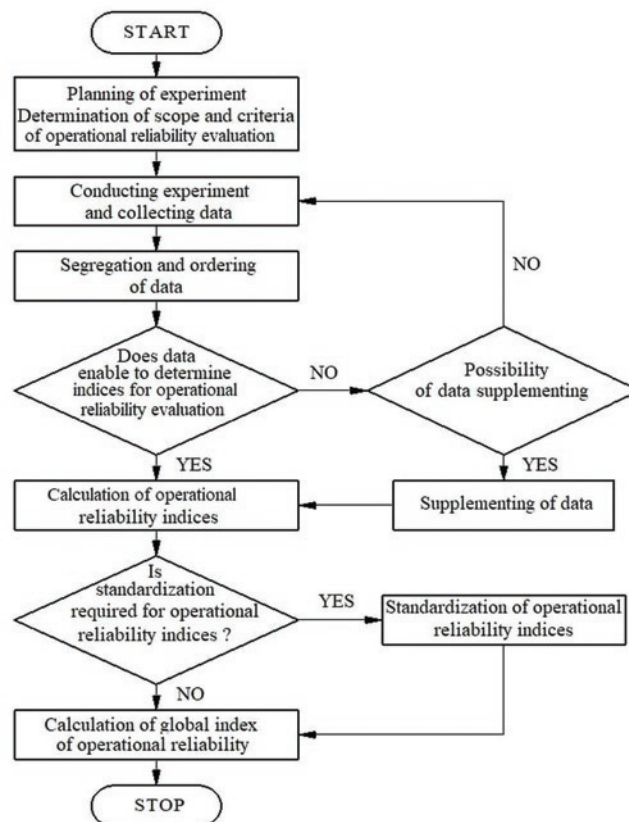

Fig. 1. Algorithm for evaluation of operational reliability of vehicles

6. Selection of the vehicle makes in the transport company on the basis of the evaluation of their operational reliability

It is common knowledge that the benefits of unifying the model/make of the manufacturer of the vehicle fleet in the specialized transport company can be great. They result, in particular, from an actual possibility of a significant reduction of the overall costs of servicing and repairing a uniform fleet compared to another company with the similar fleet, but including the varied models/makes. These benefits are without any doubts even greater if the company unifies its vehicle fleet to the model/make of the manufacturer that currently has the least failure frequency in the market in relation to other vehicle makes, which may result, inter alia, from a reduction in the overall costs of repairing such unified fleet and its greater operational reliability.

It was proposed to the specialized road transport company, currently operating on the national market, to unify the make of light commercial vehicles (category N1) from the four vehicle makes already used on the market (A, B, C and D) on the basis of the results of ob-

serving their operational reliability, in particular the failure frequency or breakdown frequency that prevent them on a periodical basis from being used. As known, the benefits of such a procedure for the company are multiple, especially it enables, inter alia, to reasonably limit a quantity of the vehicle makes possessed to the one make, characterized by the vehicles with a relatively low failure frequency, which significantly reduces the costs of the conducted economic activity.

On the request of the company, the study was undertaken, during which data was collected containing targeted and detailed information on the exploitation of those vehicles, concerning their quantity in terms of featuring the concerned make of the manufacturer and a mileage to the first and subsequent failures (breakdown). A duration of the vehicle downtime in the service station for at least one day - 8 working hours was assumed to be the failure (breakdown). In the studied company, A make consisted of 19 vehicles, B make - 20, C make - 36, and D make - 40 vehicles.

Due to the large number of data collected during the concerned research, this study presents the selected monitoring data concerning only the failure frequency of A-make vehicles (Table 1 and 2).

