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Dobrivoje Ćatić[1]
Vladimir Ćatić[2]

DETERMINING THE RELIABILITY OF BRAKE BOOSTERS IN LIGHT COMMERCIAL VEHICLES

ABSTRACT: The paper presents the results of research related to the analysis of the reliability of brake boosters in light commercial vehicles. To consider the reliability of mechanical systems, it is necessary to understand the structure, functioning, and potential failure modes that can lead to the loss of operational capability of the system under consideration. Based on operational data, statistical indicators of the random variable of time until the first failure of the brake boosters and the parameters of the approximate model were determined. Statistical data processing was performed using a computer program. For the approximation of the empirical distribution of the random variable, due to its generality and flexibility in adapting to the empirical distribution, the three-parameter Weibull distribution was used. The results of graphical and non-parametric testing confirm that the Weibull distribution can be used as an approximate model. The conclusion of the paper highlights the importance of considering and modeling the reliability of elements in technical systems, the possibilities of using the obtained results, and the directions for further research in this field.

KEYWORDS: reliability, motor vehicles, braking system, brake booster, Weibull's distribution

INTRODUCTION

The braking system is one of the vital systems of the complex mechanical system of a motor vehicle and plays a crucial role in the safety of the vehicle and the people in traffic [9]. It is a typical example of systems in motor vehicles, whose structure is determined by the function of its purpose, as defined by current international and national regulations on vehicle safety in traffic. To increase the efficiency of the braking system in terms of deceleration and stopping the vehicle, and to reduce the force needed to activate the brake control, brake boosters are integrated into the transmission mechanisms of service brakes [5]. Researching the reliability of these devices is of great importance for improving vehicle safety in traffic.

The reliability modeling of brake boosters was carried out using the Weibull distribution. This distribution is, without a doubt, the most widely used in the field of reliability. This directly results from its parametric nature and the wide range of possibilities to interpret very different laws of random variables by selecting appropriate parameter values. Thanks to this, the Weibull distribution can be used as an approximate model for all three periods of the lifespan of mechanical elements. The determination of the parameters of the Weibull approximate distribution is most quickly and accurately conducted using a computer and appropriate software. The application of the least squares method for the analytical determination of the parameters of the three-parameter Weibull distribution, the explanation of the program algorithm, and its practical application are provided in [4].

To reduce the time and cost of testing for reliability evaluation, various accelerated testing procedures are applied. Accelerated testing plans enable the statistical acceleration of tests. By applying accelerated testing plans, the reliability of the drum brake cylinder [2] and the steering linkage joint of light commercial vehicles [3] were determined.

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[1] *Dobrivoje Ćatić, Full Profesor, Faculty of engineering, University of Kragujevac, 34000 Kragujevac, 6 Sestre Janjić Street, Serbia, caticd@kg.ac.rs*

[2] *Vladimir Ćatić, Software engineer, HTEC Group, Bulevar Milutina Milankovica 7DJ, Belgrade 11070, Serbia, vladimir.catic@htecgroup.com*

THE ROLE AND IMPORTANCE OF THE BRAKE BOOSTER IN THE HYDRAULIC TRANSMISSION MECHANISM

The transmission mechanisms of the service brakes in motor vehicle braking systems are designed in various ways [7]. Depending on the energy source used to activate the brakes, the transmission mechanisms can be: without servo assistance, with servo assistance, or with full servo action. In cases where braking cannot be achieved solely by the driver's effort, certain amplification from an external energy source is introduced, meaning that brake boosters are incorporated into the transmission mechanism. These devices can differ not only in their construction but also in their operating principles. In passenger vehicles, the brake booster is most commonly directly connected to the master brake cylinder and is shared by both branches of the hydraulic system. In commercial vehicles, brake boosters are separate units, and typically two are installed (one for each branch). The simplest way to supply energy to the brake booster is by using the vacuum in the intake manifold of an internal combustion engine. If this is insufficient, for example in diesel engines where the vacuum in the intake manifold is relatively low and inadequate for this purpose, special vacuum pumps are used.

