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IN-SERVICE ANALYSIS OF TRAM WHEEL SET LIFE

Summary. The paper presents some results of in-service tests on tram wheel set life. The measurements of wheel rim undercut and wear on the rolling diameter of tram wheel set wheels are a data base for calculating tram rolling wheel life in two aspects: wheel operation conditions and materials from which the wheels were made.

ANALIZA EKSPLOATACYJNA TRWAŁOŚCI ZESTAWÓW KOŁOWYCH TRAMWAJÓW

Streszczenie. Praca zawiera wybrane wyniki eksploatacyjnych badań trwałości zestawów kołowych tramwaju. Wyniki pomiarów podcięcia obrzeża kół oraz zużycia na średnicy tocznej kół zestawów kołowych tramwaju stanowią, między innymi, bazę danych służącą do przeprowadzenia obliczeń trwałości koła tocznego tramwaju w dwóch aspektach: warunków pracy koła oraz materiałów, z których te koła wykonano.

1. INTRODUCTION

The life of an object, element or a set is defined as either the time period of its operation counted from the moment it comes into service until it is eliminated or the time period of its operation until its first failure [1].

In the former aspect, what is meant is the overall life of the whole object, tram for example, i.e. the set of all the component elements of the vehicle, under systematic diagnostic monitoring (measurement of wear) from the beginning of service until failure. The latter aspect refers to partial life, i.e. of a selected element of the tram, e.g. the wheel set life, in particular the wear of the wheel on the rolling circle or the rim.

The aim of the in-service analysis of tram wheel set life is to investigate the effect of tram service conditions on the values of the median and modes calculated on the basis of Weibull distribution function graphs.

2. RESEARCH METHODOLOGY

The detailed analysis covered the wear of wheel sets (Fig. 1) of 105Na high-floor trams and compared the wear of wheel sets (Fig. 2) of NGT6 low-floor trams.

During the in-service investigation of the wear of wheel rim undercut and the wear on the tram axle set “rolling circle” relevant data bases were created using the following nomenclature [4]:

TB_1 –NGT6 tram, new bands before regeneration,

TB_2 –NGT6 tram, bands after regeneration.
TK –105Na tram,
n – drive truck,
t – rolling truck,
D – rolling circle diameter [mm],
O – rim,
D_1 – diameter of the first wheel (axle 1),
D_2 – diameter of the second wheel (axle 1),
D_3 – diameter of the third wheel (axle 2),
D_4 – diameter of the fourth wheel (axle 2),
O_1 – rim of the first wheel (axle 1),
O_2 – rim of the second wheel (axle 1),
O_3 – rim of the third wheel (axle 2),
O_4 – rim of the fourth wheel (axle 2),
Z – material wear,
m_1 – material V101,
m_2 – material P70T,
m_3 – material P60T.

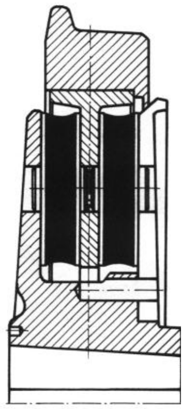

Fig. 1. General view of KONSTAL wheel –105Na tram
Rys. 1. Widok ogólny koła typu KONSTAL – tramwaj 105Na

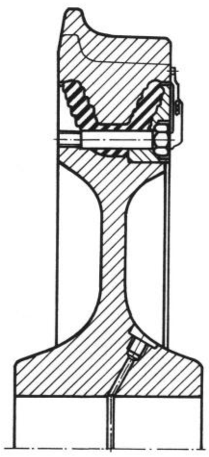

Fig. 2. General view of wheel – the latest design – NGT6 tram
Rys. 2. Widok ogólny koła – najnowsze rozwiązanie – tramwaj NGT6

The results of wear measurements have been presented as Weibull distribution function graphs and in tables.

3. SOME RESULTS OF TESTS

Weibull distribution is frequently used in mathematical modelling of technical objects life, including wheel sets [2]. Weibull distribution reliability, in other words, the probability of correct operation $R(x_i)$ is expressed by equation (1):

$$R(x_i) = \exp\left[-\left(\frac{x_i}{\alpha}\right)^{\beta}\right] \tag{1}$$

where: β – parameter of distribution curve shape ($\beta > 0$), α - parameter of scale, connected with object's mean life ($\alpha > 0$).

