

# MONITORING OF THE TECHNICAL CONDITION OF SEMI-TRAILER TRUCKS

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## Summary

The article presents results of the reliability study of controlled groups of vehicles possessed by two road transport enterprises working in the international transport sector (truck tractors – VOLVO FH 1242T – 50 unit and MERCEDES-BENZ 1844 ACTROS LS -100 units, semi-trailers SCHMITZ, KRONE and KÖGEL – 50 units from each of the semi-trailers company). Possibilities for reliability increasing and reduction of the maintenance and repair cost are defined. The results of the reliability evaluation of vehicles during three years of operation with a different annual run (from brand new up to  $440 \cdot 10^3$  km, including warranty period) are presented. Based on the conducted studies of failures and details malfunctions, units and systems of the vehicles, the average operating time to failure or occurrence of malfunctioning, the probability of failure-free operation, and the time spent on repairs were determined. Asymmetric graphs of working capacity disturbance were obtained, which allowed determining the level of construction design perfection, the technological accuracy of equipment assembly and the quality of fastening works. The inadequate adaptability to operate on the roads of the CIS was reflected by symmetric distribution laws. The least reliable aggregate and assembly elements were identified.

**Keywords:** semi-trailer, control group, failings of operability, failure, malfunction

## 1. Introduction

The motor transport plays an important role in increasing the rates of integration processes. The use of semi-trailer trucks provides connections between the markets of Europe and Asia, Baltic and Black Sea States. Most of the semi-trailer trucks, that execute freight transport, belongs to leading world manufacturers the considerable part of which are truck tractors MERCEDES-BENZ 1844 ACTROS LS, with trailers "SCHMITZ", "KRONE", "KÖGEL". There is no doubt regarding the authority of these producers, however, in the real operation conditions, the reliability has a big importance.

Over the years, the automobile industry has been continuously bedevilled by the continuous recall of vehicles as a result of manufacturing defects of different companies. The recall of vehicles in the automobile industry is not limited to any particular manufacturer.

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Defective components or parts have always been attributed for the reason for the recalls, while some have attributed it to uncontrolled growth and expansion. For automobile companies to keep up with the growth of the automobile industry; it must be ready at all times to satisfy its numerous customers with quality, reliable and affordable products [1].

Reliability is one of the properties that customers of truck tractors value highest [2, 3, 4]. For transport companies, the question of reliability of prominent producers remains still unanswered. Realization of high technical and economic parameters of semi-trailer trucks is possible only when there is a high potential of reliability and its decline would in general substantially influence the efficiency of use of semi-trailer trucks.

Scientific works [5 - 9] expose the problem regarding the reliability of truck tractors. For example, according to the scientific work [10], the failure rate of each vehicle in service is 0.73 faults per vehicle (for the vehicles in service that have reported claims). The percentage distribution of failures and malfunctions is determined for GKB-817 and GKB-8350 trailer systems and units limiting reliability are identified [7]. It was found that 89.2% of all failures and malfunctions fall on the trailer - pivoting device, frame, suspension, brakes, and platform [7].

The purpose of the scientific work, presented in the article, is to inspect a controlled group of truck tractors MERCEDES-BENZ 1844 ACTROS LS in their warranty exploitation period and of trailers of the brands "SCHMITZ", "KRONE", "KÖGEL".

## 2. Problem statement and analysis

The analysis of semi-trailer trucks within the first year of operation showed that a lot of vehicles require repairs. At the middle annual run of  $89.4 \cdot 10^3$  km, in order to remove defects, adjustment and diagnostic works on vehicles, it was about 300 times necessary to submit them to MERCEDES-BENZ authorised service centres in Germany, France, and Italy. In this period, because of tractors operability troubles, about 800 service requests were placed. More than 50 % of vehicles visited the service centres only one time, more than 25 % 3 to 4 - times, about 20 % 5 to 10 times. Until 300 days of vehicle operation, the amount of guarantee repair requirements seems to be according Poisson law. The occurrence of faults is satisfactorily approximated by a linear relationship with the coefficient 0.8717 (fig. 1). The time intervals between two consecutive faults are distributed according to an exponential law [11].