A schematic diagram of the hydraulic transmission mechanism (hydraulic system) of the service brake of light commercial vehicles is shown in Figure 1 [8]. This mechanism belongs to the group of transmission mechanisms with partial servo action. It is a so-called dual-branch mechanism, which allows the vehicle to brake via one branch if the other branch fails (for example, if oil leaks from one branch due to a hose damage). The connection of the brake cylinders is designed so that one branch comprises the brakes on the front wheels, and the other branch on the rear wheels.

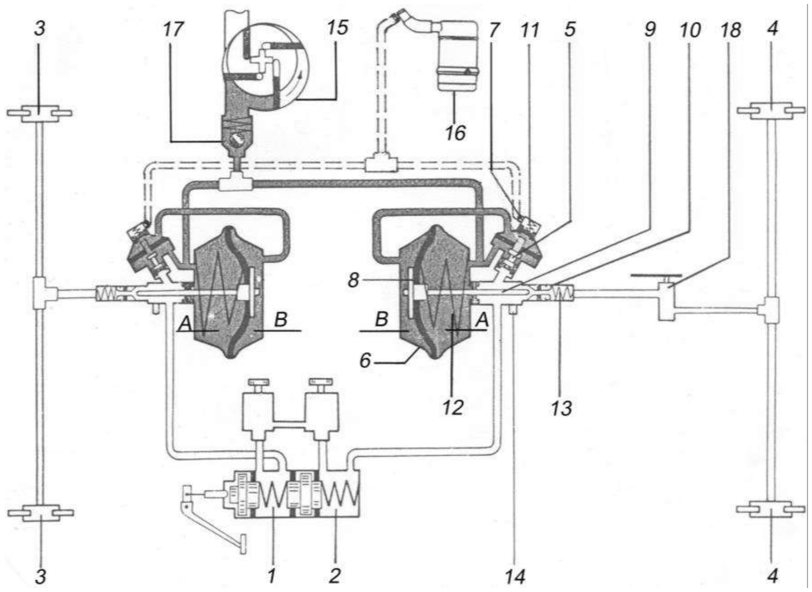


Figure 1 Schematic diagram of the hydraulic transmission mechanism of the service brake

The components of the hydraulic transmission mechanism include: the master brake cylinder, wheel brake cylinders, brake boosters, a depressor, a brake regulator, an oil reservoir, pipes, connectors, etc. In the study [1], along with the description of these components of the hydraulic transmission mechanism, explanations of their operation are provided. The operation of the brake booster and vacuum pump is explained alongside the operation of the hydraulic system.

The hydraulic system shown in Figure 1 operates as follows [6]. Pressing the brake pedal creates hydrostatic pressure in chambers (1) and (2) of the master brake cylinder for the dual-branch hydraulic system. From the master cylinder, the oil is carried through pipes to the brake boosters, separately for each branch of the system. The increased pressure in the hydraulic system activates the valve (5) in the brake booster, which interrupts the connection between chambers (A) and (B) of the pneumatic cylinder (6), in which a certain vacuum is always maintained while the engine is running. By interrupting communication between chambers (A) and (B), valve (5) simultaneously allows atmospheric pressure to enter chamber (B) through opening (7). The pressure difference between the chambers (vacuum on one side and atmospheric pressure on the other) causes the elastic diaphragm (8) to move, to which the piston (9) of the hydraulic cylinder (10) is firmly attached at its center. In this way, a force proportional to the pressure difference in chambers (A) and (B) is applied to the piston (9). The movement of the piston in the hydraulic cylinder significantly increases the pressure received from the master brake cylinder. This increased pressure is then carried to the brake cylinders of the front (3) and rear (4) wheels, and the brakes are activated.

