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Ramy SHALTOUT*, Cristian ULIANOV
NewRail - Newcastle Centre for Railway Research, Newcastle University
Newcastle upon Tyne, NE1 7RU, United Kingdom
Luis BAEZA
Centro de Investigación de Tecnología de Vehículos, Universitat Politècnica de València
Camino de Vera s/n, Valencia, 46022, Spain
**Corresponding author*. E-mail: ramy.shaltout@ncl.ac.uk

DEVELOPMENT OF A SIMULATION TOOL FOR THE DYNAMIC ANALYSIS OF RAILWAY VEHICLE - TRACK INTERACTION

Summary. The importance of modelling and simulation in the field of railway systems has greatly increased in the last decades. Various commercial simulation packages have been developed and are used to analyse the dynamic performance of railway systems. However, although sometimes the user needs to analyse various non-standard solutions, the possibility to integrate further modifications into the structure of such software is quite limited. Therefore, in some cases, in particular for specific modelling and analysis tasks, a feasible option is to develop flexible and robust simulation tools capable of using different configurations by modifying the models performing the dynamic analysis. The paper presents the mathematical modelling background and the conceptual design of a new of a new computational tool for the dynamic simulation of railway vehicle systems. The formulations employed in the proposed mathematical model are based on the multibody techniques. The developed model uses a combined frame of references that allows the use of independent coordinates without the possibility to have singularity configurations depending on the rotation sequence. The simulation tool is designed in a flexible form that enables the study of different configurations of the railway vehicles, as well as various track combinations.

ROZWÓJ SYMULACYJNEGO NARZĘDZIA DO ANALIZY DYNAMIKI INTERAKCJI POJAZD SZYNOWY - TOR

Streszczenie. W ostatnich dziesięcioleciach znacznie wzrosło znaczenie modelowania i symulacji w dziedzinie systemów kolejowych. Różne rodzaje symulacji komercyjnych pakietów zostały opracowane i są używane do analizy dynamiki wydajności systemów kolejowych. Jednak czasami użytkownik musi analizować różne niestandardowe rozwiązania, a możliwość integracji dalszych zmian w strukturze takiego oprogramowania jest dość ograniczona. W związku z tym w niektórych przypadkach, w szczególności dla konkretnych zadań modelowych, realną opcją jest opracowanie narzędzi symulacyjnych, pozwalających na elastyczne i niezawodne użycie różnych konfiguracji modeli przy wykonywaniu analizy dynamicznej. Artykuł prezentuje nowe narzędzie modelowania i obliczania dynamicznych symulacji układów pojazdu szynowego. Formuły stosowane w proponowanym modelu matematycznym są oparte na technikach wieloobiektowych.

1. INTRODUCTION

Modelling and simulation of railway system dynamics is a complex interdisciplinary topic. The difficulties in modelling the railway systems are generated by various complex factors such as the complex geometry of the vehicle and track components including wheels and rails, the non-linearities in the calculation of the contact forces in the interface between the wheel and rail surfaces and the number of degrees of freedom of the whole system [2, 22]. The first step in building railway models for dynamic analysis of railway vehicle–track interaction includes the development of detailed mathematical models that describe the actual behavior of the modelled parts. The second step consists of the development of numerical models describing the mechanics of the railway system components. The success in the definition of the vehicle-track dynamic simulation depends on the complexity of the mathematical models defining the railway system. The selection of the types of models for the components of the railway systems depends on many aspects in relation with the purpose of simulation, the applied frequency range, the quality of the output results and the availability of the input data for the simulation model [14].

The commercial simulation packages are widely used in order to predict the behavior and validate design modifications of the railway systems before and during the operation in realistic working conditions [6].

This paper aims to introduce the mathematical models and the development of a new computational tool used for the dynamic analysis of the railway systems using multibody system formulations, that consider the railway vehicles and all types of rail guided systems as a connection of rigid bodies. The motion of each body of the modelled system was determined by means of six Degrees of Freedom (DoF). Various authors have been working on similar models using multibody formulations in the past years and subsequently reported their results (Shabana, [19]); (Pombo and Ambrósio, [16]); (Escalona, Hussien et al., [7]); (Fisette and Samin, [9]). The mentioned authors have developed other techniques based on dependent coordinate systems, which have a principal advantage that there is no singular configuration that can be obtained. In comparison with previously reported methodologies, the model presented in this paper uses a combined frame of references that allows the use of independent coordinates without the possibility to have singularity configurations depending on the rotation sequence. The simulation tool was developed in MATLAB environment, as previously validated for a similar model [10], in a flexible form that enables any changes that can be made on the vehicle model configuration or track combination.