Table 1. List of the A make vehicles along with their mileage to first failure

A make		Failure [km]						
Vehicle Number		1	2	3	4	5	6	7
A1	Mileage [km]	35 031	43 312	46 485	48 651			
A2		25 962						
A3		77 859						
A4		43 535						
A5		55 503						
A6		70 638						
A7		91 465						
A8		79 339	80 601	88 760				
A9		57 051	81 500					
A10		77 000	112 967					
A11		50 307	100 702	125 472	133 117	135 525	165 556	
A12		56 012	67 509	71 586	79 542			
A13		78 199						
A14		87 655						
A15		24 786	106 163	106 775				
A16		103 363						
A17		90 263						
A18		39 720	57 500	65 642	96 292	120 021	130 417	147 162
A19		45 068	63 996	71 063	72 939	103 074	129 011	

Table 2. Mileages between subsequent failures of the vehicles of A make [km]

A make	Failure number					
Vehicle number	2-1	3-2	4-3	5-4	6-5	7-6
A1	8 281	3 173	2 166			
A8	1 262	8 159				
A9	24 449					
A10	35 967					
A11	50 395	24 770	7 645	2 408	30 031	
A12	11 497	4 077	7 956			
A15	81 377	612				
A18	17 780	8 142	30 650	23 729	10 396	16 745
A19	18 928	7 067	1 876	30 135	25 937	

On the basis of the data presented in Table 1, the value of the index relating to the mean mileage to the first failure and the mean failure intensity to the mileage of 75,000 km of the vehicles of A make was determined. It can be easily perceived that only a few vehicles of this make features a great failure frequency. The data in this table were used to determine the mileage between the subsequent failures of the vehicles of this make (Table 2).

On the basis of the data presented in Table 2, a large dispersion of mileage between the subsequent failures of the vehicles of the A make is visible. The value of this dispersion results from an impact of the varied factors during the exploitation of these vehicles, in that also random factors.

The indices of the mean failure intensity of the vehicles featuring the individual makes were determined for the set-point value of 75,000 km of the service life/mileage. The results of the calculations are presented in Table 3.

Mean mileage of the vehicles of A make to first failure:

$$L_{u,A} = \frac{1}{N(0)}\left(L_1 + L_2 + \ldots + L_{N(0)}\right) = \frac{1}{N(0)}\sum_{i=1}^{N(0)} L_i,$$

$$L_{u,A} \cong 62,566\,\text{km}.$$

Maximum value of the mean mileage to the first failure had the vehicles of C make – $L_{u,max}$ = 71,835 km (Table 3).

Standardized index of the mean mileage to first failure of the vehicles of A make:

$$L_{u,Anorm} = \frac{L_{u,A} - L_{u,min}}{L_{u,max} - L_{u,min}},$$

$$L_{u,Anorm} \cong 0.576.$$

Mean failure intensity $\lambda_{u,A}(75,000)$ of the vehicles of A make to the mileage of 75 000 km:

$$\lambda_{u,A}(75,000) = \frac{l*n(l)}{N(0)*L},$$

$$\lambda_{u,A}(75,000) \cong 0.141\left[\frac{\text{failures}}{75,000\,\text{km}}\right].$$

Standardized index of the mean failure intensity of the vehicles of A make:

$$\lambda_{u,Anorm}(75,000) = 1 - \frac{\lambda_{u,A}(75,000) - \lambda_{u,n}}{\lambda_{u,max} - \lambda_{u,min}},$$

$$\lambda_{u,Anorm}(75,000) \cong 0.799.$$

Mean mileage between failures of the vehicles of A make:

$$L_{m,A} = \frac{1}{\sum_{j=1}^{N(0)}\left(\sum_{i=1}^{n_j}n_{ij}-1\right)}\sum_{j=1}^{N(0)}\sum_{i=2}^{n_j}l_{ij} = \frac{1}{\sum_{j=1}^{N(0)}\left(n_j-1\right)}\sum_{j=1}^{N(0)}\sum_{i=2}^{n_j}l_{ij} =$$

$$L_{m,A} \cong 17,700\,\text{km}.$$

Maximum value of the mean mileage between failures had the vehicles of B make – $L_{m,max}$ = 18,470 km (Table 3).