When the action on the brake pedal ceases, the return spring (11) opens valve (5), thereby establishing a connection and equalizing the pressure in the chambers on the left and right sides of the elastic diaphragm of the pneumatic cylinder. The return springs of the pneumatic cylinder (12) and the hydraulic cylinder (13) of the brake booster return the diaphragm (8) and the piston (9) to their initial positions, releasing the brakes. The screw (14) is used to release air from the part of the hydraulic system extending from the master cylinder to the brake booster. The brake boosters are powered by a a vacuum pump (depressor). The depressor (15) is driven by an internal combustion engine and serves both brake boosters. For simpler power transmission, it is mounted on the engine block. The air that the depressor draws in at the beginning of operation, until a certain vacuum level is reached, is compressed into the engine sump. Therefore, it is important that the air, which enters the engine block via the brake booster and depressor, is purified. This is achieved by supplying air to chamber (B) of the brake booster through the engine's air filter (16). If the air were not purified, dust particles would lead to accelerated abrasive wear of engine parts and a significant reduction in the lifespan of this system. It is important to note here that if the pneumatic (air) hoses of the brake booster rupture, the depressor becomes a compressor. Since the outlet branch of the depressor is connected to the engine housing, it leads to the creation of high pressure in the housing and the expulsion of oil. A greater capacity of the depressor can be achieved by installing a vacuum reservoir. The check valve (17) allows air to pass only from the pneumatic cylinders to the depressor.

As shown in Figure 1, the brake boosters consist of: a housing, a diaphragm, a piston and cylinder, a return spring, and a valve. The housing is attached to the vehicle's body. It is made of steel or aluminum. The flexible diaphragm is located inside the housing and divides the device into two chambers. The diaphragm converts the difference in air pressure in the chambers into a force that acts on the piston of the hydraulic cylinder, increasing the hydrostatic pressure in the hydraulic system. The valve controls the airflow in the chambers.

The loss of operational capability of the brake booster can occur due to the failure of its components or the failure of connecting elements or the vacuum device [10]. Pipes, flexible hoses, and connectors are used to connect the brake booster to the other components of the hydraulic system. Damage to the pipes and hoses leads to the leakage of brake fluid and to the complete or partial loss of the braking system's operational capability. Damage to the air system results in the failure of the brake booster. Additionally, damage to the diaphragm prevents the servo action. A broken return spring slows down the complete release of the brakes. The complete or partial loss of the brake booster's operational capability significantly affects the efficiency of the service brake and the safety of the vehicle in traffic.

STATISTICAL DATA PROCESSING AND ANALYSIS OF RESULTS

As part of the research on the reliability of the braking system of light commercial vehicles, operational tests of critical components of the braking system were conducted. Due to the importance of efficient and reliable operation of the braking system, data on the operating time until failure of the brake booster was collected. The brake booster belongs to the group of repairable items. After a failure, appropriate maintenance measures are taken to restore its operational capability. Therefore, it is important to emphasize that the collected data pertains to the operating time until the first failure. The operating time until failure was measured in kilometers traveled. The obtained dataset on the operating time until failure of the brake booster, arranged in ascending order, is shown in Table 1.

Table 1 Operating times until failure of the brake booster system of light commercial vehicles.

Ordinal numeral of failure	Distance travelled	Ordinal numeral of failure	Distance travelled	Ordinal numeral of failure	Distance travelled	Ordinal numeral of failure	Distance travelled
1	57,570	6	97,350	11	134,162	16	245,709
2	63,000	7	116,138	12	143,434	17	256,850
3	63,521	8	119,706	13	203,861	18	258,285
4	68,635	9	126,170	14	205,405	19	272,125
5	72,047	10	132,833	15	231,542	20	314,515

With the use of software to determine the theoretical model of empirical distribution, as described in detail in [1], numerical characteristics of the statistical series are obtained:

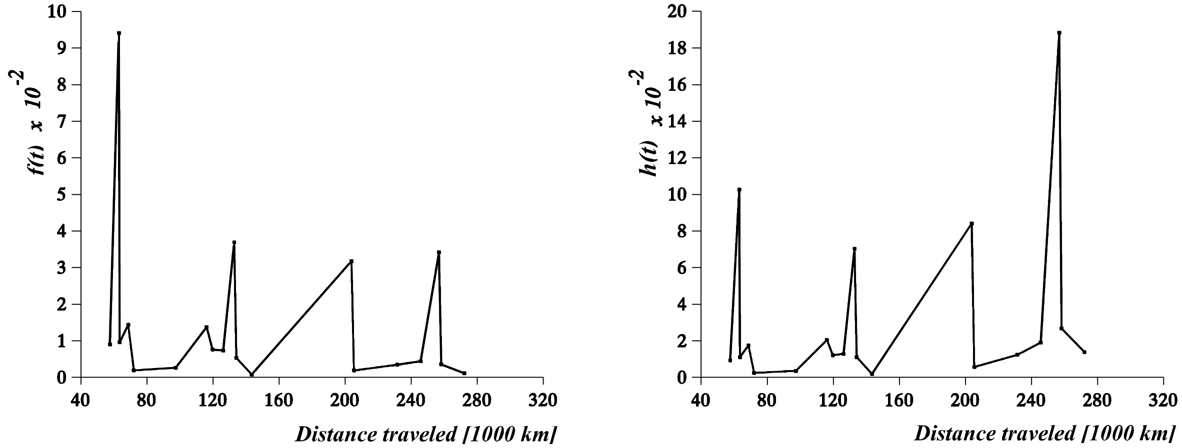
- mean value t_{sr} = 159,143 km,
- standard deviation σ = 81,921 km,
- median t_{50} = 133,497 km,
- coefficient of asymmetry K_a = 0.332 and
- coefficient of flatness K_e = 1.608.

In continuation of the program, and based on procedures for assessing functional indicators of the distribution of a random variable for a small number of samples ($n < 30$), estimated values are obtained: unreliability $F(t)$, reliability $R(t)$, operational time density until failure $f(t)$ and failure intensity $h(t)$ of brake boosters. These values are calculated for the midpoints of time intervals and are presented in Table 2.

Table 2 Estimated values of functional indicators of the distribution of the random variable

i	t_i	$F(t_i)$	$R(t_i)$	$f(t_i)$	$h(t_i)$
1	57,570	0.03431	0.96569	0.90275E-02	0.93483E-02
2	63,000	0.08333	0.91667	0.94088E-01	0.10264E+00
3	63,521	0.13245	0.86765	0.95854E-02	0.11048E-01
4	68,635	0.18147	0.81863	0.14367E-01	0.17550E-01
5	72,047	0.23049	0.76961	0.19373E-02	0.25173E-02
6	97,350	0.27941	0.72059	0.26091E-02	0.36208E-02
7	116,138	0.32843	0.67157	0.13739E-01	0.20458E-01
8	119,706	0.37755	0.62255	0.75835E-02	0.12181E-01
9	126,170	0.42657	0.57353	0.73570E-02	0.12828E-01
10	132,833	0.47559	0.52451	0.36884E-01	0.70321E-01
11	134,162	0.52451	0.47549	0.52868E-02	0.11119E-01
12	143,434	0.57353	0.42647	0.81122E-03	0.19022E-02
13	203,861	0.62255	0.37745	0.31748E-01	0.84112E-01
14	205,405	0.67167	0.32843	0.18755E-02	0.57104E-02
15	231,542	0.72069	0.27941	0.34601E-02	0.12384E-01
16	245,709	0.76961	0.23039	0.43999E-02	0.19098E-01
17	256,850	0.81863	0.18137	0.34160E-01	0.18834E+00
18	258,285	0.86765	0.13235	0.35419E-02	0.26761E-01
19	272,125	0.91677	0.08333	0.11564E-02	0.13877E-01
20	314,515	0.96579	0.03431		

Illustrations of graph charts depicting the estimated values of operational time density until failure $f(t)$ and failure intensity $h(t)$ for brake boosters, presented as polygons, are shown in Figure 2. In preliminary analyses, these graph charts can be used to determine hypothetical distribution models.



a) b)

