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ANALYSIS OF THE RELIABILITY OF THE "ALTERNATOR - ALTERNATOR BELT" SYSTEM

ABSTRACT

Before starting and also during the exploitation of various systems, it is very important to know how the system and its parts will behave during operation regarding breakdowns, i.e. failures. It is possible to predict the service behaviour of a system by determining the functions of reliability, as well as frequency and intensity of failures.

The paper considers the theoretical basics of the functions of reliability, frequency and intensity of failures for the two main approaches. One includes 6 equal intervals and the other 13 unequal intervals for the concrete case taken from practice.

The reliability of the "alternator - alternator belt" system installed in the buses, has been analysed, according to the empirical data on failures.

The empirical data on failures provide empirical functions of reliability and frequency and intensity of failures, that are presented in tables and graphically. The first analysis performed by dividing the mean time between failures into 6 equal time intervals has given the forms of empirical functions of failure frequency and intensity that approximately correspond to typical functions. By dividing the failure phase into 13 unequal intervals with two failures in each interval, these functions indicate explicit transitions from early failure interval into the random failure interval, i.e. into the ageing interval. Functions thus obtained are more accurate and represent a better solution for the given case.

In order to estimate reliability of these systems with greater accuracy, a greater number of failures needs to be analysed.

KEY WORDS

reliability, failures, frequency of failures, intensity of failures

1. INTRODUCTION

Before starting and also during the usage of various systems, it is very important to know how the system and its parts will behave during exploitation regarding breakdowns, i.e. failures (the system being out of service due to a failure). It is possible to predict the service behaviour of a system by determining statistical functions of reliability, frequency and intensity of failures. Reliability is the probability that the system will successfully perform a given function without failing, with a certain level of confidence and within the allowed deviation limits.

The reliability of the "alternator - alternator belt" is analysed in this paper, according to the empirical data about failures of such systems installed in the new buses. The analysed systems are repairable, that is, after such a failed system has been repaired, the repaired system is considered as a new one, regarding reliability.

The work shows theoretical basics and the empirical data on the "alternator - alternator belt" system failures, provide the empirical functions of reliability, frequency and intensity of failures, that are presented in tables and graphically.

2. THEORETICAL BASICS OF FUNCTIONS THAT DETERMINE RELIABILITY

2.1. Functions of unreliability, reliability, frequency and intensity of failures

Based on the law on theory of probability the following can be written:

$$f(t)=\frac{dF(t)}{dt} \tag{2.1}$$

where f(t) is the failure frequency function. The reliability function can be obtained from the formula (2.1) by means of the failure frequency function.

$$R(t)=1-F(t)=1-\int_{0}^{\infty} f(t)dt=\int_{t}^{\infty} f(t)dt \tag{2.2}$$

Therefore, if the mathematical form of the failure frequency function f(t) is known, the reliability can be determined as the function of time t.

If n systems are analysed at a time, after a certain time t there will be n_1 systems that have not failed and

$n_2 = n - n_1$ systems that have failed. At one time during the analysis, reliability can be expressed as follows:

$$R(t)=\frac{n_1(t)}{n}=\frac{n_1(t)}{n_1(t)+n_2(t)} \tag{2.3}$$

where $n_1(t)$ is the number of systems that have not failed until time t, and $n_2(t)$ is the number of systems that have failed until time t. The equation (2.3) gives the probability of service without failure, of any of the n systems during the time t. Reliability R(t) is the time function of system operation and over time the number of failures will increase, and the reliability will decrease.

Failure intensity function $\lambda(t)$ can be written in the following form:

$$l(t)=\frac{1}{n_1(t)}\cdot\frac{dn_2(t)}{dt}=-\frac{1}{R(t)}\cdot\frac{dR(t)}{dt} \tag{2.4}$$

or

$$\lambda(t)=\frac{F(t)}{R(t)} \tag{2.5}$$

Formula for the failure intensity function (2.5) can be applied for any failure frequency function.

Failure intensity function $\lambda(t)$ shows the variation in the failure intensity during the system service life. The slope of the failure intensity function is steeper than the failure frequency function f(t), and therefore more sensitive to changes, whereas the failure frequency function f(t) has the extreme maximum value, and for this value it gives the time when most of the failures occur.

2.2. Function of failure frequency, intensity and the system service life

At the beginning of using a certain technical system, a greater number of failures usually occur, caused by omissions in production and control, and often called failures due to fabrication faults. Later, during usage, these early failures are replaced by failures for which the causes are not known exactly. These, so-called random failures, most probably occur when the stresses exceed the innate resistance of the system. The frequency of random failures is approximately constant over time. Failures due to wear (fatigue, corrosion) start to occur with the ageing of the system.