Standardized index of the mean mileage between failures of the vehicles of A make:

$$L_{m,Anorm} = \frac{L_{m,A} - L_{m,min}}{L_{m,max} - L_{m,min}},$$

$$L_{m,Anorm} \cong 0.909.$$

The results of calculations of the individual reliability indices for the vehicles of the studied makes are summarized in Table 3 and presented in Figures 2-7.

On the basis of Table 3 and Fig. 2, it is known that on average the highest mileage to the first failure (71,835 km) is characterized by the vehicles of C make. Whereas, the lowest mean mileage to the first failure (62,566 km) is recorded for the vehicles of the A make, and the relative difference between the two makes is relatively high, amounting to approximately 13%. Therefore, the vehicles of C make compared to the other makes have the lowest failure frequency in the initial period/first year of their use.

On the basis of Fig. 3, it is known that the vehicles of A and B makes, while compared to other makes in their first year of use, are characterized by the highest failure - breakdown intensity (frequency). The failure frequency of the vehicles of both A and B makes can be considered to be three times higher than the failure frequency of the other makes - C and D. This may mean that the vehicles of both A and B makes in the first year of their use failed on average three times more frequently than the vehicles of C and D makes.

On the basis of Fig. 4, it is known that the vehicles of A and B makes during the entire period of their monitoring (over the years under the study) had on average a 30% higher mileage between subsequent failures than the vehicles of C and D makes. The vehicles of all A, B, C and D makes fulfilled the requirement for the minimum

Table 3.   Results of calculations of operational reliability indices for vehicles of k (A, B, C, D) makes

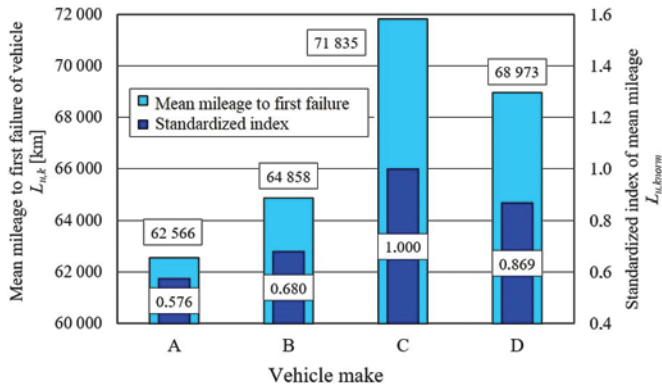| Make	Operational reliability indices					
	Mean mileage to first failure $L_{u,k}$ [km]	Standardized index of the mean mileage to first failure $L_{u,knorm}$	Mean failure intensity $\lambda_{u,k}$ [failure. /75000 km]	Standardized index of the mean failure intensity $\lambda_{u,knorm}$	Mean mileage between failures $L_{m,k}$ [km]	Standardized index of the mean mileage between failures $L_{m,knorm}$
A	62 566	0.576	0.141	0.799	17 700	0.909
B	64 858	0.680	0.159	0.760	18 470	1.000
C	71 835	1.000	0.059	0.980	11 269	0.150
D	68 973	0.869	0.051	1.000	13 298	0.389

Fig. 2. Mean mileage of vehicles of a given make to first failure and the corresponding standardized mean mileage index
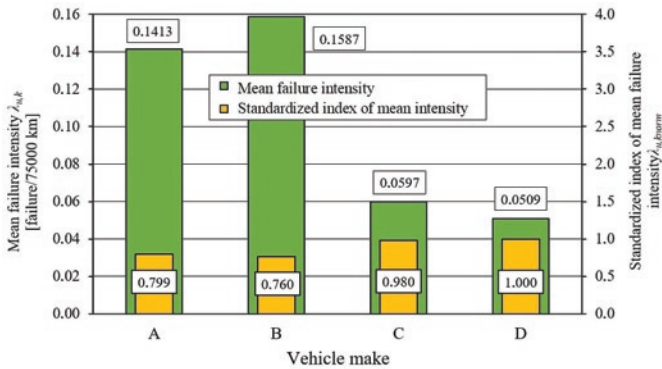