Weibull distribution function $F(x_i)$, also called unreliability function or failure probability function, is expressed by equation (2):

$$F(x_i) = 1 - R(x_i) = 1 - \exp\left[-\left(\frac{x_i}{\alpha}\right)^{\beta}\right] \tag{2}$$

The function of failure intensity (hazard) for this distribution $\lambda(x_i)$ is derived from equation (3):

$$\lambda(x_i) = \frac{\beta}{\alpha} \cdot \left(\frac{x_i}{\alpha}\right)^{\beta-1} \tag{3}$$

The probability density function $f(x_i)$ has the form (4):

$$f(x_i) = \lambda(x_i) \cdot R(x_i) = \frac{\beta}{\alpha} \cdot \left(\frac{x_i}{\alpha}\right)^{\beta-1} \cdot \exp\left[-\left(\frac{x_i}{\alpha}\right)^{\beta}\right] \tag{4}$$

The median (mean value) - m_e:

$$m_e = \alpha \cdot \sqrt[\beta]{-\ln 0{,}5} \tag{5}$$

The mode (modal value) - x_{ex}:

$$x_{ex} = \alpha \cdot \sqrt[\beta]{\frac{\beta - 1}{\beta}} \qquad \beta > 1 \tag{6}$$

The expected value of random variable X (mean period until failure) $E(X)$ is calculated from equation [6, 16, 46]:

$$E(X) = \alpha \cdot \Gamma\left(\frac{1}{\beta} + 1\right) \tag{7}$$

where: $\Gamma(p)$ – gamma function

Density function:

$$f(x_i) = \frac{\delta}{\theta} \cdot x_i^{\delta-1} \cdot \exp\left(-\frac{x_i^{\delta}}{\theta}\right) \tag{8}$$

Function of failure intensity:

$$\lambda(x_i) = \frac{\delta}{\theta} \cdot x_i^{\delta-1} \tag{9}$$

3.1. Whee set life in the aspect of wheel rim wear

Calculations for specimen $TB_1(m_1,O, n)$

The values of Weibull distribution parameters α and β for specimen $TB_1(m_1,O, n)$ are:
$\alpha = 41\ 272$
$\beta = 6{,}29$

After substituting the values of parameters α and β the correct operation function and Weibull distribution function take the form:

$$R(x_i) = \exp\left[-\left(\frac{x_i}{41272}\right)^{6,29}\right] \tag{10}$$

$$F(x_i) = 1 - \exp\left[-\left(\frac{x_i}{41272}\right)^{6,29}\right] \tag{11}$$

Fig. 3 illustrates the correction operation function $R(x_i)$ of tram wheel band and distribution function $F(x_i)$.

The projection of the intersection point of the two curves onto the horizontal axis gives the median value (m_e) of tram wheel band operation time.

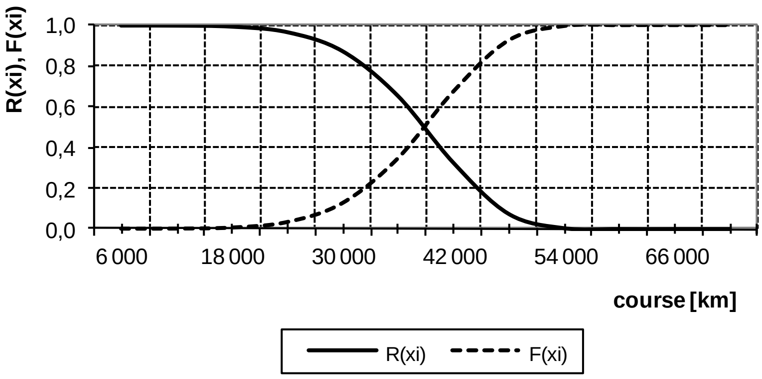

Fig. 3. Function of correct operation function $R(x_i)$ and distribution function $F(x_i)$ of tram wheel band – specimen $TB_1(m_1,O, n)$, $m_e = 38\,937$ [km]