Figure 1 shows a typical form of the failure frequency function f(t), and Figure 2 presents the typical form of the failure intensity function $\lambda(t)$ for technical systems.

The interval of failures due to fabrication faults (0 to t_1), functions f(t) and $\lambda(t)$ are decreasing. The characteristic of random failures (from t_1 to t_2) is the approximately constant value $\lambda(t)$ and the decreasing exponential function f(t). On the ageing interval (from

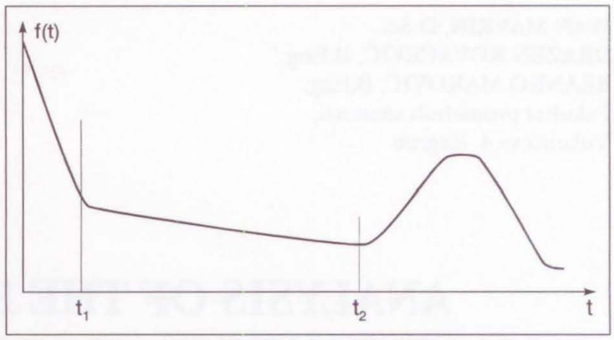

Figure 1 - Typical failure frequency function for technical system

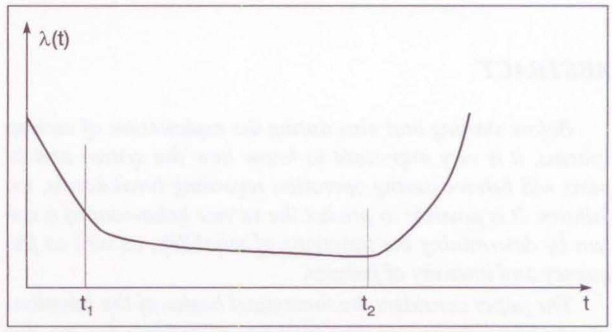

Figure 2 - Typical failure intensity function for technical systems

t2 to ∞) $\lambda(t)$ is an increasing function and its value tends to infinity, whereas f(t) has one extreme around which most of the failures occur. Practice has shown that many technical systems have the failure intensity curve $\lambda(t)$ which corresponds to the curve in Figure 2.

Many high-reliability part manufacturers put these parts into service before installing them into a higher assembly, thus bringing them to the beginning of the interval of constant failures. The same is being done with the completed system, so that the user has no early failures which may be very inconvenient, and sometimes even disastrous. At the beginning of the ageing interval (at the moment t_2) the failure intensity increases suddenly and then the best thing is to replace the part which has been in service for the t_2 time. Such a replacement increases the overall reliability of the system. For systems and parts whose reliability corresponds to the curves in Figures 1 and 2, the greatest reliability is achieved by pre-operating of the system up to the time t_1, by exploitation on the interval t_1 to t_2 and by replacement at the moment t_2. For the moment t_2 it is necessary to provide spare parts on stock, which will replace the old ones that have been operated over t_2 time. Unfortunately, many systems have no defined curves f(t) and $\lambda(t)$ as in Figures 1 and 2, so that such analysis cannot be applied to them.

It should be noted that the variable t (time) does not necessarily have to express the operating hours, so that, e.g. for road vehicles time t can be expressed in clocked up kilometres.

3. ALTERNATOR FAILURES ON THE BUSES

End of 1995 and beginning of 1997, Zagreb public transport carrier purchased 15 new buses.

End of November 1995, 5 buses started to be used, which clocked up between 120,000 and 166,000 kilometres each until May 12, 1998 in urban mass transportation. In January 1997, further 10 buses started to be used, and until May 12, 1998 these clocked up between 30,000 and 101,000 kilometres in urban mass transportation.

There is a maintenance card for each bus, recording very strictly all the failures, repairs, maintenance, and overhauls, which are performed regularly. These maintenance cards of each bus show that the failure of the "alternator - alternator belt" system occurs most often on the vehicle cards. The breakdown and failure of this system, namely, will not affect the normal exploitation of the bus during a working day. This breakdown is recorded by the failure of the "alternator - alternator belt" system on the dashboard. This breakdown is repaired when the bus arrives to the garage, by repairing or replacing the necessary part.