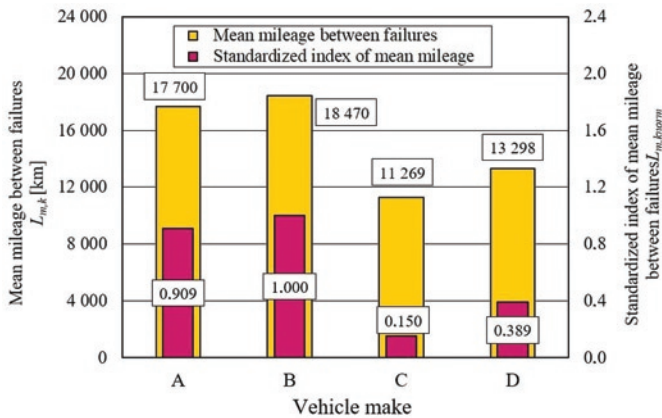*Fig. 3. Mean failure intensity of vehicles and corresponding standardized index of mean failure intensity*

Fig. 4. Mean mileage of vehicles of given make between failures and corresponding standardized index of mean mileage between failures of vehicle
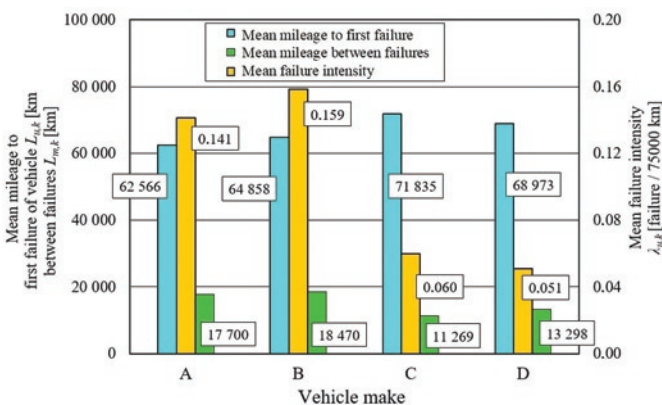

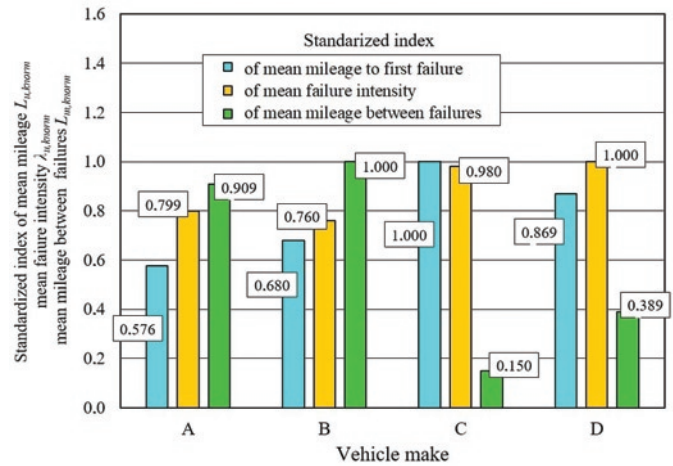*Fig. 5. Summary of reliability indices of vehicles of studied makes*

Fig. 6. Summary of standardized reliability indices for studied A, B, C and D makes of vehicles

value of $L_{m,min}$ = 10,000 km of mileage between subsequent failures/breakdowns applicable in the company.

On the basis of the results obtained above, the summary charts were drawn up, which present the results of the study of the concerned, targeted operational reliability of the vehicles of the individual makes in a form allowing for their mutual comparison (Fig. 5 and 6).