Rys. 3. Wykresy funkcji prawdopodobieństwa poprawnej pracy $R(x_i)$ i dystrybuanty $F(x_i)$ obręczy koła tramwaju – próbka $TB_1(m_1,O, n)$, $m_e = 38\,937$ [km]

After substitution of α and β parameters, the failure density function $f(x_i)$ and failure intensity function $\lambda(x_i)$ takes the form:

$$\lambda(x_i) = \frac{6,29}{41272} \cdot \left(\frac{x_i}{41272}\right)^{5,29} \tag{12}$$

$$f(x_i) = \frac{6,29}{41272} \cdot \left(\frac{x_i}{41272}\right)^{5,29} \cdot \exp\left[-\left(\frac{x_i}{41272}\right)^{6,29}\right] \tag{13}$$

Fig. 4 illustrates the graphs of the failure density function $f(x_i)$ and failure intensity function $\lambda(x_i)$ of tram wheel band..

The maximum of failure density curve corresponds to the mode value (x_{ex}) of the distribution in question: $x_{ex} = 40\,153$ [km]

The expected value defining the mean value until failure is: E(X) = 38 375 [km].

Fig. 5 illustrates a set of median values after Weibull distribution of the wear of wheel set rims. Specimen $TB_1(m_1,O,n)$ has the lowest median value, specimen $TB_1(m_2,O,t)$ the highest.

Fig. 6 shows a set of mode values of wheel set rims after Weibulla distribution. As in the case of the median, specimen $TB_1(m_1,O,n)$ has the lowest mode value, while specimen $TB_1(m_2,O,n)$ has the highest.

In table 1 the results of calculations of tram wheel set life in the aspect of wheel set rim wear after Weibull distribution in the function of mileage [km] have been tabulated.

From the analysis of the data given in table 1 it follows that the highest values of the median, mode and expected values are found in the wheel sets made from material $m_{2,}$ which are used in NGT6 tram.

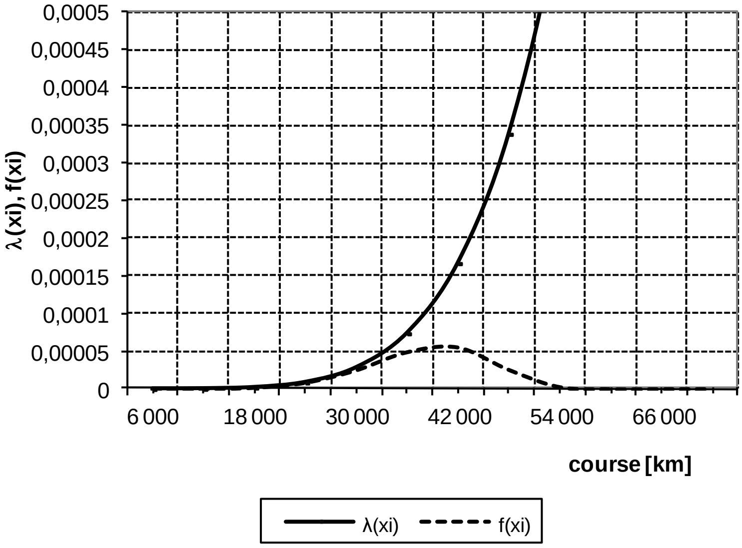

Fig. 4. Functions of failure density $f(x_i)$ and intensity $\lambda(x_i)$ of tram wheel band – specimen $TB_1(m_1,O, n)$, x_{ex} = 40 153 [km]

Rys. 4. Wykresy funkcji gęstości $f(x_i)$ i intensywności uszkodzeń $\lambda(x_i)$ obręczy koła tramwaju – próbka $TB_1(m_1,O, n)$, x_{ex} = 40 153 [km]