All the above mentioned buses use self-excited alternators without brushes, with a paired, V-section alternator belt

In case the alternator (or the alternator belt) fails, the consumer devices in the vehicle consume the power from the battery (which is then not being charged). The duration of further operation of the vehicle depends on the time of battery discharge, which depends on the battery capacity, discharge intensity of the accumulated electrical energy, etc.

3.1. Obtaining functions which determine the reliability out of the empirical data about the "alternator - alternator belt" system failures

Failures of the "alternator - alternator belt" systems (further in the text alternator) have been analysed in 26 failures of this system taken from the vehicle cards of the 15 new buses used in urban mass transport.

New alternators and belts have been installed in the new buses. After each repair or replacement of a certain part, the reliability analysis always considered as if a new alternator was installed, since this is a repairable system. It is worth mentioning that alternator is neither checked nor repaired during regular bus overhauls, but one rather waits for it to fail. The time variable until failure t has been taken as expressed in clocked up kilometres of each bus.

Table 1 shows 26 alternator failures after a certain amount of clocked up kilometres.

Table 1 - Clocked up kilometres by buses until alternator failure

Ordinal number of the failure	Clocked up kilometres until failure
1	5 932
2	11 218
3	14 286
4	14 489
5	16 105
6	21 138
7	21 971
8	37 221
9	41 894
10	43 008
11	48 145
12	56 226
13	58 000
14	61 304
15	62 833
16	63 708
17	65 223
18	67 121
19	69 357
20	71 352
21	75 006
22	80 231
23	82 548
24	91 784
25	111 156
26	119 386

In order to determine the optimal number of intervals, the following expression is often recommended:

$$k = 1 + 3{,}3 \cdot \log n_2 = 1 + 3{,}3 \cdot \log 26 = 5{,}67$$

for n_2 equal intervals. In this case:

$$k = 1 + 3{,}3 \cdot \log 26 = 5{,}67$$

Considered: number of intervals k = 6. Since the latest failure occurred after approximately 120,000 clocked up kilometres, the length of interval has been determined $\Delta t = \frac{120000}{6} = 20000$ km.

Table 2 shows the basic indicators, formulas and the procedure for defining the empirical functions which determine the reliability for 6 intervals.

Table 2 - Determining empirical functions of failure frequency, intensity and reliability of alternator for 6 intervals

Indicator	Formula	Intervals 1.	2.	3.	4.	5.	6.
Length of interval, Δt [$10^3 \cdot$ km]		20	20	20	20	20	20
Interval boundaries, [$10^3 \cdot$ km]		0-20	20-40	40-60	60-80	80-100	100-120
Interval mean, [$10^3 \cdot$ km]		10	30	50	70	90	110
Number of failures on the interval	$n_1(t)-n_1(t+\Delta t)$	5	3	5	8	3	2
Number of failures until moment t, $n_2(t)$	$\sum_{i=1}^{i} n_2(t_i)$	5	8	13	21	24	26
Total number of properly functioning alternators until moment t, $n_1(t)$	$n-n_2(t)$	21	18	13	5	2	0
Probability of operation without failure (reliability), $R_e(t)$	$\frac{n_1(t)}{n}$	0.808	0.692	0.5	0.192	0.077	0
failure frequency, $f_e(t)$ [$10^{-6} \cdot km^{-1}$]	$\frac{n_1(t)-n_1(t+\Delta t)}{n \cdot \Delta t}$	9.62	5.77	9.62	15.38	5.77	3.85
failure intensity, $\lambda_e(t)$ [$10^{-6} \cdot km^{-1}$]	$\frac{f_e(t)}{R_e(t)}$	11.91	8.34	19.24	80.1	74.94	$+\infty$

According to Table 2, functions $f_e(t)$, $\lambda_e(t)$ and $R_e(t)$ (Figures 3, 4 and 5) have been graphically presented for 6 intervals.

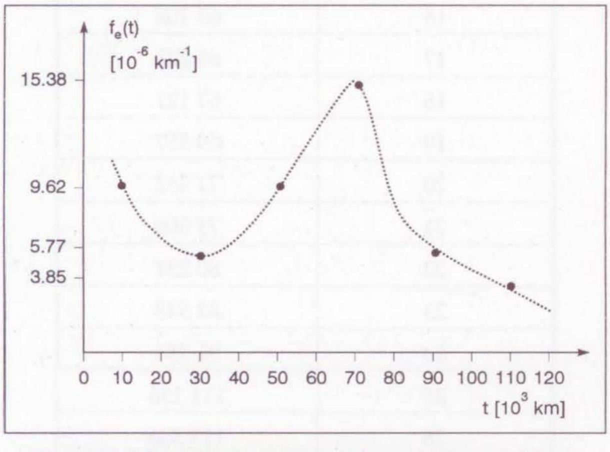

Figure 3 - Graphical presentation of the empirical frequency function of alternator failure for 6 intervals