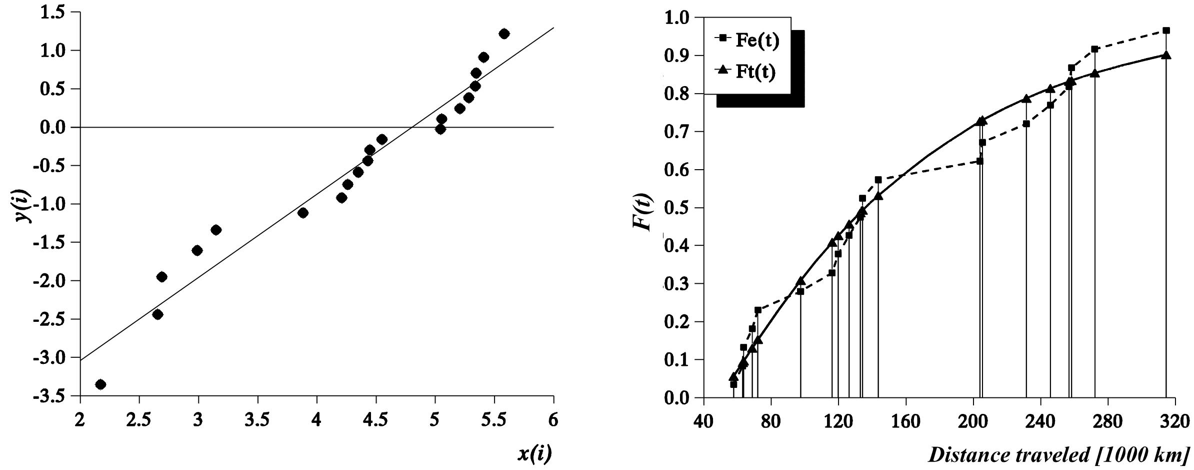
Figure 2 Diagrams of estimated values for distribution of: a) density and b) intensity of brake boosters failure

Analytical determination of Weibull distribution parameters using the least squares method is performed through computer-based approximation of the empirical distribution of operational time until failure of brake boosters. The algorithm used is detailed in the paper [4]. After 18 iterations of halving the interval of possible values of the location parameter of the Weibull distribution, and determining the sign of the second derivative of the approximate quadratic parabola, the following parameters are obtained: location parameter γ = 48,792 km, scale parameter η = 122,027 km, and shape parameter β = 1.084. Based on these parameters, the expression for the probability of faultless operation of brake boosters is formulated:

$$R(t) = e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}} = e^{-\left(\frac{t-48.792}{122.027}\right)^{1{,}084}} \tag{1}$$

During the determination of the probability of proper functioning for brake boosters and all other functional reliability indicators derived from expression (1), time *t* is expressed in kilometers of distance traveled.

To verify the validity of the approximation, graphical testing on Weibull probability paper and nonparametric testing using Kolmogorov and Mizes tests were conducted. Figure 3 a) displays the arrangement of points with transformed *x* and y coordinates for the specific value γ = 48,792 km on Weibull probability paper. The linear arrangement of the points in Figure 3 a) indicates that the approximate model meets the conditions for graphical testing.



a) b)

Figure 3 a) Arrangement of points on probability paper for Weibull distribution, b) Graphical representation of deviations of Weibull approximate distribution from empirical distribution

For testing of hypothetical distribution model, according to Kolmogorov test, it is necessary to determine the greatest absolute value of difference between theoretical model and estimated values of distribution functions of operation time until failure. Table 3 contains a segment of output list of a program that relates to this part. Figure 3 b) presents graphical representation of deviations of theoretical approximate model $F_t(t)$, from empirical distribution $F_e(t)$.

Table 3 Deviations of Weibull approximate curve from estimated values of distribution function of operation time until failure

i	***t_i***	***$F_e(t_i)$***	***$F_t(t_i)$***	***delta***
1	57,570	0.0343	0.0560	0.0217
2	63,000	0.0833	0.0925	0.0092
3	63,521	0.1324	0.0960	0.0363
4	68,635	0.1814	0.1302	0.0512
5	72,047	0.2304	0.1527	0.0777
6	97,350	0.2794	0.3080	0.0286
7	116,138	0.3284	0.4084	0.0799
8	119,706	0.3775	0.4260	0.0485
9	126,170	0.4265	0.4567	0.0303
10	132,833	0.4755	0.4869	0.0114
11	134,162	0.5245	0.4928	0.0317
12	143,434	0.5735	0.5319	0.0416
13	203,861	0.6225	0.7266	0.1040
14	205,405	0.6716	0.7304	0.0588
15	231,542	0.7206	0.7877	0.0671
16	245,709	0.7696	0.8137	0.0441
17	256,850	0.8186	0.8320	0.0133
18	258,285	0.8676	0.8342	0.0335
19	272,125	0.9167	0.8543	0.0624
20	314,515	0.9657	0.9023	0.0634