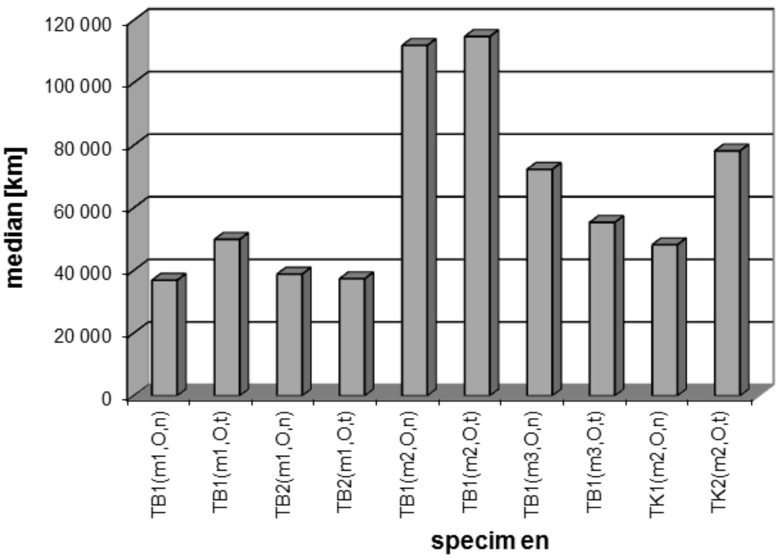

Fig. 5. Rim undercut: median values after Weibulla distribution

Rys. 5. Podcięcie obrzeża: zestawienie zbiorcze wartości mediany według rozkładu Weibulla

On the basis of the analysis of wheel band life in the aspect of rim undercut the following general conclusions can be formulated:

- material V101 *(m_1)* in NGT6, for rim undercut, shows the lowest value of the median – 38 937 km ,
- material P70T *(m_2)* in NGT6, for rim undercut, shows the highest value of the mode – 125 689 km,

- material V101 *(m_1)* "before" and "after" reprofiling shows a similar value of the median,
- material P70T *(m_2)* in 105Na, for rim undercut, shows the value of the median lower than for NGT6.

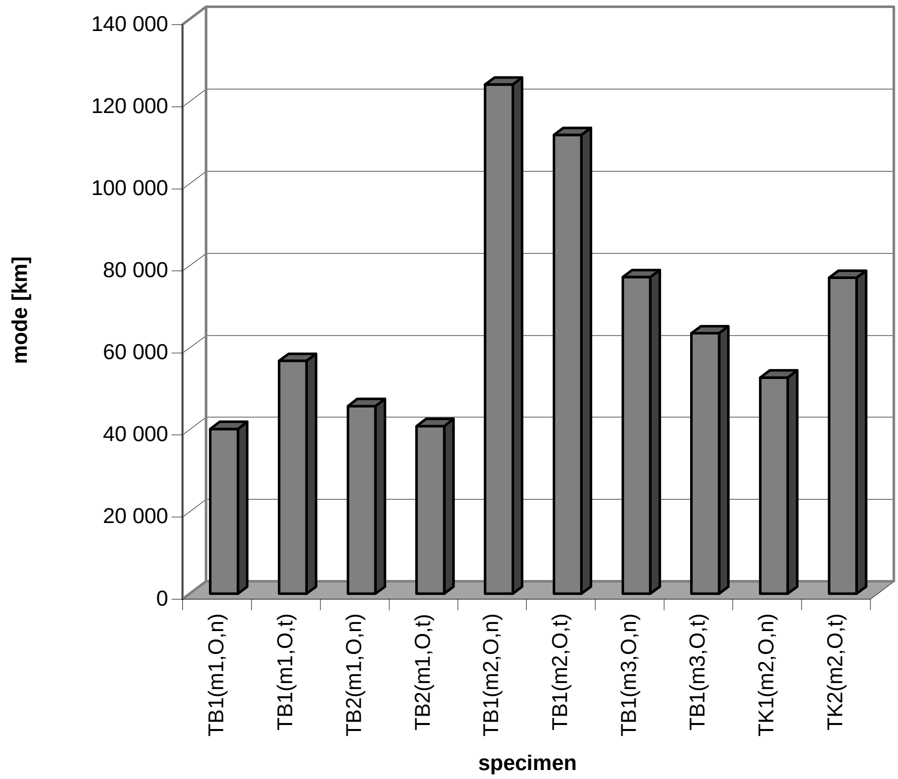

Fig. 6. Rim undercut: mode values after Weibulla distribution
Rys. 6. Podcięcie obrzeża: zestawienie zbiorcze wartości mody według rozkładu Weibulla