On the basis of the results of the study of the operational reliability of the vehicles of the individual makes in the company referred to herein above, it is concluded that the highest mean mileage to the first failure (71,835 km) is characteristic for the vehicles of C make. Whereas, the vehicles of D make have the lowest mean failure intensity (0.0509 failure /75,000 km), and the highest mean mileage between failures (18,470 km) is characteristic of the vehicles of B make.

Therefore, on the basis of the results obtained, it is not possible to directly answer a question as to which vehicles/makes have the highest operational reliability, targeted at their failure frequency. In order to facilitate the answer to the question posed as above, a simple in its design global index $W_{G,k}$ of the studied operational reliability of the vehicles in the concerned "*k*" vehicle group/make in the following form:

$$W_{G,k}\left(W_{i,k}\right) = \frac{\sum_{i=1}^{n} W_{i,k}}{n} \ , \qquad (7)$$

where: $W_{i,k}$ − standardized value of *i*-th index of the operational reliability for the studied „*k*" vehicle make, *n* – quantity of the reliability indices assumed while determining the concerned operational reliability (*n* = 3).
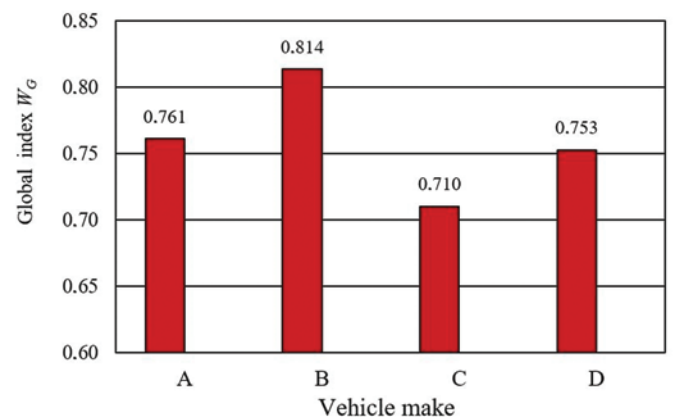

Fig. 7. Values of global index for studied A, B, C and D makes of vehicles

In the concerned study of the operational reliability, a maximum value of the target function $W_{G,max}$: is searched:

$$W_{G,max}(W_{G,k}) = max\{W_{G,k}\} = max\{W_{G,A};W_{G,B};W_{G,C};W_{G,D}\} \quad (8)$$

While using data from the calculations (Table 3) the value of the global index $W_{G,A}$ for the vehicles of A make is as follows:

$$W_{G,A} = \frac{\sum_{i=1}^{n} W_{i,A}}{n} = \frac{L_{u,Anorm} + \lambda_{u,Anorm} + L_{m,Anorm}}{3},$$

$$W_{G,A} = 0.761.$$

The values of the global index $W_{G,k}$ for the studied A, B, C and D makes of the vehicles calculated in the manner referred to in hereinabove are presented in Fig. 7.

The summary presented in Fig. 7 results that the highest value of the global index ($W_{G,B} = 0.814$) among the analyzed A, B, C and D makes of the vehicles had the vehicles of B make, which makes it possible to conclude that they have the least failure frequency among the makes subject to the analysis within the assumed range of the utility reliability. The vehicles of B make fulfil the formal requirements of the researched company as regards the required mileage to the first failure of 64,858/50,000 km, the required mileage between failures of 18,470/10,000 km and the required failure intensity of 0.159/0.500 [failure/75,000 km] much better than the vehicles of the other three makes.

The lowest value of the global index ($W_{G,C} = 0.710$) had the vehicles of C make, which was determined by their high failure frequency expressed as a small mean mileage of 11,269 km between the subsequent failures.

