Analysis of the 1435/1520 mm track gauge change systems in the aspects of reliability and efficiency

Key words: track gauge change, track gauge changing system, reliability analysis, LCC analysis

Abstract. The paper is based on the research work done at the Institute of Rail Vehicles, Cracow University of Technology, on the assessment of the reliability and efficiency of the 1435/1520 mm track gauge change systems. The efficiency of these systems depends considerably on the gauge change method relating to complex handling and track gauge change operations. The Life Cycle Cost (LCC) analysis served as the basis for a comparative analysis of the reliability and efficiency of the transport of hazardous materials with the use of the currently applied technology: wagon bogie exchange, and the technology of the future: the SUW 2000 system of self-adjusted wheel sets.

1. Introduction

Economic development depends largely on an efficient transport system which should enable reliable, safe and efficient cargo transport both domestically and internationally. Assurance of effective conditions for realization of international cargo haulage is particularly difficult for the rail transportation. It is connected with various gauges existing in Euro-Asian continent. Majority of the European countries, as well as Poland, have 1435 mm gauge tracks but the railways of the former Community of Independent States and the others, including Lithuania, Latvia and Estonia, have railways of 1520 mm gauge. In the territory of Asia a train moves on the wide gauge track (1520 mm), encounter with the normal gauge (1435 mm) lines in China and Korea again. In Spain and Portugal there are even wider, 1668 mm railway tracks. These differences cause major operational problems because at the point of contact between tracks of different gauges cargo needs to be reloaded or the rail vehicle wheel sets need to be exchanged. These operations are costly, time-consuming and require an extended infrastructure at border crossing points, including the entire and very costly warehousing and handling facilities. Moreover, these operations significantly extend transport times.

Analysis of the current situation in rail transport with track gauge change demonstrates that particular improvement is required in the track gauge change system which is used for transporting hazardous materials (chemicals, oil products). The current solutions applied at the crossing points along Poland’s eastern border, for this cargo group, are characterised by poor reliability and low efficiency, and pose a serious threat to the environment and safety of the system setting [8, 9].

2. Systems under analysis

In rail transport systems with track gauge change, cargo can be transported with the application of reloading or gauge changing technologies. In the latter, cargo is moved by the same means of transport, changed at the border-crossing point from one track gauge to another. This paper is about an assessment of the reliability and efficiency of two selected gauge change systems applied in the transport of hazardous materials:
– system 1 where the track gauge is changed through wagon bogie exchange, with the lifting of the wagon body, as currently applied;
– system 2 where the track gauge is changed with the use of the prospective method – the SUW 2000 self-adjusted wheel sets.

Table 1 presents the basic quantity/quality parameters characterising the service process in the systems concerned. The analysis leaves out the duration of the operations which consist of the train receipt, i.e. checking the securities, checking the compliance of the shipping documents, customs clearance and wagon weighing.

Table 1. Characteristics of the service process in the 1435/1520 mm points [9].

<table>
<thead>
<tr>
<th>System</th>
<th>Shift group</th>
<th>Equipment of the point 1435/1520</th>
<th>Mean shifting time</th>
<th>Mean time of the shift group exchange</th>
<th>Number of groups per 24 hours</th>
<th>Shifting capability per 24 hours</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[wagons]</td>
<td>[-]</td>
<td>[min]</td>
<td>[min]</td>
<td>[-]</td>
<td>[wagons]</td>
</tr>
<tr>
<td>1</td>
<td>10</td>
<td>10 stands with elevators</td>
<td>200</td>
<td>25</td>
<td>3</td>
<td>30</td>
</tr>
<tr>
<td>2</td>
<td>30, entire number of wagons in a train</td>
<td>Gauge changing facility</td>
<td>6</td>
<td>25</td>
<td>46</td>
<td>1380</td>
</tr>
</tbody>
</table>

3. Assessment of the systems’ reliabilities

A comprehensive reliability assessment method applied to the systems analysed takes into account such system properties as: non-destructability, durability, maintainability and system availability. The basis for assessing the systems’ reliabilities comprises operational data gathered in actual work conditions covering about 7 years of operation for the wagon bogie exchange systems, and almost 4 years for the self-adjusted wheel sets. This enabled observation of the development of operation of system elements in a variety of conditions and thus provided accurate data for reliability assessment.

