Introduction

The rapid development of computer technologies and associated software engineering techniques allowed for construction of specialized Computer Aided Engineering (CAE) software enabling engineers to perform complex computations and simulations of analyzed problems using computer models. The CAE software has specialized in multiple areas, including Finite Element Analysis (FEA), Computational Fluid Dynamics (CFD), and Multibody Dynamics (MBD), being the focus of this paper. Using the CAE tools engineers have the ability to simulate, validate and optimize targeted properties of elements and assemblies being designed. The tools provide an access to interim and final calculation results, dynamic visualization of analyzed elements as well as mathematical and experimental optimization of their parameters within the framework of the underlying model of reality.

It is therefore not surprising that CAE methods are used in many industries such as automotive, aviation, space, and shipbuilding. There is also an increasing number of specialized CAE tools in the area of railways and rail vehicles engineering, including VI Rail, Vampire, E - train, Medina and Universal Mechanism. Following the CAE premise, the software enables construction of complex models, which are as close as possible to real-life conditions (given the implemented representation of the modelled phenomena) and allows one to simulate complex dynamical properties of analyzed assemblies and rails. For example, it is possible to simulate multibody systems (rail vehicles) dynamics, including analysis of running gear suspension systems in reality-close conditions. The engineers can therefore take into account all known criteria having direct impact on safety and comfort while designing vehicles.

Consequently, the advantages associated with the use of specialized software to simulate vehicle dynamics include:

• ability to test an impact of a wide set of model entry parameters values (including boundary/extreme conditions) on the dynamic behavior of the simulated object leading to a better understanding of the modelled phenomena
• selection of the optimal combination (or candidate sets) of model parameters already at the virtual simulation stage
• simulate the movement of a virtual model without the need to conduct these tests on a real object, which is associated with a reduction in production costs
• lower costs associated with research prototype thanks to fast computation (verification) cycle and elimination of suboptimal design alternatives already at the virtual simulation stage
• associated reduction in product development duration
• lower risk associated with experiments performed with the real vehicle due to the theoretical (CAE-simulated) preselection of optimal parameters.

Difficulties associated with the use of CAE include:

• sophistication of the used model of reality and its understanding
• knowledge of the software, e.g. ability to correctly interpret and resolve calculation errors
• related ability to interpret the results within the limitations of the implemented model and software environment
• high computational complexity may require significant computational resources to be available.

Since advantages outweigh by far the difficulties, the wide usage of CAE software is expected to continue and increase in the research and practical engineering work related to railway vehicles.

Railway vehicle model definition

Transportation of massive objects such as rockets, shipping engines, power turbines or transformers poses a great challenge to transportation engineers. One of the service providers in this area are railways, which for this purpose use special multi-axle and multilevel cars, known as Schnabel cars.

There exist about 80 such special cars worldwide, which have different mechanical properties and load capacity. There are two such cars used in Poland, i.e. Norca 32 (the maximum carry load of 400 tons) and Norca 24 (the maximum carry load of 250 tons).
In order to provide safe and reliable transport of massive objects one has to consider multiple impacting factors, including the extreme track radius, wheel stress on the track, speed and side inclinations as well as spatial limitations imposed by bridges and tunnels. Therefore, the wagon stability is a very important aspect in this context, which has to be supported by a complicated multilevel spring structure of the wagon.

Because of the above-mentioned factors and the fact that loaded cars are very long (about 70 meters) the traveling route is usually selected individually for each particular transport task. The speed of an empty car on a straight track is limited to 80 km/h, whereas the speed of a loaded car drops down to the maximum of 50km/h. The speed drops to even 5km/h when the car runs in the curvature and turnouts.

The model of a multilevel car with 32 axes discussed in this paper was created using the UM LOCO software package. The dynamic multilevel car model consists of interconnected level frames, which are equipped with side bearings. The lowest of the frame level in the multilevel car is connected to the bogie frame through the assembly of coil springs. It was assumed that the wheelset had a diameter of 920 mm (European profile S1002) and moved along a railway track built with rails type UIC60. Rails and wheelsets were modeled as unused items.

While creating the model, the technical parameters and performance were taken into account [1, 2]. Respective kinematic pairs in load-bearing nodes, weight of individual frame levels and spring stiffness were defined accordingly. The scheme corresponding to a half of a multilevel car and related model created in the UM LOCO environment was shown in Fig. 1. Figure 2 shows the actual car with a lateral movement of the highest frame level (0.5m).