The time required to fix failures and malfunctions according to mileages are the following: 0 -  $25 \cdot 10^3$  km - 13.0 h, 25 -  $50 \cdot 10^3$  km - 8.9 h, 75 -  $100 \cdot 10^3$  km - 14.1 h and 100 -  $125 \cdot 10^3$  km - 20.2 h. Histograms and to them corresponding Poisson distribution of service requirements recalculated to one day and to one week are shown in fig. 2. Estimated 95% confidence limits of Poisson's distributing parameter  $\mu$  are given as the following equation solutions [9]:

$$\frac{\sqrt{292}(0.8717-\mu)}{\sqrt{\mu}} = \pm 1.96. \quad (1)$$

For the service requirements amount within 24 hours, 95% confidence limits are obtained 0.767 and 0.980. For the service requirements amount within one week, respectively 6.358 and 5.796.

The analysis of failure fixing allowed to distribute them in four groups according to types of work: replacement of details, units, aggregates (57.5%), adjustment works (22.9%), fastening works (10.1%), diagnostic works (9.5%).

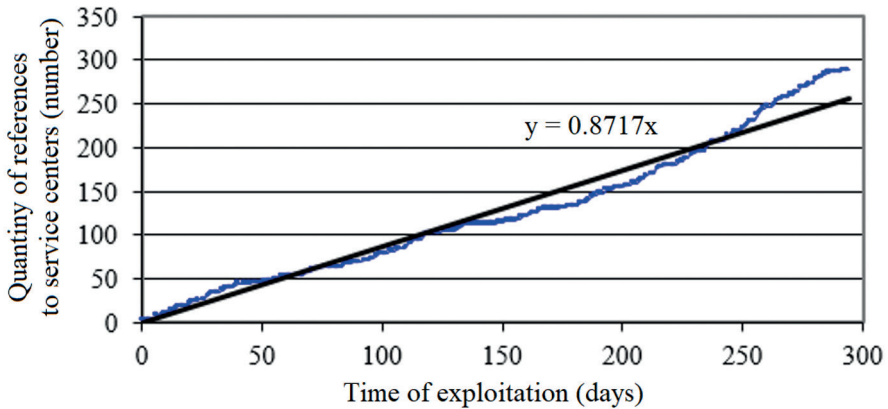


Fig. 1. Quantity of the service centres visits with the warranty repair request

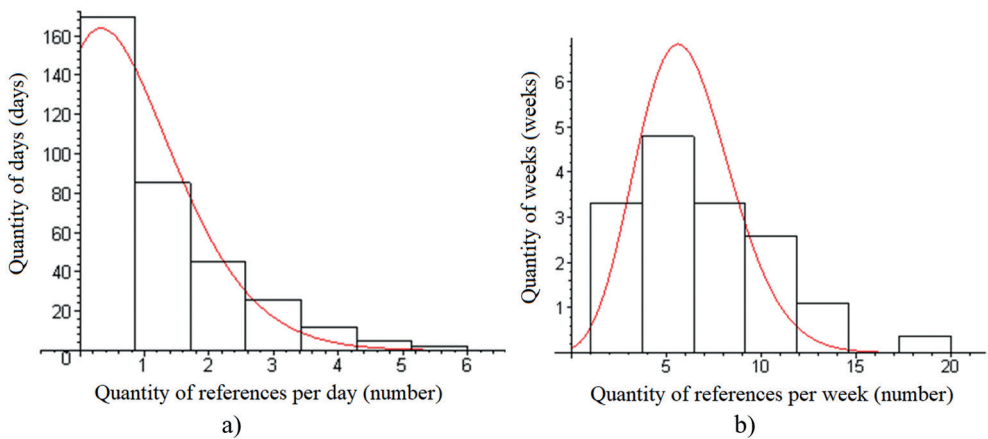


Fig. 2. Description of the service centers visits quantity with the repair request during warranty period calculated per day (a) and per week (b)

To the most characteristic works of **the first group** are: replacement of steering rods (41 pcs.), replacement of the main gearbox shaft sealing ring (34 pcs.), replacement of fuel tank (11 pcs.), replacement of cabin torsion spring (98 pcs.), repair or replacement of independent heater (56 pcs.), replacement of tachograph (16 pcs.). Replacement of sprayers, electronic blocks of aggregates and units steering, display, air and oil pipelines, sensors, the cable of ABS, generator, shock-absorbers, brake mechanisms, battery, tape recorder and refrigerator amounted to 29.0% of the general repair amount (tab. 1).