3.1 Assumptions and structure of the analysed systems

Assessment of the reliabilities of the systems concerned was comparative in its nature. Thus, the common elements which have the same effect in both systems, e.g. 1435 and 1520 mm rail infrastructure, traction vehicles and others, were excluded from the analysis and hence from the reliability structure. The interest in the compared systems focused on elements of technical equipment of the contact points of different track gauges, and the rolling stock engaged in the transport process.

In system 1, wagon bogie exchange stands together with cooperating gantry cranes are used to move a wagon from one track gauge to another. In system 2, the extended technical infrastructure of the wagon bogie exchange point is replaced with a track gauge changing stand. As regards the rolling stock, the most significant differences in the reliability assessment concern wagon bogies. In system 1, two sets of bogies assigned to one wagon are required to effect transport along tracks of different gauges: one for the 1435 mm and the other for the 1520 mm track, which are exchanged at the border crossing point. In system 2, on the other hand, bogies of one type are used which are equipped with adjusted wheel sets, enabling the wagon to move along 1435 and 1520 mm rail tracks.

The assumptions made in Table 2, combined with an analysis of the actual condition, enable the determination of the number of elements within systems 1 and 2 and their reliability structures.
Table 2. Assumptions of the reliability analysis [4].
Tabela 2. Założenia do analizy niezawodnościowej [4].

<table>
<thead>
<tr>
<th>L.p.</th>
<th>ELEMENT</th>
<th>ASSUMPTIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Type of cargo transported</td>
<td>Hazardous materials transported in cistern wagons</td>
</tr>
<tr>
<td>2</td>
<td>Number of wagons exchanged at the 1435/1520 mm point of contact</td>
<td>5,483.0 [wagons/year]</td>
</tr>
<tr>
<td>3</td>
<td>Capacity of the exchanged wagon</td>
<td>48.0 [tonnes]</td>
</tr>
<tr>
<td>4</td>
<td>Wagon turnover: - system 1 - system 2</td>
<td>10.6 [days] 8.0 [days]</td>
</tr>
<tr>
<td>5</td>
<td>Transport distance (one way, along the 1435 mm and the 1520 mm track, half each)</td>
<td>1,100.0 km</td>
</tr>
<tr>
<td>6</td>
<td>Duration of system operation</td>
<td>25 years</td>
</tr>
</tbody>
</table>

The reliability structure of system 1 (Fig. 1) is mapped through serially connecting four subsystems – P1.1, P1.2, P1.3 and P1.4:

- subsystem P1.1 comprises a total of 176 bogies of the 2XTa type per a 1435 mm track (element 1.1), making up a reliability structure with a sliding reserve with the order of redundancy \( k = 10 \). It means that for 160 basic bogies, an operational reserve of 16 elements is made, each of which can replace any basic bogie in the event of its destruction;

- subsystem P1.2 is made of a total of 176 bogies of the 18-100 type per a 1520 mm track (element 1.2), which, by analogy to subsystem P1.1, are mapped by a reliability structure with a sliding reserve with the order of redundancy \( k = 10 \). Analysis of the subsystems P1.1 and P1.2 assumes that the reserve bogies cannot be destroyed when not in operation and that a bogie’s non-operating condition does not affect its reliability. It is assumed further that the time during which a destroyed bogie is replaced by a reserve element practically equals zero and the changing device is absolutely reliable;

![Fig. 1. Reliability structure of system 1.](image-url)
- subsystem P1.3 consists of 14 bogie exchange stands (element 1.3) which are mapped as a threshold structure of the 10 out of 14 type. At least 10 stands are necessary to achieve the assumed number of wagons exchanged at the border point. The 10 out of 14 threshold structure means that subsystem P1.3 is in the state of correct operation when at least 10 out of 14 bogie exchange stands correctly perform the functions they are allocated;
- subsystem P1.4 includes 3 gantry cranes (element 1.4) which are mapped by means of the serial reliability structure.

The reliability structure of system 2 (Fig. 2) is mapped through serially connecting two subsystems P2.1 and P2.2:
- subsystem P2.1 consists of a total of 132 bogies of the 4RS/N type per 1435 and 1520 mm track (element 2.1), which make up a reliability structure with a sliding reserve with the order of redundancy \( k = 10 \). It means that for 120 bogies of the 4RS/N type an operational reserve of 12 elements are made each of which can replace any basic bogie in the case of destruction. Like in subsystems P1.1 and P1.2 in system 1, it is assumed that the time during which a destroyed bogie is replaced with a reserve element is practically equal to zero and the changing device is absolutely reliable;
- subsystem P2.2 comprises one track gauge changing stand (element 2.2).