2. RAILWAY MODELLING AND SIMULATION METHODOLOGY

By using modern simulation packages, it is possible to carry out realistic simulation of the dynamic behaviour of railway vehicles. Most of commercial simulation tools use mature and reliable theoretical basis of the mathematical modelling. User friendly graphical interfaces are used nowadays in the simulation packages in order to facilitate the users making changes on the dynamic analysis of the railway systems.

Fig. 1 illustrates the main general methodology followed by the simulation packages used for the dynamic analysis of railway vehicle–track interaction. Taking into account that numerical models are used in all stages of vehicle design and development, it is necessary to develop a methodology to assess how much we may rely on the results obtained from simulations [14]. This methodology should consider the agreement between the experimental results and the results obtained by numerical simulation, which is called the process of model validation and verification [10-11].

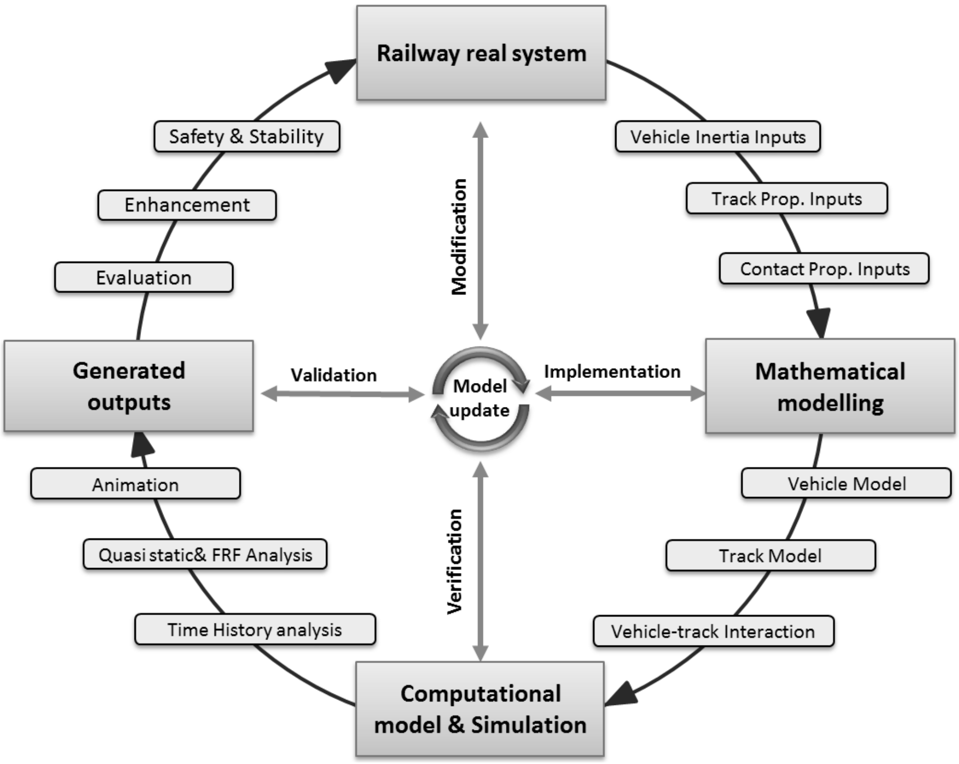

Fig. 1. General methodology for the development and validation of simulation packages for railway system analysis
Rys. 1. Ogólna metodologia rozwoju i walidacji pakietów symulacyjnych do analizy systemu kolejowego

3. VEHICLE-TRACK MULTIBODY MODEL

The accurate description of both the vehicle and the track is essential for the dynamic analysis of railway systems [3]. The dynamic forces generated at the track-vehicle interaction mainly depend on the spatial track centreline [18, 21]. In this paper, the analytical segment approach is used to parameterise the track centreline [15-16].

3.1. Track geometry subscription

The Track reference frame used in the model is defined with three orthogonal coordinates axis (X_T Y_T Z_T) identified by the sub index (T). The track reference frame is located at the track centreline between the left and right rail profiles and moves with a velocity equal to the nominal vehicle velocity. The direction of the X_T axis is pointing to the longitudinal direction referring to the rolling direction of the moving body along the track, Z_T axis pointing to the vertical direction normal to the track horizontal plane and the Y_T axis is parallel to the rail head as shown in Fig. 2. The number of the track reference frame is selected to be equal to the number of the wheelsets in the vehicle model.