Table 1
Results of calculations of tram wheel set life in the aspect of wheel rim wear

No..	Type of specimen	Median m_e [km]	Mode x_{ex} [km]	Expected value E(X) [km]
1	$TB_1(m_1,O,n)$	38 937	40 153	38 375
2	$TB_1(m_1,O,t)$	55 400	56 800	54 813
3	$TB_2(m_1,O,n)$	51 153	45 708	53 579
4	$TB_2(m_1,O,t)$	51 166	40 833	55 446
5	$TB_1(m_2,O,n)$	124 188	124 102	124 589
6	$TB_1(m_2,O,t)$	125 689	111 779	131 858
7	$TB_1(m_3,O,n)$	74 826	77 162	73 824
8	$TB_1(m_3,O,t)$	68 748	63 519	71 201
9	$TK_1(m_2,O,n)$	51 172	52 729	50 576
10	$TK_2(m_2,O,t)$	78 328	77 018	79 169

3.2. Tram wheel set life in the aspect of wheel band wear on the rolling circle

A set of median values of wheel set wear on the rolling circle, after Weibull distribution, has been shown in Fig. 7. The lowest median value was found in specimen $TB_1(m_2,D,t)$, the highest in specimen $TB_2(m_1,D,n)$.

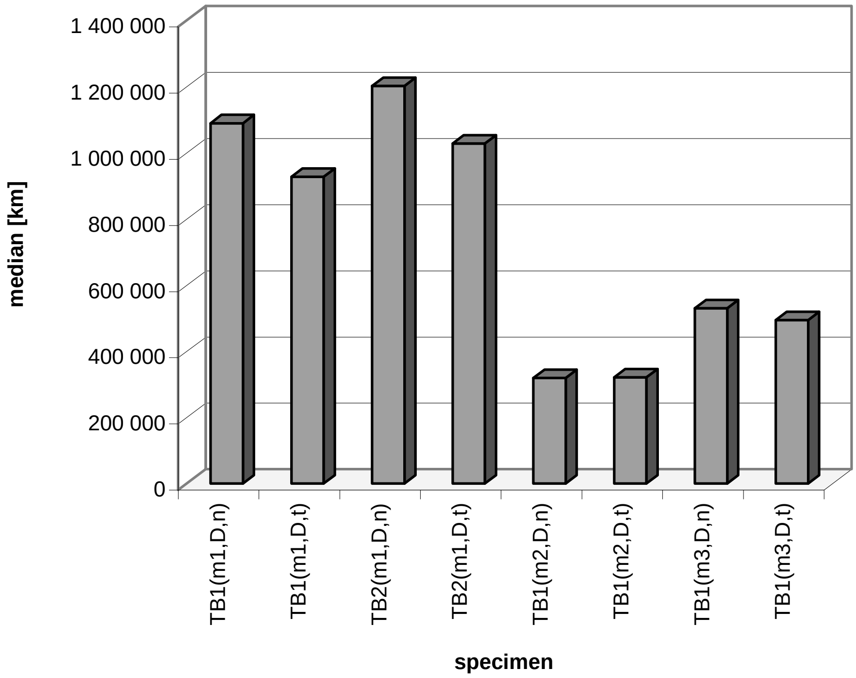

Fig. 7. Wheel set wear on the rolling circle – median values after Weibull distribution
Rys. 7. Zużycie zestawu kołowego na kręgu tocznym - zestawienie biorcze wartości mediany według rozkładu Weibulla

Fig. 8 illustrates the mode values, after Weibull distribution, for wheel set wear on the rolling circle. As in the case of the median, the lowest mode value was found in specimen $TB_1(m_2,D,n)$, the highest was found in specimen $TB_2(m_2,D,n)$.

In table 2 the results of calculations of tram wheel set life in the aspect of axle set wear on the rolling circle after Weibull distribution have been tabulated.