At the beginning of alternator operation (for t=0), functions $f_e(t)$ i $\lambda_e(t)$ have the value zero (no failure yet), whereas the reliability of the system equals 1. Functions $f_e(t)$ (Figure 3) and $\lambda_e(t)$ (Figure 4) have the form which resemble the curves from Figures 1 and 2, where the interval of early failures is approximately up to 20,000 km of alternator operation. Further 20,000 km of operation is the interval of random failures, and the ageing of the system begins after approximately 40,000 km of operation. The highest frequency of failures is after 70,000 km (Figure 3), and after 90,000 km the number of properly functioning al-

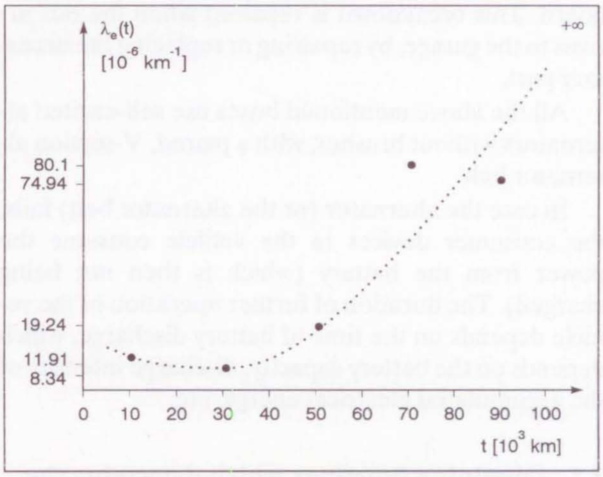

Figure 4 - Graphical presentation of the empirical intensity function of alternator failure for 6 intervals

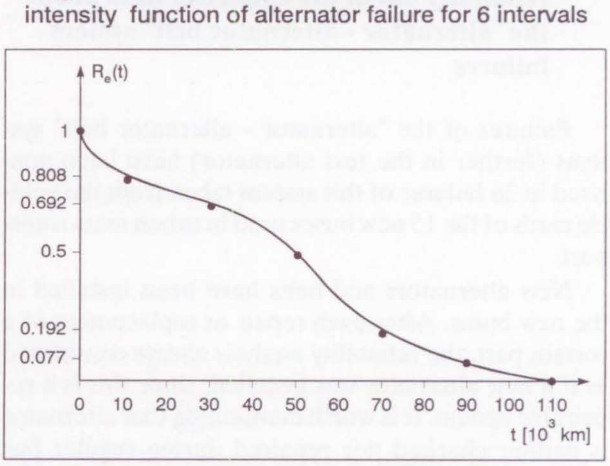

Figure 5 - Graphical presentation of the empirical function of the reliability of alternator operation for 6 intervals

Table 3 - Determining the empirical functions of failure frequency, intensity and alternator reliability for intervals

Indicator	Formula	Intervals												
		1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.
Length of interval, Δt [$10^3 \cdot$ km]		11.2	3.3	6.6	16.1	5.8	13.2	5.1	2.4	3.4	4.3	8.8	11.6	27.6
Interval boundaries, [$10^3 \cdot$ km]		0-11.2	11.2-14.5	14.5-21.1	21.1-37.2	37.2-43	43-56.2	56.2-61.3	61.3-63.7	63.7-67.1	67.1-71.4	71.4-80.2	80.2-91.8	91.8-119.4
Interval mean, [$10^3 \cdot$ km]		5.6	12.8	17.8	29.1	40.1	49.6	58.7	62.5	65.4	69.2	75.8	86	105.6
Number of failures on the interval	$n_1(t) - n_1(t+\Delta t)$	2	2	2	2	2	2	2	2	2	2	2	2	2
Number of failures until moment t, $n_2(t)$	$\sum_{i=1}^{i} n_2(t_i)$	2	4	6	8	10	12	14	16	18	20	22	24	26
Total number of properly functioning alternators until moment t, $n_1(t)$	$n - n_2(t)$	24	22	20	18	16	14	12	10	8	6	4	2	0
Probability of operation without failure (reliability), $R_e(t)$	$\frac{n_1(t)}{n}$	0.923	0.846	0.769	0.692	0.615	0.538	0.462	0.385	0.308	0.231	0.154	0.077	0
failure frequency, $f_e(t)$ [$10^{-6} \cdot$ km^{-1}]	$\frac{n_1(t) - n_1(t+\Delta t)}{n \cdot \Delta t}$	6.87	23.31	11.66	4.78	13.26	5.83	15.08	32.05	22.62	17.89	8.74	6.63	2.79
failure intensity, $\lambda_e(t)$ [$10^{-6} \cdot$ km^{-1}]	$\frac{f_e(t)}{R_e(t)}$	7.44	27.55	15.16	6.91	21.56	10.84	32.64	83.25	73.44	77.45	56.75	86.1	+