7. Summary and final conclusions

The research method presented in this article enables a road transport company to obtain, in a relatively simple manner, a targeted evaluation focused on the failure frequency of the operational reliability in respect of the commercial vehicles possessed by it, often of the varied makes of the manufacturer. Acquiring this evaluation requires prior monitoring of the use process of these vehicles and the application of a simple and short research procedure based on the use of classical/stationary and simple quantitative measures/indices. These indices are available in the basic and source literature on the theory of the vehicle operation.

The authors proposed the research method that allows for a multi-criteria evaluation of the operational reliability of the commercial vehicles studied due to their failure frequency, taking into account the following three evaluation criteria: mileage to the first failure, mileage between the subsequent failure and failure intensity. On the basis of this information, the proposed research method enables to obtain the targeted evaluation focused on the failure frequency of the operational reliability in respect of the vehicles and to identify the makes of the vehicles in the company, which had the least failure frequency in the monitored/set-point period of time. Thus, the vehicles of this make generated lower exploitation costs, which is what each owner of such a fleet of the vehicle strives for.

According to the authors, the proposed research method is effective, efficient and easy to apply in any transport company. The construction of this method is classical, typical for this category of the research issues. The indices used in this method for the evaluation of the operational reliability targeted at the failure frequency of the vehicles are simple and easy to use in each transport company.

It may turn out that, when a new generation/new model of the commercial vehicle is launched on the market, its exploitation reliability, compared to the former model, declared by the manufacturer or presented by the first users will be evaluated as overall good or more favorable than the previous model.

From the point of view of the authors, in such a case, it is up to the concerned company to take a decision about purchasing and adding to its fleet a new generation/new model of the vehicle that is currently being launched on the market. Each new model of the vehicle marketed in relation to the one already in use by the transport company will undoubtedly be more modern, which is primarily determined, as it is well known, by equipping the engine and the vehicle with more modern devices reducing, for example, a fuel consumption, extending maintenance intervals or ensuring a compliance with the next Euro standard in terms of the exhaust gas purity. This is probably what the purchasers of the new vehicle models will be guided by in case they are not aware more accurately or in more details of the operational reliability of the vehicle.

In the event of taking a purchase decision, the company has the opportunity to monitor the process of use of the newly purchased vehicle model on a periodical basis, upon which it can make a subsequent evaluation/re-evaluation in terms of the use of the currently possessed transport fleet using the algorithm presented in this paper. Depending on the result of the evaluation referred to hereinabove, the company may decide whether it is substantiated to unify the make or model of the light commercial vehicles possessed.

9. Conclusions

1) The extensive analyses of the exploitation process of the vehicles usually refer to a minimization of the costs linked to their use and ensuring the maximum reliability of the transport system, as well as an impact of the vehicle use on the environment or the safety aspect. However, the evaluation of the exploitation intensity of the vehicle is conducted taking into account, inter alia, a value of mileage, engine capacity, vehicle age, repair costs, revenues, technical readiness, and intensity of the use the motor vehicle.

2) The commercial vehicles in the transport company constitute unquestionably the basis of its existence. They are sometimes used under the conditions which often lead to their failure. The knowledge of the failure frequency can be easily used for the purpose of evaluating the operational reliability of the vehicles in use.

3) It is substantiated to use the proposed in the article, the effective and efficient evaluation method to evaluate the operational reliability of the commercial vehicles featuring the varied makes used in the transport companies.

4) The application of the proposed evaluation method requires prior monitoring of the process of use of these vehicles and the application of the evaluation based on the use of classical quantitative measures/indices.

5) In the researched transport company, it is justified to unify the fleet of the light commercial vehicles of B make. The aforementioned is confirmed by the results of a targeted and multi-criteria analysis of their operational reliability obtained in the concerned study. The vehicles of B brand are characterized by the relatively low failure frequency in the first year of their use. In comparison with other makes, they are characterized by a relatively high mileage to the first failure (64,858 km on average) and the highest mileage between the subsequent failures/breakdowns (18,470 km on average) in the successive years of their use.

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