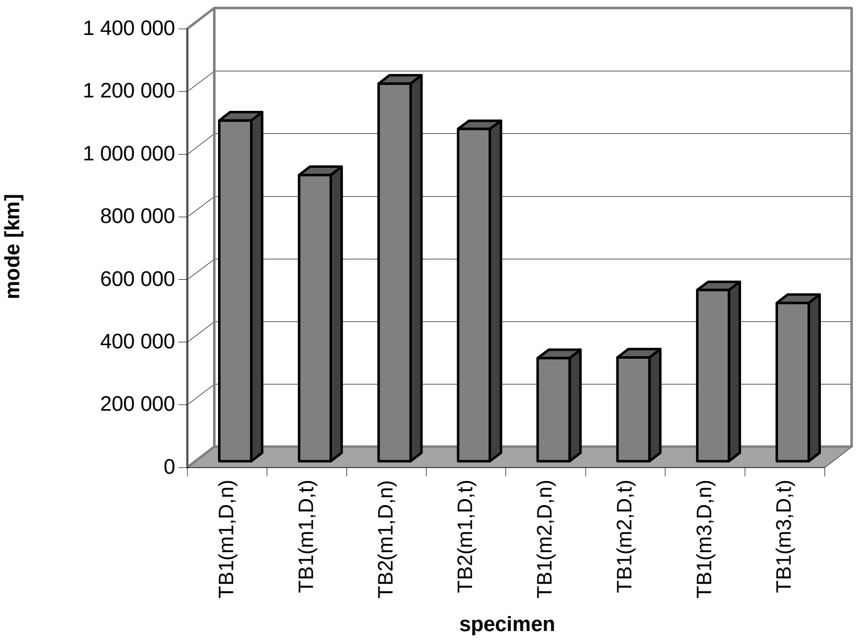

Fig. 8. Wheel set wear on the rolling circle – mode values after Weibull distribution
Rys. 8. Zużycie zestawu kołowego na kręgu tocznym - zestawienie zbiorcze wartości mody według rozkładu Weibulla

Table 2

Results of calculations of tram wheel set life in the aspect of wheel set wear on the rolling circle after Weibull distribution in the function of mileage [km]

No.	Type of specimen	Median m_e [km]	Mode x_{ex} [km]	Expected value E(X) [km]
1	$TB_1(m_1,O,n)$	1 089 902	1 087 860	1 094 465
2	$TB_1(m_1,O,t)$	927 808	913 736	936 802
3	$TB_2(m_1,O,n)$	1 202 451	1 205 772	1 204 835
4	$TB_2(m_1,O,t)$	1 028 459	1 060 524	1 015 565
5	$TB_1(m_2,O,n)$	319 200	329 139	314 661
6	$TB_1(m_2,O,t)$	320 993	330 983	316 504
7	$TB_1(m_3,O,n)$	530 655	547 016	523 141
8	$TB_1(m_3,O,t)$	495 578	505 819	491 756

On the basis of the analysis of wheel band life in reference to wear on the rolling circle some general conclusions can be drawn:

- in material V101 *(m_1)* w NGT6 on the rolling circle, the highest mode value – 1205772 km was found,
- in material P70T (m_2) w NGT6 on the rolling circle, the lowest median value – 319200 km was found,
- in material P70T *(m_2)* w NGT6 on the rolling circle, the values of median and mode were lower than in material V101 *(m_1)* and material P60T *(m_3)*.

4. FINAL CONCLUSIONS

On the basis of the comparison of in-service life of tram wheel sets in reference to wheel rim wear and wear on wheel rolling circle it can be stated that rim wear (undercutting) is a parameter deciding of the necessity of wheel reprofiling.

The wear on the rolling circle does not decide of wheel set life. What decidedly affects the decrease of the diameter on the rolling circle is the rim reprofiling.

The in-service tests on the wear have proved that the undercut of the rim made from P70T material reveals in NGT6 trams a uniform wear of all the wheel bands in the truck. This favourably affects the decrease of service costs [3] due to, among other things, maintaining the required dimensions of the wheels in both the given wheel set and the given tram truck. What is also important is the possibility of planning repair works of tram trucks and wheel band life prognosis. The results of the study can be used in the optimization of service and improvement of NGT6 trams operation economy.

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