![Diagram](image)

**Fig. 2. Reliability structure of system 2.**
P2.1, P2.2 – subsystems of system 2, 2.1) wagon bogies of the 4RS/N type with track gauge changing sets, 2.2) track gauge changing stand
Rys. 2. Struktura niezawodnościowa systemu 2.
P2.1, P2.2 – podsystemy systemu 2, 2.1) Wózki wagonowe typu 4RS/N z zestawami przestawnymi, 2.2) Torowe stanowisko przestawcze

### 3.2 Ratios used for the reliability analysis

In quantitative terms, system reliability is expressed through reliability ratios. Track gauge changing systems analysed in this paper comprise non-renewable and renewable elements. As a whole, these systems are comprised in the group of renewable objects because after a destroyed non-renewable element is replaced or a renewable element is repaired, the system regains its usefulness which was temporarily lost. In the reliability analysis, it is irrelevant how the renewal is effected, be it through replacement of the destroyed element with a new one or its repair. The time of renewal which comprised, amongst other items, the time of diagnosing the destruction, the time necessary for gathering the materials spare parts, and the time of repair, are treated as a whole. A basic characteristic of renewable objects is the renewal function \( H(t) \). For objects for which the duration of renewal is negligibly short as compared with the time of correct operation, \( H(t) \) presents the expected number of renewals equaling the number of destructions until the moment \( t \) and is defined as follows [2]:

\[
H(t) = \sum_{i=1}^{n} \frac{1}{i^b} \cdot e^{-\frac{t}{i^b}}
\]
where:

\[ F_n(t) \] – distribution function of the object’s operation until the occurrence of the n-th destruction (renewal):

\[
F_n(t) = \int_0^t F_{n-1}(t-x) dF(x); \quad F_1(t) = F(t)
\]

Figures 3 and 4 present the renewal functions for selected elements of the analysed systems: a standard 2XTa bogie (system 1) and an 4RS/N bogie with track gauge changing sets (system 2).
In addition to the renewal function, the following set of ratios is applied in the method for assessing the reliability of track gauge changing sets, as regards their elements and subsystems:
- intensity (parameter) of the destruction stream \( z(t) \);
- expected time until the first destruction \( MTTF \);
- expected time of correct operation from the completion of the \( k \)-th renewal to destruction numbered \( k \) \( MTBF_k \);
- distribution function of the destruction repair (renewal) time \( G(t) \);
- expected destruction repair time \( MTTR \);
- stationary ratio of operational readiness \( A_O \) and actual readiness \( A_R \).

The definitions of the above ratios are available from the applicable standards and the extensive body of references on durability and reliability, including: [1, 2, 3, 6]. Calculations, in turn, can be found in research papers [4, 9].

The basic reliability characteristics for a system comprising \( n \) elements each of which works and is renewable independently of the others, connected serially, can be presented as follows:
- Random variable showing the number of destructions to the system \( N_S(t) \) until the moment \( t \):
  \[
  N_S(t) = N_{i1}(t) + N_{i2}(t) + \ldots + N_{ik}(t) + \ldots + N_{in}(t)
  \]
  where:
  \( N_{i}(t) \) – random variable which stands for the number of destructions to the \( i \)-th element until the moment \( t \)
- Average number of destructions to the system until the moment \( t \), or the function of system renewal \( H_S(t) \):
  \[
  H_S(t) = E[N(t)] = \sum_{i=1}^{n} E[N_i(t)] = \sum_{i=1}^{n} H_i(t)
  \]
  where:
  \( H_i(t) \) – function of renewal of the \( i \)-th system element
- Technical readiness of the system \( A_S \):
  \[
  A_S = A_1 \cdot A_2 \cdot \ldots \cdot A_n = \prod_{i=1}^{n} A_i
  \]
  where:
  \( A_i \) – technical readiness of the \( i \)-th system element

3.3 Comparison of the reliabilities of systems 1 and 2

Figures 5 ÷ 8 provide a comparison of non-destructability, durability, maintainability and availability of systems 1 and 2 by means of selected reliability ratios. The comparison makes use of the ratio of the average number of failures to the system in one year of operation \( FR \) which, with regard to a single element, is defined as follows:

\[
FR_i = \left( \frac{H_i(t)}{T_i} \right) \cdot 8.760,0 \ \text{[uszk/rok]}
\]

where:
\( FR_i \) – average number of failures to the \( i \)-th element in one year of operation,
\( H(t) \) – function of renewal of the i-th element in the maintenance cycle,
\( T_i \) – time of operation of the i-th element in the maintenance cycle (in hours).