The model of the track used in the analysis is a generic track composed of three stages Fig. 2. The first stage is the straight line stage; the second stage is the transition curve stage and, finally, the constant radius canted curve stage.

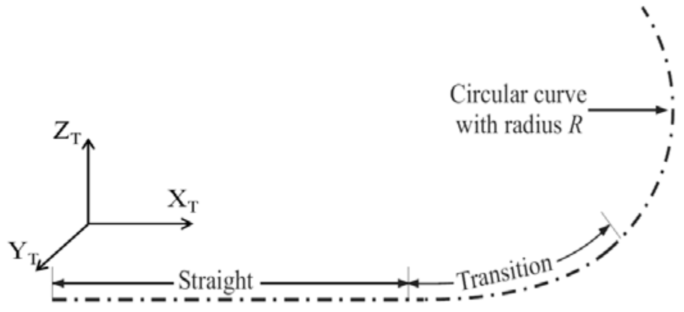

Fig. 2. Generic track model definition
Rys. 2. Definicja modelu rodzajowego toru

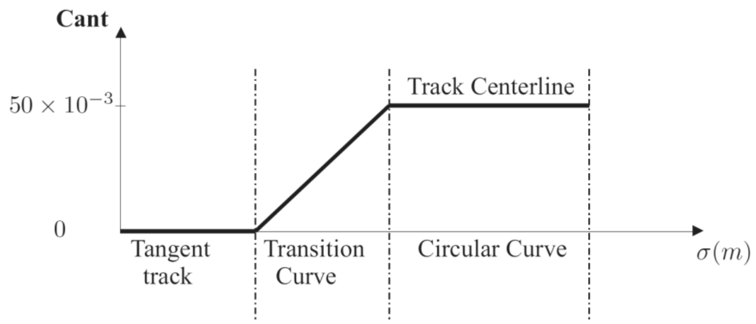

Fig. 3. Track super-elevation ramps
Rys. 3. Tor super-podniesienie rampy

Transition curves are used between straight tracks and curves or between two adjacent curves to allow gradual change in the lateral acceleration [8, 12]. The centre line of the transition curve has the same tangent at the connection points as the adjacent parts, where the curvature changes gradually from the value of one connection point to the value of the other. In the presented model, the Clothoid curve is used as an efficient transition curve connecting the straight line stage to the circular stage Fig. 3.

In order to define the position vector of an arbitrary point in the global or fixed frame of reference the vector has to be pre-multiplied by the transformation matrices required for the definition of the orientation of the rigid body [5].

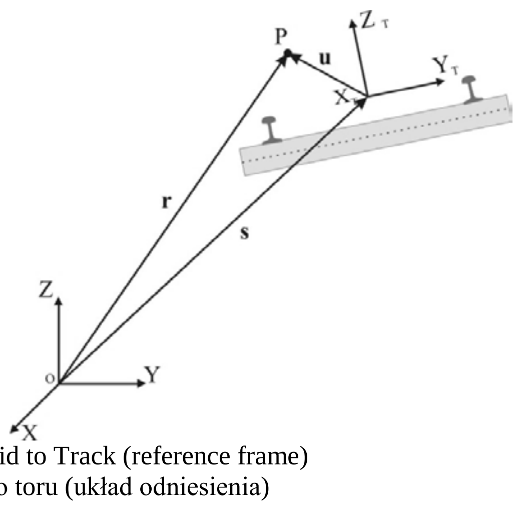

Fig. 4. Transformation from Solid to Track (reference frame)
Rys. 4. Transformacja z bryły do toru (układ odniesienia)

An important objective was to avoid the singularity problems generated due to large rotation angles [1, 21]. This has been achieved by the selection of the rotation sequences used in the definition of the transformation matrices used in the analysis. The matrix A is the transformation matrix form the track frame of reference (X_T Y_T Z_T) to the fixed frame (X Y Z), as shown in Fig. 4, and can be defined by the following equation:

$$\mathbf{A} = \mathbf{A}_z\,\mathbf{A}_y\,\mathbf{A}_x \tag{1}$$

In the meantime, the matrix B is the transformation matrix required to define the orientation of the body reference frame with respect to the track reference frame.

$$\mathbf{B} = \mathbf{B}_z\,\mathbf{B}_x\,\mathbf{B}_y \tag{2}$$

3.2. Vehicle multibody model

The dynamic analysis of multibody systems consists of the study of their motion as response to the external applied forces as well as the moments [5, 12]. In the current work, Independent coordinates are used to define the general motion of a three dimensional rigid body forming a component of the multibody system. The Cartesian coordinates system is used in the formulation due to the simplicity of its implementation in the multibody program used in the railway vehicles dynamic analysis [16, 20].

