ANALYSIS OF RELIABILITY, AVAILABILITY AND MAINTAINABILITY (RAM) OF SM48 DIESEL LOCOMOTIVE

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Summary: The paper presents the results of a RAM analysis of the SM48 diesel locomotive. The analysis was based on operational tests done on a selected sample of locomotives run by the Polish rail company PKP CARGO S.A. The paper describes selected ratios of the locomotive’s dependability, split into three groups: reliability, availability and maintainability.

1. Introduction

The subject of this paper is a RAM analysis of the SM48 diesel locomotive (Fig. 1). In the analysis, the locomotive is treated as a repairable object. For objects of this type, methods used for objects which operate until the first failure, i.e. with the use of only the functions of reliability \( R(t) \) or intensity of failures \( \lambda(t) \) are insufficient. The dependability of rail vehicles, including diesel locomotives, should be treated as a comprehensive property comprising such system characteristics as reliability, availability and maintainability (RAM) [1]:

- reliability (operability) is understood as the system’s capability to perform the required functions under stated conditions, and for a specified period of time;
- availability is the vehicle’s capability to be in a condition enabling it to perform the required functions under stated conditions, at a specified moment or for a specified time, presuming that the required external resources are provided;
- maintainability is defined as the characteristic of adaptation to repair done in order to restore the object’s operability under stated conditions with the use of prescribed methods and resources.

For a vehicle to be in the state of availability means that it is not out of operation due to preventive maintenance or inoperable due to a failure. Availability depends not only on maintenance downtimes but also on the probability of the vehicle’s failure to perform its functions (unreliability effect) [1]. Maintainability in respect of rail vehicles concerns corrective and preventive maintenance. Corrective maintenance enables restoration of the object’s operability and putting it back into operation. Preventive maintenance, on the other hand, is done as part of an object’s prescribed maintenance cycle in order to improve its reliability and control its wear [2, 3]. The aim behind effective maintenance is to minimise the mean downtime (MDT) and the related costs. General guidelines on the analysis of reliability, availability and maintainability are provided in the PN-EN 50126 standard on

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Railway Applications – Specification and Demonstration of Reliability, Availability, Maintainability and Safety [4].

For the purposes of testing and assessing the reliability of the SM48 locomotive, it was presumed that the mathematical model describing its operation is the renewal process with a finite time of renewal. Two conditions of the system and its elements are identified: operability and inoperability. A description of reliability is usually provided – account being taken of many failures and repairs – with the assumption that the renewal restores the original properties of the object in full.

SM48 locomotive’s technical data:
- Intended use: shunting (line operations)
- Axle number and configuration: 6 axles Co’Co’
- Design speed: 100 km/h
- Gear type: electric, direct current
- Service mass: 120 ± 3% tons
- Diesel engine label: 2D50M / PD1M
- Engine rated power: 880 kW (1200 KM)
- Unit fuel consumption: 165 g / KMh

Because of the volume restrictions, the paper only presents selected results of the locomotive reliability analysis, with the reliability ratios for the locomotive as a whole, without detailed calculations for its sub-assemblies and elements. The complete results of the reliability analysis are provided in [5].

2. Locomotive operational tests

The reliability assessment of the SM48 locomotive is based on operational tests done on a selected sample of locomotives numbered: SM48-060, SM48-065, SM48-122, SM48-123 and SM48-126, run by PKP CARGO S.A., its plant in Lublin, section for the operation and repair of the rolling stock in Chełm (Wschodni Zakład Spółki w Lublinie, Sekcja Eksplatacji i Napraw Taboru Trakcyjnego w Chełmie). The criterion for the selection of locomotives for the operational tests was the date of their most recent revision repair. It was presumed that a revision repair restores the original usability and reliability characteristics in full. In total, the operational tests covered the period from the beginning of November 2004 until the end of July 2011, which enabled a test of each locomotive to be performed during the periods in between of their revision repairs. Table 1 provides basic information on the process of operation of the locomotives under study.

The failures of the SM48 locomotive most frequently encountered during operation include:
- oil leaks from the internal combustion engine,
- water leaks from the cooling system,
• leaks in the pneumatic system,
• failures of the electric system (including the radiotelephone), and
• failures of the cooler fans, and other.