The following ratios were applied to compare the systems’ durabilities: \( \text{MTTF} \) – expected duration of operation until the first destruction, and \( \text{MTBF} \) – expected time of operation between destructions.

The maintainability comparison makes use of the ratio of the average cumulative time of technical servicing of the system in one year of operation \( MR \), which takes into account the total time of current and preventive servicing of the system elements. As regards a single element, this ratio was defined as follows:

\[
MR_i = \left( \frac{TN_i + TO_i}{T_i} \right) \cdot 8.760,0 \ [\text{h/rok}]
\]

where:
\( MR_i \) – average, cumulative duration of technical servicing of the i-th element in a year of operation,
\( TN_i \) – average duration of day-to-day repairs in the maintenance cycle of the i-th element,
\( TO_i \) – average duration of preventive servicing in the maintenance cycle of the i-th element,
\( T_i \) – duration of operation of the i-th element in the servicing cycle (in hours).

The comparison of the technical availability used the ratios of actual availability \( A_R \) and cumulated duration of system stoppage in the year of operation \( \text{MADT} \).

![Bar chart showing average number of failures per year for System 1 and System 2.](image)

Fig. 5. Comparison of system non-destructability.

Rys. 5. Porównanie nieuszkadzalności systemów.
Fig. 6. Comparison of system durability.  
Rys. 6. Porównanie trwałości systemów.

Fig. 7. Comparison of system maintainability.  
Rys. 7. Porównanie obsługiwalności systemów.

Fig. 8. Comparison of system availability.  
Rys. 8. Porównanie gotowości systemów.
The calculations done indicate that system 2 is characterised by higher destructability compared with system 1. Account being taken of destructions to basic and reserve elements, the average number of failures to system 2 in one year ($FR_2$) is 2.8 times higher compared with system 1 (Fig. 5). Lower durability of system 2, indirectly follows therefrom. Assuming a 10% unloaded reserve for 4RS/N bogies, failures to the system occur after 330 hours of operation on average, whilst in system 1 the average time between failures ($MTBF_1$) is more than 2 times longer (Fig. 6). The average number of failures, however, is not sufficient to comprehensively assess the track gauge changing sets. What is important is not only the number and frequency of failures but also their type and, consequently, the time spent to repair them. Figure 7 shows that despite higher destructability, the cumulative repair time in system 2 in a year ($MR_2$), is 40% shorter than for system 1. It follows from the comparison of availability that system 2 is characterised by a higher ratio of technical availability ($AR_2$) and a more than 30 times shorter duration of technical stoppages during the year ($MADT_2$) compared with system 1 (Fig. 8).

4. Assessment of the systems’ efficiencies

The LCC (Life Cycle Cost) model was used to compare the efficiencies of rail gauge changing systems characterised by different reliabilities. The measure of economic efficiency was the total cost of system functioning, so-called LCC durability cycle cost calculated over a 25-year period of operation [5, 10]. The analysis applied a procedure conforming with the recommendations proposed in the PN-EN 60300-3-3 Standard “Reliability Management. Guidelines for Applications – Estimating the Life Cycle Cost”. The method was described by the author in his paper [9]. The basis for developing the model are the parameters relating to non-destructability, maintainability and availability, set under the reliability analysis.

4.1 Life cycle cost model

A common cost model was developed for the analysed systems where the LCC is expressed in the following formula:

$$LCC = KI + KE$$

where:

$KI$ – system investment costs,

$KE$ – system operation costs.

The investment costs $KI$ are a total of the capital outlays necessary for effecting transport in the system concerned. The operation costs $KE$ comprise the costs of system maintenance and use. The analysis was comparative in its nature and hence the model included only the categories which are different for the assessed systems. The structure of costs taken for the analysis is presented in Figure 9.