ternators is very small (reliability lower than 7.7%, Figure 5). Fifty percent reliability of the system is after about 45,000 km, and after 70,000 km the reliability is extremely low (lower than 20%).

Since only 6 intervals have been taken for the studied number of failures 26, in further analysis of the alternator reliability, the case with 13 unequal intervals is taken. Each interval includes two failures, and the interval lengths are rounded up to 100 km. Table 3 presents the basic indicators, formulas and the procedure for defining empirical functions that determine the reliability for 13 unequal intervals.

The aim is to find out and compare the results obtained with 6 equal intervals with the results for 13 unequal intervals.

According to Table 3, functions $f_e(t)$, $\lambda_e(t)$ and $R_e(t)$ have been graphically presented (Figures 6, 7, and 8) for 13 intervals.

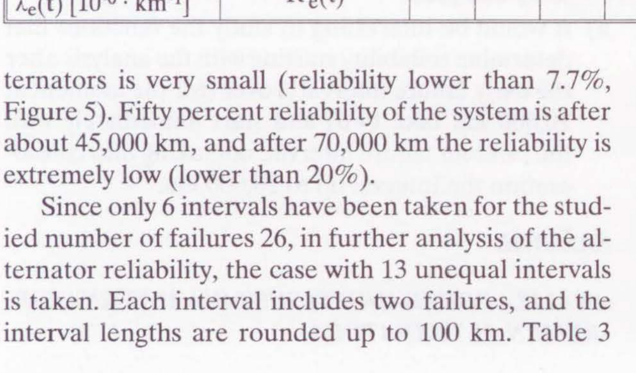

Figure 6 - Graphical presentation of the empirical function of the alternator failure frequency for 13 intervals

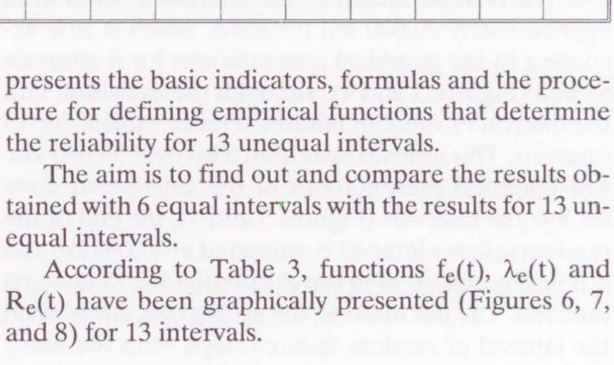

Figure 7 - Graphical presentation of the empirical function of the alternator failure intensity for 13 intervals

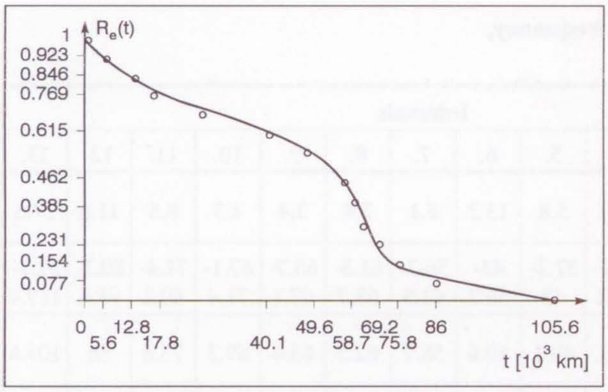

Figure 8 - Graphical presentation of the empirical function of the alternator operation reliability for 13 intervals

4. ANALYSIS OF THE OBTAINED RESULTS

By selecting 13 unequal intervals, the functions $f_e(t)$ (Figure 6), and $\lambda_e(t)$ (Figure 7) show extreme similarity to the typical functions of failure frequency and intensity for technical systems (Figures 1 and 2). The value deviations in the first and the fifth interval were most probably caused by the insufficient number of studied alternators.