Table 1. Information about the process of locomotive operation

<table>
<thead>
<tr>
<th>Beginning of observation</th>
<th>End of observation</th>
<th>Time of operation</th>
<th>Kilometrage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Total</td>
<td>Average per locomotive</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Total</td>
</tr>
<tr>
<td>1.11.2004</td>
<td>30.07.2011</td>
<td>262,800.0 hrs</td>
<td>52,560.0 hrs/loc.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>712,800.0 km</td>
<td>142,560.0 km/loc.</td>
</tr>
</tbody>
</table>

The structure of the recorded failures demonstrated the lowest reliability of the following assemblies:
• PD1M internal combustion engine (cooling and lubricating systems),
• pneumatic system, and
• machinery and electric system.

3. Selected locomotive RAM ratios

The data gathered during the operational tests was analysed and organised. A formal recording of the information gathered and processed was preliminarily made in Microsoft Excel electronic format. Then, using the capabilities of the Statistica, MiniTab and Mathematica packages, the reliability analysis was performed to include:
• development of histograms of the times of correct operation and failure repairs,
• verification of hypotheses on the forms of distributions of the times of correct operation and of failure repairs,
• estimation of unknown distribution parameters,
• determination of basic statistical parameters, and
• calculation of reliability ratios.

Selected reliability ratios are provided in sections 3.1 ÷ 3.3. They are based on the formulae and definitions contained in [6, 7, 8, 9].

3.1 Reliability ratios

As part of the assessment of the SM48 locomotive’s reliability, the following were determined:
• cumulative distribution function of time of operation to failure, \( F(t) \),
• renewal function in the maintenance cycle, \( H(t) \),
• Mean Time To Failure, \( MTTF \), and
• Mean Time Between Failures, \( MTBF \).

Histograms of the time of operation were made for the Mean Time To Failure (MTTF) ratio, and the basic statistical parameters were calculated: mean, standard deviation, variance, total of all failures, minimum, maximum and medium, first and third quartile together with confidence intervals. The graphs show the empirical
cumulative distribution function of the time to first failure (so-called unreliability function) and the theoretical cumulative best match distribution function. The quality of the match between the theoretical distribution and the empirical data was presented using function maps. In order to verify the hypotheses on the distribution form, the confidence level of 95% was assumed and the Anderson-Darling (A-D) Normality Test was applied. In order to estimate the parameters of distribution, times of correct operation and of failure repairs, the maximum likelihood estimation was applied.

a) Cumulative distribution function of time of operation to failure \( F(t) \)

Figure 2 presents a histogram of the frequency of the SM48 locomotive failures with the basic statistical parameters and confidence intervals of 95%.

![Figure 2. Histogram of the frequency of SM48 failures with basic statistical parameters and confidence intervals of 95%](image)

The test confirmed, at a 95% confidence level, the correspondence between the empirical distribution of correct operation to SM48 locomotive failure and the Weibull distribution with the following parameters: \( a=1.435 \) and \( b=898.9 \) (Fig. 3).

![Figure 3. a) Empirical and theoretical cumulative distribution functions for the Weibull distribution of time of operation to failure of SM48 locomotive, b) Match between the Weibull distribution and empirical data](image)
The following were determined on the basis of the estimated distribution parameters:

- probability density function of time of correct operation to failure:

\[
f(t) = \frac{a}{b} \left( \frac{t}{b} \right)^{a-1} \exp\left( -\frac{t}{b} \right) = 8.285 \times 10^{-5} \exp(-5.773 \times 10^{5} \cdot t^{0.435}) \cdot t^{0.435}, \quad \text{for } t \geq 0 \tag{1}
\]

- cumulative distribution function of time of operation to failure:

\[
F(t) = 1 - \exp\left( -\frac{t}{b} \right) = 1 - \exp(-5.773 \times 10^{5} \cdot t^{0.435}), \quad \text{for } t \geq 0 \tag{2}
\]

b) renewal function between locomotive revision repairs \( H(t) \)

The renewal function \( H(t) \) defines the average number of locomotive failures as a function of time of correct operation. Since the time spent renewing the locomotive between the successive revision repairs does not exceed 1.5% of the time of correct operation, the \( H(t) \) was considered to be negligibly small in the calculations. In such a case, the renewal function expresses the mean time of renewals equalling the number of failures until the time \( t \). The graph for the empirical renewal function with the theoretical match between the successive revision repairs (4 years of operation) is presented in Fig. 4. The graph of the \( H(t) \) function provides the mean number of failures of the SM48 locomotive as a function of time. The data indicates that in between of the revision repairs, there are 96 locomotive failures on average, with the following occurrences:

- 20 during the first year of operation after revision repair,
- 21 during the second year of operation,
- 31 during the third year of operation, and
- 24 during the fourth year of operation.