**The second group** deals with regulation works: suspension level control crane (61.1 %), angels of wheels positions and coupling device (17.4 %), head lights (16.8 %), and engine exhaust toxicity (4.7 %).

**The third group** deals with fastening works: cowlings and spoilers (56.4 %), suspension level control crane (16.6 %), fuel tank, refrigerator, independent heater and other (27.0 %).

**The diagnostic group** includes diagnostics of the computer system (35.7 %), diagnostics of the fuel system (11.9 %), diagnostics of brakes (13.1 %), turbo-compressor (13.1 %), electrical equipment and refrigerator (13.1 %).

Table 1. Description of failings of operability, causing replacement of details, units, aggregates

Name of detail, unit, aggregate	To general amount, %
Cabin torsion spring	21.0
Independent heater	20.5
Steering rods	8.6
Headlight glass	8.6
Main gearbox shaft sealing ring	7.2
Tachograph	3.3
Fuel tank	2.3
Turbo compressor	1.7
Other	29.0

Characteristically, vehicle downtime with short fixing time (till 2 hours and up 2 to 4 hours) amounted 7.8 % and 7.6 %, 22.2 % of downtime is caused by repairs of duration up 4 to 8 hours. 62.4 % of downtime is caused by malfunctions repairs of duration more than 8 hours (fig. 3). Replacement of gearbox casing, rear axle, and aggregates control units required 72, 114 and 216 hours [12, 13].

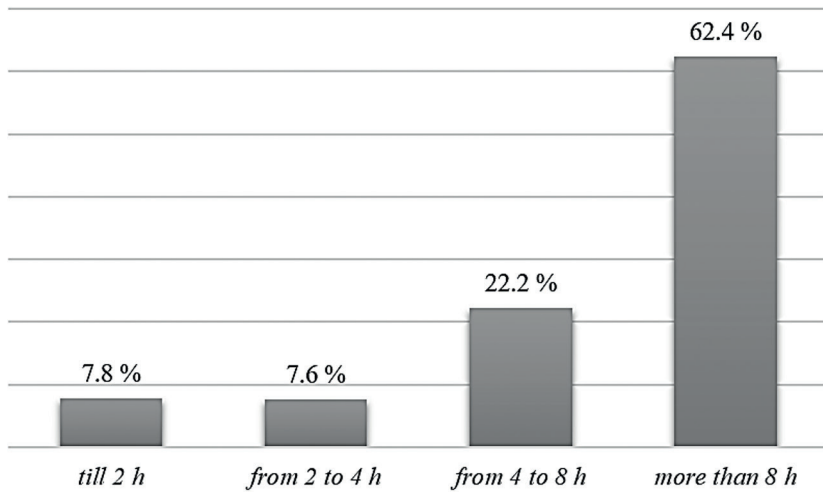


Fig. 3. The vehicle downtime distribution during repairs

It should be noted that by classifying the violations of the technical condition of vehicles by external characteristics most of them are related to wear, breakage, loosening the tightening torque and the abrasion. The proportion of the wear failures is about 20% and the weakening of the fastening is more than 60%. It is characteristic that the number of the last ones decreases with mileage [9].

Based on performed calculations is established that generally vehicle malfunction within the warranty period of operation can be described by normal distribution law [9, 11]:

$$f(t) = 0.0325e^{-\frac{(t_i-45)^2}{302.18}}, \quad (2)$$

where  $t_i$  – mileage on the  $i$ -th interval of the statistical series,  $10^3$  km.

Estimation of vehicle technical condition failures, by its type, character, causes, and repair time are significantly different among each other. Research of laws describing the distribution of corresponding operating time between failures indicates that they occur symmetrically. But in larger numbers, they have asymmetric distributions. Characteristics several asymmetric of them described by  $\beta$ -distribution is shown in the tab. 2, fig. 4. Symmetric distribution laws indicate a design that is not adapted to specific operating conditions on the roads of the low quality. Asymmetric distributing laws in a number of cases suggest to construction or assembling technology imperfections [5]. Analysis of these laws allowed to know better the failure character, their physical essence, to develop a strategy for their prevention, to model and predict violations of the vehicle technical condition.