![Diagram](image-url)

**Fig. 1.** A general view of the car, a) scheme mid-32 axial car b) vehicle created in the UM LOCO 6.0 environment c) lateral movement of the highest level.
The simulation was performed with the following assumptions:

- Ideal straight track: \( R = \infty \) m (rails modeled as unused – UIC60)
- loaded car weight (brutto): \( m_{\text{lad}} = 672 \times 10^3 \) kg
- empty car weight: \( m_{\text{proz}} = 272 \times 10^3 \) kg
- cargo weight: \( m_{\text{lad}} = 400 \times 10^3 \) kg
- wheelset weight: \( m_z = 1,5 \times 10^3 \) kg
- weights of frame levels: \( m_1 = 5,5 \times 10^3 \) kg, \( m_2 = 20 \times 10^3 \) kg, \( m_3 = 32 \times 10^3 \) kg, \( m_{\text{ramy}} = 36 \times 10^3 \) kg, \( m_{\text{ramy}} + m_{\text{lad}} = 436 \times 10^3 \) kg
- dimensions of the base longitudinal frame levels: \( B_2 = 6000 \) mm, \( B_3 = 12000 \) mm, \( B_4 = 30250 \) mm
- spacing of slide bearings for individual frame levels \( A_n = 2000 \) mm (\( n = 1...3 \))
- center of mass of individual frame levels: \( H_{m1} = 0,72 \) m, \( H_{m2} = 0,94 \) m, \( H_{m3} = 1,245 \) m, \( H_{m\text{lad}} = 1,66 \) m
- 1st level spring stiffness \( k_x = 6,81 \times 10^5 \) N/m [3]
- speed of an empty / loaded car \( V = 5, 10, 20, 50, 70 \) km/h.
- lateral displacement of the highest frame level \( \Delta \text{lad} = 0,1m,0,15m…0,5m \).

**Simulation results**

Calculations executed for a statically determinable structure confirmed that the pressure of the car wheelset under the full load of ca. 400 tons was about 20 tons, what is compliant with railways standards. Consequently, a correctly configured car structure contributes positively to an optimal distribution of pressure across individual frame levels, and ultimately to the appropriate wheel load on the rail. Exceeding the allowed rail pressure would endanger the safe movement of wagons having a complex structure. The force acting on a wheelset of the 32-axle car may also be derived using the following equation:

- for a loaded car:
  \[
  m_{\text{reader}} = \left( m_{\text{lad}} + m_{\text{ramy}} \right) + 2 \times m_3 + 4 \times m_2 + 8 \times m_1 + 32 \times m_x = 672 \times 10^3 \text{kg} \\
  Q_1 = \frac{m_{\text{reader}} \cdot g}{L_0} = 2,059 \times 10^5 \text{N}
  \] (1.1)

- for an empty car:
  \[
  m_{\text{proze}} = m_{\text{ramy}} + 2 \times m_3 + 4 \times m_2 + 8 \times m_1 + 32 \times m_x = 272 \times 10^3 \text{kg} \\
  Q_1 = \frac{m_{\text{proze}} \cdot g}{L_0} = 8,5 \times 10^3 \text{N}
  \] (1.2)

where:
- \( m_{\text{lad}} = 672 \times 10^3 \) kg – loaded car weight,
- \( m_{\text{proze}} = 272 \times 10^3 \) kg – empty car weight,
- \( g = 9,81 \text{m/s}^2 \) – gravity acceleration,
- \( L_0 = 32 \) – numbers of wheelsets in the car.
Table 1.1 shows the normal force for different speeds of an empty and loaded car obtained from simulations executed in the UM LOCO environment. The obtained values of normal forces are similar to the results obtained from equations 1.1, 1.2. Consequently, the results confirm the above-given observation that the car construction structure has an impact on the resulting wheel pressure on the rail. Figures 3 and 4 show the resulting graph of normal forces an empty and loaded car, respectively. Simulation was carried out for the ideal track without a lateral displacement of the highest frame level.

Tab. 1.1. The normal force obtained in UM LOCO.

<table>
<thead>
<tr>
<th>Car weight [ton]</th>
<th>Car Speed [km/h]</th>
<th>Normal Force [kN]</th>
</tr>
</thead>
<tbody>
<tr>
<td>272</td>
<td>5, 10, 20, 50, 70</td>
<td>41</td>
</tr>
<tr>
<td>672</td>
<td></td>
<td>104</td>
</tr>
</tbody>
</table>

Fig. 3. Wheel pressure on the rail in the UM LOCO for a loaded car: a) Normal forces of the car, b) Normal forces on all wheelsets, c) Normal forces in the first wheelset.

Fig. 4. Wheel pressure on the rail in the UM LOCO for a loaded car, a) Normal forces of the car, b) Normal forces on all wheelsets, c) Normal forces in the first wheelset.

The performed experiments included also simulation of the car movement dynamics considering a lateral displacement of the highest frame level. Table 1.2 summarizes the normal forces for an empty car moving with a constant speed of 5 km/h (the left/right side: Q_{nL}/Q_{nP}). It can be seen (via the obtained values of normal forces) that the change of the wagon structure geometry caused by the lateral displacement of the highest frame level reduces the load on one side of the car and increase the load on the other side. The allowed lateral displacement of the highest frame level in the NORCA car is limited to 0.5 m. In practice, the lateral displacement of an empty car is not used, because the loading gauge limit is not exceeded in this state. Figure 5 shows the normal forces reaction for an empty with the lateral displacement of the highest frame level equal to 0.5 m.
The lateral displacement of an empty car running with the speed of 5 km/h does not impact the car movement stability (Table 1.2).