![Graph](image)

**Fig. 4. SM48 locomotive renewal function between revision repairs**

For analytical purposes, the empirical form of the locomotive renewal function may be presented as follows:
Maciej Szkoda
ANALYSIS OF RELIABILITY, AVAILABILITY AND MAINTAINABILITY (RAM) OF SM48 DIESEL LOCOMOTIVE

\[ H(t) = 1.641 + 0.0019t + 2.5464 \times 10^4 t^2 \quad \text{for} \quad 0 \leq t \leq 35040 \]  
(3)

where:

\( t \) – time of locomotive operation in [hrs]

c) Mean Time To Failure, \( MTTF \)

The Mean Time to Failure calculated on the basis of the correct operation distribution function is:

\[ MTTF = \int_0^\infty t \cdot f(t) dt = \int_0^\infty t \cdot [1 - \exp(-5.773 \times 10^3 \cdot t^{1.435})] dt = 816.2 \text{ [hrs]} \]  
(4)

The statistical estimate of time of operation to first failure calculated on the basis of operational data comprising 5 maintenance cycles is:

\[ MTTF^* = 816.0 \text{ [hrs]} \]  
(5)

d) Mean Time Between Failures, \( MTBF \)

The Mean Time Between Failures of the locomotive calculated on the basis of the distribution function of the time between failures is:

\[ MTBF = \int_0^\infty t \cdot f(t) dt = \int_0^\infty t \cdot [1.559 \times 10^3 \exp(-1.4246 \times 10^3 \cdot t^{1.064})] dt = 386.4 \text{ [hrs]} \]  
(6)

The statistical estimate of the mean time between failures calculated on the basis of operational data is:

\[ MTBF^* = 385.2 \text{ [hrs]} \]  
(7)

It follows from the above calculations that the first failure of the SM48 locomotive after a revision repair occurs after 816 hours (approx. 34 days) of operation, on average, and the next unplanned failures occur every 386 hours (approx. 16 days) of operation, on average.

3.2 Maintainability ratios

The assessment of maintainability of the SM48 locomotive is about both planned and preventive maintenance activities performed during its maintenance cycle. For planned maintenance, the empirical and theoretical renewal time distribution function \( G(t) \) and the mean time to repair \( (MTTR) \) were determined. The \( MTTR \) comprises the time of repair and of the technical delays involved in diagnosing the failure and gathering the spare parts.

a) Renewal time cumulative distribution function \( G(t) \) and mean time of renewal, \( MTTR_B \)

The basis for determining the cumulative distribution function and the mean time of renewal was provided by the operational data obtained from 658 planned
maintenance activities performed on SM48 locomotives in 2004 ÷ 2011 at PKP CARGO S.A. Figure 5 shows a histogram of the number of SM48 locomotive renewals with the basic statistical parameters and confidence intervals of 95%.

Fig. 5. Histogram of the number of SM48 locomotive renewals with the basic statistical parameters and confidence intervals of 95%

The estimated parameters of lognormal renewal time distribution are: \( a = 1.444 \) and \( \sigma = 0.7675 \) (Fig. 6). Hence, the locomotive renewal time cumulative distribution function is:

\[
G(t) = 0.5 \left[ 1 + \Phi \left( \frac{\ln(t) - 1.444}{0.7675 \sqrt{2}} \right) \right], \text{ for } t > 0
\]  

(8)

where:

\[
\Phi(z) = \frac{2}{\sqrt{\pi}} \int_0^z \exp(-t^2) dt \quad \text{Gauss distribution function}
\]

Fig. 6. a) Empirical and theoretical lognormal renewal time cumulative distribution functions, b) Match between the lognormal distribution and the empirical data
The mean renewal time calculated on the basis of the renewal time distribution function is:

\[ MTTR_s = \exp\left( a + \frac{\delta^2}{2} \right) = 5.7 \text{ [hrs]} \]  

(9)

The statistical estimate of the mean renewal time is:

\[ MTTR_s = 5.5 \text{ [hrs]} \]  

(10)

It follows from the above calculations that the mean renewal time (planned maintenance) for the SM48 locomotive is 5.7 [hrs], on average.

b) Mean time to preventive maintenance

Preventive maintenance of the SM48 locomotive includes planned vehicle downtimes and maintenance activities. The activities which are part of the different maintenance jobs are specified in the *Technological Documentation for the Maintenance System: TECM2 SM48 Diesel Locomotive [10]*. Based on the data obtained from PKP CARGO S.A., the mean times of the different maintenance activities were calculated. The calculations are given in Table 2.