Table 2. Statistical description of the appearance of disrepairs and refuses

Name of aggregate, systems	Distribution law	Density of distribution
Aggregates		$0.175 \cdot 10^{-5} (8.71+t)^{1.75} (84.06-t)^{1.67}$
Suspension		$1.054 (0.52+t)^{0.29} (73.43-t)^{0.04}$
Steering rod		$0.0008 (-3.89+t)^{1.30} (72.46-t)^{0.52}$
Electrical equipment	$\beta$ -distribution	$0.3771 (-4.11+t)^{0.21} (73.88-t)^{0.14}$
Fuel tank		$0.00001 (25.06+t)^{2.05} (71.09-t)^{0.26}$
Main gearbox shaft sealing ring		$0.0022 (7.60+t)^{0.82} (72.45-t)^{0.58}$
Independent heater		$0.3138 (7.92+t)^{0.71} (69.80-t)^{0.39}$

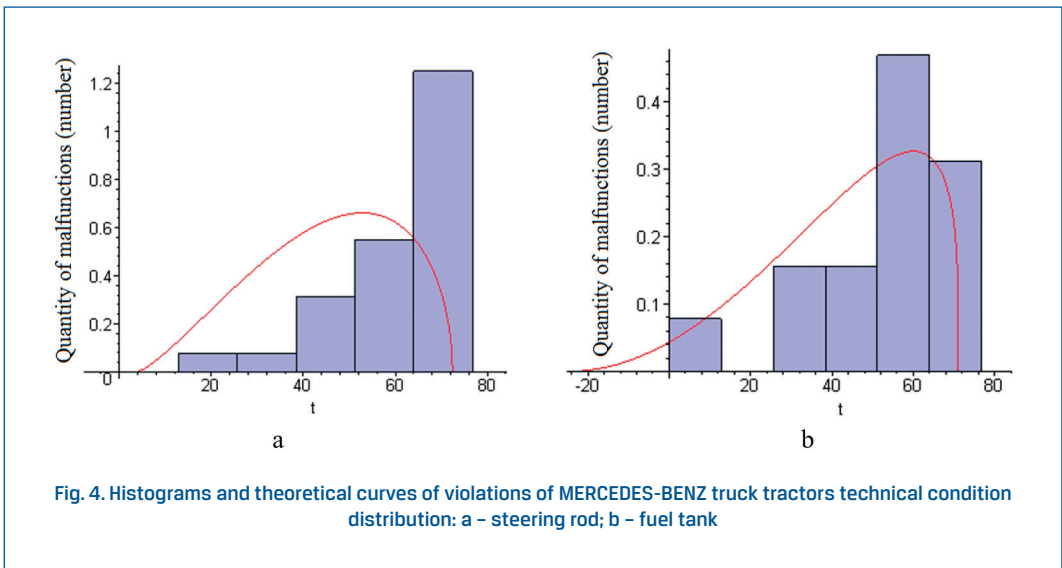


Fig. 4. Histograms and theoretical curves of violations of MERCEDES-BENZ truck tractors technical condition distribution: a – steering rod; b – fuel tank

Inspection of "SCHMITZ", "KRONE" and "KOGEL" semi-trailers was taken out in two phases within two years of operation. The first year middle annual run of "SCHMITZ" is  $98 \cdot 10^3$  km, of "KRONE" is  $166 \cdot 10^3$  km and of "KOGEL" is  $300 \cdot 10^3$  km. Characteristic operability failures are: failures and malfunctions of the brake system, failures or defect of the ABS system work, the door and sidewall joint and locking mechanism wear, failures of pneumatic system tightness, cracks of welded connections, suspension level control crane failures, compressed air reservoir fixture disruption, axles displacements and skew. Some regularities and statistical description of semi-trailers disability types (malfunctions and failures formation) are shown in table 3.

Table 3. Statistical description of malfunctions and failures of semi-trailers

Name of trailer	Mathematical expectation, $\bar{M}$ , $10^3$ km	Standard deviation, $\sigma$ , $10^3$ km	Parameters of the $\beta$ -distribution		Failure density
			$\alpha$	$b$	
SCHMITZ	75.24	29.29	2.962	84.232	$0.7 \cdot \left(\frac{t}{84.232}\right)^{1.962} \cdot e^{-\left(\frac{t}{84.232}\right)^{2.962}}$
KRONE	139.55	37.05	4.923	152.753	$0.65 \cdot \left(\frac{t}{160.67}\right)^{7.214} \cdot e^{-\left(\frac{t}{160.97}\right)^{8.214}}$
KÖGEL	244.7	43.36	6.83	262.56	$0.57 \cdot \left(\frac{t}{262.56}\right)^{5.83} \cdot e^{-\left(\frac{t}{162.56}\right)^{6.83}}$