Tab.1.2. Normal forces of a loaded car with lateral displacement of the highest frame level.

<table>
<thead>
<tr>
<th>( \Delta ) milad [m]</th>
<th>0,1</th>
<th>0,15</th>
<th>0,2</th>
<th>0,25</th>
<th>0,3</th>
<th>0,35</th>
<th>0,4</th>
<th>0,45</th>
<th>0,5</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Q_{nL} ) [kN]</td>
<td>42</td>
<td>42</td>
<td>43</td>
<td>43</td>
<td>43</td>
<td>44</td>
<td>44</td>
<td>45</td>
<td>45</td>
</tr>
<tr>
<td>( Q_{nP} ) [kN]</td>
<td>41</td>
<td>40</td>
<td>40</td>
<td>39</td>
<td>39</td>
<td>38</td>
<td>38</td>
<td>38</td>
<td>37</td>
</tr>
</tbody>
</table>

Fig. 5. Wheel pressure on the rail in the UM LOCO for a loaded car, a, d) Normal force in the first wheelset for empty car, b, c) Normal forces on all wheelsets.

The speed of a loaded car on a straight track is limited to 50 km/h. While using the lateral displacement of the highest frame level, the loaded car can move with the maximal speed of 5 km/h. Consequently, simulations were performed for the speed of 5 km/h and allowed values of the lateral displacement. The results showed that the lateral displacement of the highest frame level at a speed of 5 km/h did not cause movement stability loss. Furthermore, change in the car structure geometry caused by the lateral displacement of the highest level frame unweighted one side of the wagon while moving the load to the other side, resulting in the one axle load increase up to 15t.

Tab.1.3 The normal forces for loaded car with lateral movement of the highest level frame.

<table>
<thead>
<tr>
<th>( \Delta ) milad [m]</th>
<th>0,1</th>
<th>0,15</th>
<th>0,2</th>
<th>0,25</th>
<th>0,3</th>
<th>0,35</th>
<th>0,4</th>
<th>0,45</th>
<th>0,5</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Q_{nL} ) [kN]</td>
<td>114</td>
<td>118</td>
<td>122</td>
<td>126</td>
<td>132</td>
<td>139</td>
<td>141</td>
<td>143</td>
<td>149</td>
</tr>
<tr>
<td>( Q_{nP} ) [kN]</td>
<td>96</td>
<td>90</td>
<td>87</td>
<td>81</td>
<td>76</td>
<td>66</td>
<td>66</td>
<td>64</td>
<td>59</td>
</tr>
</tbody>
</table>
Summary

The movement stability and structural statics of a Schnabel car on a straight track was investigated using the CAE UM LOCO environment. The multilevel empty/loaded car with classical bogie (box frames) exhibits stable dynamic behaviour within the safety margins while moving with the maximal speed of 5 km/h and lateral displacement of the highest frame level of 0.5m. In practice, the lateral displacement is used only when the car is loaded. The analysis showed that the use of lateral displacement (change in the car structure geometry) unweighted one side of the wagon while moving the load to the other side, resulting in the one axle load increase up to 15t.

Abstract

Methodology used to model dynamics of a 32 axial car moving on an ideal straight track and resulting simulation results are presented. The simulation was performed for the car moving at low speed in an empty/loaded state with a lateral movement of the highest level load frame. The values of normal forces (derived from wheel pressure) obtained under dynamic conditions allowed to determine the maximal car speed and lateral movements of its highest level load frame still maintaining the movement stability (safety). The car model and simulation of the dynamic forces exerted while in motion were evaluated within the Universal Mechanism LOCO 6.0 environment.

Dynamika 32 osiowego wagonu specjalnego w torze prostym – model i symulacja

Streszczenie

W artykule opisano zarówno wyniki symulacji jak i metodologię przyjętą podczas modelowania dynamiki wagonu 32-osiowego w torze idealnie prostym. Symulację przeprowadzono dla wagonu poruszającego się z małą prędkością w stanie próżny/ladowny z przemieszczeniem poprzecznym najwyższego poziomu ramowego. Otrzymane wartości sił normalnych (pochodzących od nacisków kół) w warunkach dynamicznych, pozwoliły wyznaczyć dla jakich prędkości jazdy wagonu oraz przemieszczeń najwyższego poziomu ramowego wagonu wieloosiowego zachowana jest stateczność ruchu (bezpieczeństwo ruchu). Model wagonu oraz jego symulację dynamiki ruchu wykonano w środowisku UM LOCO 6.0.

LITERATURA / BIBLIOGRAPHY