Figures 6 and 7 show that the interval of early failures (fabrication faults) of the alternator takes until approximately 20,000 km travelled, which is true according to the graphical presentations for 6 intervals as well (Figures 3 and 4), although the transition into the interval of random failures is more explicit for 13 intervals. This interval lasts until a bit over 50,000 km. For graphical presentations of the calculation done for 6 equal intervals (Figures 3 and 4), the end of the random failures interval is estimated at 40,000 km and it is not so explicit as in the calculation for 13 unequal intervals. The last interval, the ageing one, starts when the interval of random failures stops, with the maximum failure frequency after 62,500 clocked us bus kilometres, indicated by the maximum of function $f_e(t)$ (Figure 6), and very fast increase of function $\lambda_e(t)$ in that area (Figure 7).

The empirical function of reliability $R_e(t)$ in Figure 5, with 6 equal intervals changed significantly (Figure 8) when 13 unequal intervals were considered. The curve itself $R_e(t)$ is better defined and shows greater accuracy. The unusual behaviour of function $\lambda_e(t)$ for more than 60,000 km (constant value of the function up to approximately 90,000 km) (Figure 7) is not important any more for the assessment of reliability of the alternator system. After 82,550 km, namely, 3 more properly functioning alternators remained, and the last one failed only after 119,400 km (3 failures in the interval of 36,850 km).

5. CONCLUSION

The following may be concluded by calculations, graphical presentations and analysis of the failures of 26 "alternator - alternator belt" systems installed in buses:

1) With the 13 unequal intervals studied, compared to the 6 equal intervals, more credible optimal solutions for the curves $R_e(t)$, $f_e(t)$ and $\lambda_e(t)$ are obtained.
2) The analysis of functions $R_e(t)$, $f_e(t)$ and $\lambda_e(t)$, carried out by dividing the time period into 13 unequal intervals shows more explicit transitions between characteristic phases (phases of early and random failures, and failures due to wear), than the analysis with 6 equal intervals.
3) Functions $R_e(t)$, $f_e(t)$ and $\lambda_e(t)$ (Figures 3, 4, 6 and 7) correspond to typical functions common for the technical systems.
4) It should be noted that the failure of the "alternator - alternator belt" system has no disastrous impact on the further normal operation of the vehicle. However, by determining the reliability of this system, it may be predicted at what time a certain number of spare parts necessary for timely repair need to be available on the stock.
5) For a more accurate estimation of reliability of these systems, a greater number of failures needs to be analysed.
6) It would be interesting to study the functions that determine reliability starting with the analysis after the early failure interval is over (for the moment at 20,000 km take t=0) and start immediately with the random failure interval, not taking into consideration the interval up to 20,000 km.

SAŽETAK

ANALIZA POUZDANOSTI SUSTAVA ALTERNATOR-REMEN ALTERNATORA

Pri puštanju u rad, a također i tijekom korištenja nekog sustava, veoma je bitno poznavati kako će se sustav ponašati tijekom korištenja obzirom na pojavu kvara, odnosno otkaza. Ponašanje sustava tijekom korištenja moguće je predvidjeti određivanjem funkcija pouzdanosti, te gustoće i intenziteta otkaza.

U radu su dane teoretske osnove funkcija pouzdanosti, te gustoće i intenziteta otkaza za dva osnovna pristupa. Jedan je sa 6 jednakih intervala, a drugi s 13 nejednakih za konkretni slučaj iz prakse.

Provedena je analiza pouzdanosti sustava alternator - remen alternatora koji su ugrađeni u autobuse, a prema empirijskim podacima o otkazima.

Iz empirijskih podataka o otkazima dobivene su empirijske funkcije pouzdanosti, te gustoće i intenziteta otkaza, koje su prikazane tablično i grafički. Prva analiza izvedena razdiobom srednjeg vremena između otkaza na 6 jednakih vremenskih *intervala dala je oblike empirijskih funkcija gustoće i intenziteta otkaza koje približno odgovaraju tipičnim funkcijama. Razdiobom vremena otkaza na 13 nejednakih intervala sa po dva otkaza u svakom intervalu ove funkcije pokazuju izrazite prijelaze iz intervala ranih otkaza u interval slučajnih otkaza, odnosno u interval starenja. Ovako dobivene funkcije su vjerodostojnije i predstavljaju bolje rješenje za dati slučaj.*

Za točnije utvrđivanje pouzdanosti ovih sustava potrebno je pri analizi koristiti veći broj otkaza.

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