The phenomenon of axle displacement and skew is not frequent, but in several cases of displacement up to 50 mm and skew up to  $2^\circ$  can be observed. This failure disturbs vehicle dynamics behaviour. The reason of this failure can be crack or weakening of suspension adapter nut, weakening of joint nuts and joint bushing failure. If the defect is not detected in time, wear of adjusting plate, joints and bushings take place. Displacement of axes causes additional tensions in suspension elements and leads to the bellows cracks formation, a bad function of shock absorbers and, as a result, to breakage of shock absorber bracket and to the violation of other fixtures. Axle skew is the reason of increased fuel consumption, uneven and increased tire tread wear, leads to a shift of the semi-trailer gravity centre, and in difficult operating conditions on roads disturbs the dynamic behaviour of the vehicle.

Inspection of vehicles on the second year of operation taken out with middle annual run: "SCHMITZ" -  $230 \cdot 10^3$  km, "KRONE" -  $303 \cdot 10^3$  km, "KÖGEL" -  $440 \cdot 10^3$  km. Results of this inspection show that character of failures and malfunction distribution is significantly changed. In several systems, the amount of failures was decreased (for example in case of suspension level control crane). On the other hand – failures that not observed before takes place (crack or weakening of elements-to-frame fixture, malfunction of electrical components, floor and floor fixtures cracks). Crack and weakening of suspension adapter nut, axle skew in a small amount remained, as shown in the tab. 4.

The reason of crack formation and weakening of elements-to-frame fixtures is breakage of bracket rack and the cross beam, wear of elements at the interfaces what causes load increasing for other frame elements resulting in their failure. In the operation process under influence of external terms, destruction of semi-trailer wire isolation and electric devices take place. This leads to short circuits in the electrical system, increasing wires temperature to high values and to their undesired connection. Under the act of external factors, destruction of parts to semi-trailer bogie frame fixtures take place. That causes their damage.

Table 4. Description of the semi-trailers operability failures within the second phase, %

Name of malfunction	SCHMITZ	KRONE	KÖGEL
Failure of the brake system operability	3.0	16.0	16.0
Door and side walls joint and locking mechanism wear	11.0	11.0	18.0
Defects of shock absorbers fixture	28.0	3.0	–
Leaking of the pneumatic system	11.0	12.0	20.5
Failure of the compressed air reservoir fixture	–	3.0	–
Axles displacement and skew	1.0	5.0	2.5
Suspension level control crane failure	–	–	3.5
Weld cracks	–	2.0	3.5
Leaking shock absorbers	2.0	3.0	–
Defects of the spare wheel carriage	4.0	–	–
Breakage and weakening of elements-to-frame fixture	17.0	5.0	15.0
Electrical equipment failure	15.0	4.0	12.0
Floor and floor fixtures cracks	4.0	6.0	9.0

### 3. Method for creating the assortment of spare parts

Efficient work and reliable support of the semi-trailer trucks in the operational conditions are provided by the assortment of spare parts. The size and assortment of them play an important role in the cost of the transport process. Therefore, there is an acute problem in the feasibility of storing spare parts in the enterprise stock. The creation of the criterion to determine the appropriateness of preserving a particular part can save the resources of the enterprise if this criterion is based on the quality work parameters of the enterprise.

One of the essential characteristics of the transport enterprise work quality is the coefficient of technical readiness, which is determined by the  $i$ -th type of parts as the ratio of the time in flawless work  $t_{iwork}$  to the amount of the same time plus the forced downtime (for repair purposes) of the vehicle taken for the same calendar period  $t_{irepair}$  [14]:

$$k_i = \frac{t_{iwork}}{t_{iwork} + t_{irepair}}, \quad (3)$$

where the repair time  $t_{irepair}$  contains both of the actual time  $t_{irepair}^*$  required to the vehicle repair, and the waiting time  $t_{iwaiting}$  for delivery of the spare part, i.e:

$$k_i = \frac{t_{iwork}}{t_{iwork} + t_{irepair}^* + t_{iwaiting}}. \quad (4)$$

Taking into account the random nature of the values  $t_{irepair}^*$ ,  $t_{iwaiting}$  and  $t_{iwork}$  are taken as average values in the expression for the coefficient  $k_i$ .