<table>
<thead>
<tr>
<th>No.</th>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Time of control maintenance activity, PK</td>
<td>MTTR\textsubscript{PK}</td>
<td>4.0 hrs</td>
</tr>
<tr>
<td>2</td>
<td>Time of planned maintenance, P1</td>
<td>MTTR\textsubscript{P1}</td>
<td>12.0 hrs</td>
</tr>
<tr>
<td>3</td>
<td>Time of planned maintenance, P2</td>
<td>MTTR\textsubscript{P2}</td>
<td>24.0 hrs</td>
</tr>
<tr>
<td>4</td>
<td>Time of planned maintenance, P3</td>
<td>MTTR\textsubscript{P3}</td>
<td>3.0 days</td>
</tr>
<tr>
<td>5</td>
<td>Time of planned maintenance, PD</td>
<td>MTTR\textsubscript{PD}</td>
<td>25.0 days</td>
</tr>
<tr>
<td>6</td>
<td>Time of revision repair, R</td>
<td>MTTR\textsubscript{R}</td>
<td>66.0 days</td>
</tr>
<tr>
<td>7</td>
<td>Time of main repair, G</td>
<td>MTTR\textsubscript{G}</td>
<td>92.0 days</td>
</tr>
</tbody>
</table>

3.3 Technical availability ratios

In order to assess the locomotive’s technical availability, the operational availability ratio \( A_O \) and the actual availability ratio \( A_R \) were used. These ratios present the mean technical availability of the locomotive between its revision maintenances [4]. The definition of the \( A_O \) and \( A_R \) ratios comprises both the reliability and maintainability ratios determined in sections 3.1 ÷ 3.3.

a) Operational availability ratio, \( A_O \)

The mean time between revision maintenances based on operational data:

\[ TZ = 301848 \text{ [hrs]} \]  

(11)

The mean time when the locomotive is inoperable due to planned maintenances between revision repairs is:
\[ TN = H(T_{na}) \cdot MTTR_a = 99.5 \cdot 5.7 \text{ [hrs]} = 567.2 \text{ [hrs]} \] (12)

where:
\begin{align*}
H(T_{NR}) & \text{ – function of the SM48 locomotive renewal between revision repairs,} \\
MTTR_B & \text{ – mean time of locomotive renewal.}
\end{align*}

Based on the above parameters, the operational availability ratio was calculated:

\[ A_o = \frac{TZ}{TZ + TN} = \frac{30184.8 \text{ [godz]}}{30184.8 \text{ [hrs]} + 567.2 \text{ [hrs]}} = 0.9815 \] (13)

The ratio \( A_o \) of 0.9815 means that the locomotive is out of operation due to planned repairs and preventive maintenances for 139 hours in a year on average.

b) Ratio of actual availability \( A_R \)

The average locomotive downtime during planned downtimes and maintenance activities between the successive revisions:

\[ TO = \sum (PU_i \cdot MTTR_i) = 42880 \text{ [hrs]} \] (14)

where:
\begin{align*}
PU_i & \text{ – number of planned downtimes or maintenance activities,} \\
MTTR_i & \text{ – mean time of planned downtimes or maintenance.}
\end{align*}

Based on the above parameters, the actual availability ratio was defined as:

\[ A_a = \frac{TZ}{TZ + TN + TO} = \frac{30184.8 \text{ [hrs]}}{30184.8 \text{ [hrs]} + 567.2 \text{ [hrs]} + 42880 \text{ [hrs]}} = 0.8614 \] (15)

The ratio \( A_R \) of 0.8614 means that the locomotive is out of operation because of corrective and preventive maintenance for 1046 on average in one year.

4. Conclusions

The paper presents selected results of the RAM analysis for the SM48 diesel locomotive. The basic reliability ratios were calculated which relate to such vehicle characteristics as: reliability, availability and maintainability. The tests, supplemented with an analysis of the wear and tear of the locomotive’s assemblies and elements, significant from the viewpoint of railway traffic, provided the basis
for a modification of the locomotive maintenance cycle. The reliability ratios thus determined can also form the basis for a Life Cycle Cost (LCC) analysis.

References

[4] PN-EN 50126 Railway applications. The specification and demonstration of Reliability, Availability, Maintainability and Safety (RAMS)

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