As it may be seen from Table 3, the largest deviation of theoretical model from empirical distribution is for the result No. 13 and amounts to 0.1040. For number of samples, *n* = 20 and given level of significance for Kolmogorov's test $\alpha = 0.20$, $\lambda_\alpha = 1.07$, permitted value of difference is:

$$D_n = \frac{\lambda_\alpha}{\sqrt{n}} = \frac{1.07}{\sqrt{20}} = 0.2393 \qquad (2)$$

Since the maximal deviation is less than permitted value of difference, Weibull approximate distribution satisfies the Kolmogorov's test for adopted level of significance.

For non-parametric testing of the Weibull approximate distribution, the Mises test was also used. The calculated comparative size of the deviation between the theoretical and empirical models for this test is $n\omega^2 = 0.0548$. With the adopted significance level $\alpha = 0.2$, the allowable tabulated deviation value is $n\omega^2(\alpha)=0.2412$. Since the calculated value for the Mises test is lower than the tabulated value for the adopted significance level, it can be concluded that the Weibull approximate distribution satisfies this test.

Based on the graphs of the estimated values of the failure rate (Figure 2b)), it can be concluded that there is a constant failure rate. This means that the failures of the brake booster occur suddenly during normal operation. As a result of the program approximation of the statistical data set using the least squares method, a three-parameter Weibull approximate distribution with a shape parameter $\beta = 1.084$ was obtained. In the two-parameter Weibull distribution, if $\beta = 1$, an exponential distribution is obtained, whose parameter λ is the reciprocal of the scale parameter η. The obtained value of the shape parameter β might lead to the incorrect conclusion that an exponential distribution could be used to approximate the statistical data set. However, the operating time until the first failure at 57,570 km is not negligible in relation to the operating time until the failure of the last object. This means that there is a significant period of operation in which no failures occurred. The location parameter or the minimum value parameter of the random variable γ enabled the approximate model to be translationally shifted in the positive direction of the horizontal axis. This means that if a transformed coordinate system were adopted whose vertical axis is shifted to the right by the parameter γ, it could be asserted that an exponential distribution could be used for a hypothetical approximate model. In reality, it deals with a two-parameter exponential distribution, whose density graph is shifted to the right by the value of this second parameter, specifically in this case, by the value of γ.

CONCLUSIONS

By testing machine elements and systems for reliability assessment under operational conditions, a realistic picture of their behavior concerning the loss of operational capability is obtained. This approach takes into account all influential factors on lifespan, which are random in nature and difficult to assess and simulate for laboratory testing purposes. Determining the reliability distribution law represents the ultimate goal of any data analysis in the field of reliability. This process has significant implications for conclusions and decisions related to the practical application of the obtained results. Programmatic determination of the parameters of the three-parameter Weibull distribution, unlike graphical and graph-analytical methods, allows for achieving satisfactory accuracy of results with great speed. Due to this and the well-known properties of this distribution concerning the interpretation of different laws of random variables, the Weibull approximate distribution often emerges as the optimal solution compared to other theoretical models. Knowing the reliability distribution law of machine elements enables the determination of the reliability of the entire system based on the reliability of its components, the planning of maintenance measures, the planning of spare parts production, the determination of the optimal warranty period for components or the entire system, and so on. In this study, a small sample method was applied to determine the estimated values of reliability indicators, specifically through median rank estimation. In this regard, further research could involve determining the confidence interval of the distribution as a whole. Additionally, systematic collection of data on the failures of brake boosters during operation would allow for the planning and execution of accelerated tests for the reliability assessment of the considered object.

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