The coefficient of readiness of the whole vehicle  $k$  is determined on the basis of the "weak link" principle, i.e:

$$k = \min_{0 \leq i \leq n} k_i. \quad (5)$$

To estimate the influence of the waiting time  $t_{i\text{waiting}}$  on the availability factor, the following equations are introduced:

- the coefficient of technical readiness without regard to the waiting time:

$$k_i^0 = \frac{t_{i\text{work}}}{t_{i\text{work}} + t_{i\text{repair}}^*}, \quad (6)$$

- change of the coefficient of technical readiness:

$$\begin{aligned} \Delta k_i &= k_i - k_i^0 = \frac{t_{i\text{work}}}{t_{i\text{work}} + t_{i\text{repair}}^* + t_{i\text{waiting}}} - \frac{t_{i\text{work}}}{t_{i\text{work}} + t_{i\text{repair}}^*} = \\ &= \frac{t_{i\text{work}} t_{i\text{waiting}}}{(t_{i\text{work}} + t_{i\text{repair}}^* + t_{i\text{waiting}})(t_{i\text{work}} + t_{i\text{waiting}})}. \end{aligned} \quad (7)$$

Then the relative change in the coefficient of readiness is expressed as

$$\frac{\Delta k_i}{k_i^0} \cdot 100\% = \frac{t_{i\text{waiting}}}{t_{i\text{work}} + t_{i\text{repair}}^* + t_{i\text{waiting}}} \cdot 100\%. \quad (8)$$

Considering that  $t_{i\text{work}} = t_{i\text{repair}}^*$  for real values  $t_{i\text{waiting}} = 336$  (h) and  $t_{i\text{work}} = 9333$  (h) the following result can be received  $\frac{\Delta k_i}{k_i^0} \cdot 100\% \approx 3.4\%$ .

Preliminary calculation shows that the absence of spare parts in the stock can make a significant change in the availability factor, and thus violate the practical limitations  $k \geq 0.86$ .

When determining criteria for choice of spare parts assortment to storage, the product of multiplication  $\mu_i = p_i t_{i\text{waiting}}$  is considered, where is the probability of failure of the  $i$ -th part in a certain period of time, which has the same expression unit as  $t_{i\text{waiting}}$ . The choice of this value is due to the fact that even with a high probability of failure of some parts, but with a short delivery time of it, there is no need to store them. On the other hand, with a low probability of failure and a long waiting time, the value may be quite inconsiderable, even though such details usually require storage in the stock because of the long delivery time.

In practice, when using motor vehicles, the readiness coefficient is considered to be acceptable if it satisfies the condition  $k \geq 0.86$ . According to (5), this means that the condition  $k_i \geq 0.86$  must be satisfied for all  $i=1,2,\dots,n$ . Thus from (4) the expressions are obtained:

$$\begin{aligned} k_i &= \frac{t_{i\text{work}}}{t_{i\text{work}} + t_{i\text{repair}}^* + t_{i\text{waiting}}} = \frac{p_i t_{i\text{work}}}{p_i t_{i\text{work}} + p_i t_{i\text{repair}}^* + p_i t_{i\text{waiting}}} = \\ &= \frac{p_i t_{i\text{work}}}{p_i t_{i\text{work}} + p_i t_{i\text{repair}}^* + \mu_i} \geq 0.86. \end{aligned} \quad (9)$$

Consequently:

$$\mu_i \leq \frac{p_i(0.14t_{iwork} - 0.86t_{irepair}^*)}{0.86} \quad (10)$$

If condition (10) is satisfied for some of values  $i=1,2,\dots,n$ , the  $i$ -th type part does not require storage in the stock. This condition would be done if the  $i$ -th detail defects in at least at one vehicle. The condition under which the  $i$ -th detail does not need to be stored in a stock when there are  $N$  vehicles of this type has the following form:

$$t_{iwaiting}(1 - (1 - p_i)^N) \leq \frac{p_i(0.14t_{iwork} - 0.86t_{irepair}^*)}{0.86} \quad (11)$$

The replacement of condition (10) with condition (11) is due to  $0 \leq 1 - p_i \leq 1$ , it is  $1 - p_i \geq (1 - p_i)^N$ , therefore  $N > 1$ . So

$$p_i = (1 - (1 - p_i)) \leq (1 - (1 - p_i)^N). \quad (12)$$

If condition (11) is done, then condition (10) is also fulfilled for each vehicle. The equation acquires the following form:

$$\mu^N \leq \frac{p_i(0.14t_{iwork} - 0.86t_{irepair}^*)}{0.86} \quad (13)$$

and presents a condition for which the  $i$ -th type part does not require storage in the stock if there are  $N$  vehicles of this type.