One of the principal tasks in LCC modelling is to define the cost allocation structure which consists of decomposing the cost categories at the highest level following from the LCC formula adopted, into the component costs. Each category of costs should be divided until the lowermost level, the so-called cost element, is achieved. The cost element is a value which cannot be expressed as a total of other costs. It is definable by means of mathematical formulae containing parameters, fixed values or functions. The advantage of this approach is that it is systematised and orderly thus ensuring a high level of confidence that all cost elements of considerable importance in the LCC have been taken into account. The concept of defining cost elements in the LCC model can be found, *inter alia*, in one of the programmes
of the U.S. Department of Defence, Integrated Logistics Support (Directive DOD 4100.35 1968) and in the PN-EN 60300-3-3 Standard of 2006 [4, 5, 7].

In the model applied, one of the cost elements were the costs of current maintenance $KUB_n$ relating to current repairs done after a system element is destroyed. The $KUB_n$ incorporate both the costs of labour and materials, including spare parts. In order to set the $KUB_n$, the renewal functions $H(t)$ determined in the reliability analysis were used. The current maintenance costs for a single element of the system $KUB_n$ were expressed in the following formula:

$$KUB_n = [H_n(t_i) - H_n(t_{i+1})] \cdot [(MMH_n \cdot CPH_n) + ACM_n] \ [\text{zł/rok}]$$

where:
- $H_n(t_i)$ – value of the function of renewal of the $i$-th element in the $i$-th year of operation;
- $MMH_n$ – average labour intensity of a current repair of the $i$-th element;
- $CPH_n$ – cost per man-hour of a current repair of the $n$-th element;
- $ACM_n$ – average cost of consumption of materials in a current repair.

Generally, 19 costs elements defined on 54 parameters and functions were applied in the LCC model. The LCC calculation was based on non-discounted cost figures. The cost appraisal was based on the 2008 (net) fixed prices.

### 4.2 LCC model analysis

The LCC model analysis performed with the use of the CATLOC software demonstrated that in comparison with the currently applied wagon bogie exchange, the application of SUW 2000 self-adjusted wheel sets in the transport of hazardous materials ensures a decisively higher efficiency of the transport system. In Fig. 10 a comparison of the LCC for systems 1 and 2 is provided, calculated for a period of 25 years of operation. The LCC of system 2 is PLN 3.2 million lower compared with system 1. It can be read from Fig. 11, which presents the LCC structure, that despite definitely higher investment costs in system 2, considerable savings – of more than PLN 18.9 million – are achieved in the costs of operations [9].
In order to estimate the impact of changes in the parameters and cost elements on the \( LCC \), a sensitivity analysis was performed. In system 2, in which SUW 2000 self-adjusted wheel sets are applied, the analysis comprised the following parameters:

- average number of failures to system elements;
- technical availability of the subsystems;
- labour intensity of current repairs of system elements;
- labour intensity of the maintenance of preventive maintenance of system elements;
- man-hour costs of preventive and current maintenance operations;
- system downtime cost;
- cost of a bogie with track gauge changing sets.

The sensitivity analysis demonstrated that the factor which determines, to the highest degree, the economic efficiency of the application of the SUW 2000 system in the transport of hazardous materials is the cost of a bogie with track gauge changing sets. A decrease in the current price of the bogie by 20% reduces the \( LCC \) of the system by 11.5% or more than
PLN 8.5 million. Very important amongst the reliability parameters is the ratio of technical readiness of the subsystems and the average number of destructions to system elements. An increase in system non-destructability by 20% through increasing the reliability of bogies equipped with track gauge changing wheel sets, reduces the LCC by 2.6% or PLN 1.9 million. The sensitivity analysis demonstrated further that with the currently-offered price of a bogie with track gauge changing sets and the reliability parameters calculated, the efficiency of the SUW 2000 system is limited by the transport distance of up to 1460 km [4, 9].

5. Conclusions

A reliable and efficient rail transport system is the basis for economic development and trade between countries of Europe and Asia. Work on new methods of overcoming the differences between track gauges, more efficiently than is currently applied, seem to be necessary. The paper presents a concise comparison of the reliabilities and efficiencies of two selected systems with track gauge change applied in the transport of hazardous materials. The LCC analysis was applied to assess the efficiency as a method which enables a comprehensive assessment, taking into account all phases of the project life cycle. The analysis demonstrated that the level of reliability of the SUW 2000 self-adjusted wheel sets is satisfactory and competitive vis a vis wagon bogie exchange. The application of self-adjusted wheel sets for transport distances of less than 1500 is economically justified.

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