Practically,  $t_{iwork}$  is many times larger than  $t_{irepair}^*$  [15] and therefore the right-hand side of the condition (13) is always positive.

The calculation procedure of the parameters entering into the criterion for determining the type of parts intended for storage, according to the data obtained from observations, includes the following:

Determination of the time in flawless work  $t_{iwork}$  as an average time between two failures/defects of a  $i$ -th type part. Time  $t_{iwork}$  is defined as the ratio of the average run between two failures of the  $i$ -th type part, running with an average operating speed identified by the vehicle's on-board computer. Thus

$$t_{iwork} = \frac{1}{M} \sum_{m=1}^M \frac{1}{k_m} \sum_{j=0}^{k_m} \frac{1}{v_{mj}^{average}} L_{mj} \quad (14)$$

where  $L_{mj}$  - the mileage of  $m$ -th vehicle between  $j$ -th and  $j+1$ -th failures of the  $i$ -th part type  $j=0,1,2,\dots,k_m$ ;  $k_m$  - the number of failures of the  $i$ -th part during the whole observation time;  $v_{mj}^{average}$  - average operating speed for the mileage  $L_{mj}$ ;  $M$  - the number of vehicles with  $i$ -th type part malfunctioning.

Repair time  $t_{irepair}^*$  is the average time measured in real conditions. Time  $t_{iwaiting}$  is defined as the average waiting time between the order and delivery of the part and it is calculated theoretically. If this part is available in a stock, then  $t_{iwaiting} = 0$ .

Probability  $p_i$  is defined as

$$p_i = \frac{1}{M} \sum_{m=1}^M \frac{v_m^{average} k_m}{L_m}. \quad (15)$$

where  $L_m$  – mileage of the  $m$ -th vehicle for the whole observation time;  $v_m^{average}$  – the average operating speed of the  $m$ -th vehicle for the entire observation time,  $m=1,2,\dots,M$  and  $M$  – the number of the vehicle in which a defected part of the  $i$ -th type was identified.

Usage of this method makes possible to assume recommendations about the expediency of storing spare parts in the stock of the motor transport enterprise.

## 4. Conclusions

The executed estimation of the reliability of west European semi-trailer truck revealed the least reliable aggregates and units that need construction and quality improvements. Practically this information is used to determine the amount of repair works needed to eliminate a certain defect. It was found out in the research, that the occurrence of a certain failure in the MERCEDES-BENZ 1844 ACTROS LS truck tractors during the warranty operation period is approximated as the linear relation and the number of vehicles arrived for servicing has a Poisson distribution. The average time for repair works of vehicles in the mileage up 0 to  $100 \cdot 10^3$  km is 12.1 h. Distribution of the total repair time showed that the greater part of them (62.4%) comprises more than 8 h. To the main type of repair work during the warranty period is the replacement of parts, units, and aggregates (57.5%). Poisson distribution per day and per week is calculated for the number of vehicles that arrived for servicing during the warranty period as well as the loss of the semi-trailer trucks time for the stay.

The reasons for failures and defects occurring in the researched vehicles were found. It is also found out that the most of these reasons, having asymmetrical laws of distribution, reflect the construction imperfection, disturbance of the assembling technological processes and the maladjustment of vehicles to the operation on Ukrainian roads conditions.

The obtained results represent a quantitative estimation and a basic description of the regularity of occurred defects and failures – they can be utilized in the practical activities of warranty maintenance service centres, as well as for development of recommendations concerning the manufacturing technology perfection of transport machinery and the planned volume of spare parts for dealers and service centres.

The proposed criterion based on the technical readiness coefficient of the automobile park, the probability of defect formation, the time for repair work and the time from order to delivery of details to the stock, which makes it possible to determine the expediency of storing spare parts, can be used to define the optimal assortment and quantity of spare parts in the transport enterprise stock.

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