The *Lagrangian* approach is implemented to develop the equations of motion of the multibody system used in the developed simulation tool [6, 13]. Due to the linear independency of the generalised coordinates, the application of *D'Alembert- Lagrange's* equation leads to *Lagrange's* Equation in the following form:

$$\left[\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{\mathbf{q}}}\right) - \frac{\partial T}{\partial \mathbf{q}}\right]^{\mathrm{T}} = \mathbf{Q} \tag{3}$$

where: $\mathbf{q}$, $\dot{\mathbf{q}}$ define the vectors of generalised coordinate and velocities respectively; $\mathbf{Q}$ is the generalised force vector associated to the generalised coordinates vector and can be written as follows:

$$\mathbf{Q} = \begin{bmatrix} \mathbf{Q}_{\overline{\mathbf{W}}}^{\mathrm{T}} \\ \mathbf{Q}_{\boldsymbol{\theta}}^{\mathrm{T}} \end{bmatrix} \tag{4}$$

There is no motion constraints applied for the proposed multibody system. By this way, the algebraic set of equations describing the kinematic constraints is avoided, as well as the need of the stabilisation techniques used for the solution of such system of equations [13].

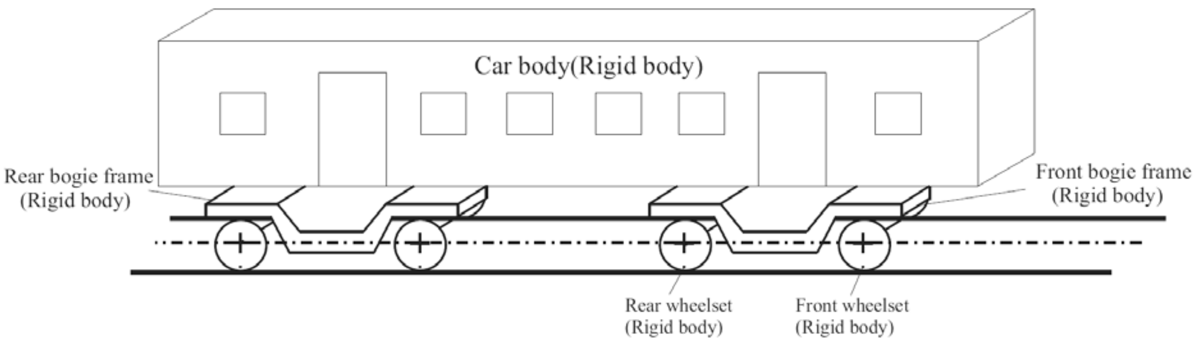

Fig. 5. Schematic model of TGV001 railway vehicle
Rys. 5. Schemat modelu pojazdu kolejowego TGV001

The modelling approach presented in this paper considers the car body, bogie frames and wheelsets Fig. 5, as rigid bodies due to their high structural stiffness. The rigid bodies are connected by means of spring elements. The forces generated by these elements are a function of the relative motion and velocity between two bodies connected by the spring elements. Table 1 depicts all the parameters of the solid bodies used in the multibody model of TGV001 vehicle.

Table 1

Solid bodies' parameters for the TGV001 multibody model

Parameter	Value	Unit
Car body		
Mass	43200	[kg]
Mass moment of inertia of car body about *X* axis	69677.28	[kg.m^2]
Mass moment of inertia of car body about *Y* axis	2430000	[kg.m^2]
Mass moment of inertia of car body about *Z* axis	2430000	[kg.m^2]
Bogie		
Frame mass	3020	[kg]
Mass moment of inertia of Bogie about *X* axis	2130.912	[kg.m^2]
Mass moment of inertia of Bogie about *Y* axis	4063.712	[kg.m^2]
Mass moment of inertia of Bogie about *Z* axis	4063.712	[kg.m^2]
Wheelset		
Mass	1500	[kg]
Mass moment of inertia of wheelset about *X, Z* axis	799.35	[kg.m^2]
Mass moment of inertia of wheelset about *Y* axis	93.75	[kg.m^2]
Semi-wheelset base	799.35	[kg.m^2]
Suspension Elements		
Primary suspension stiffness in longitudinal direction	3.90×10^7	[N.m]
Primary suspension stiffness in lateral direction	7.85×10^6	[N.m]
Primary suspension stiffness in vertical direction	9.75×10^5	[N.m]
Damping coefficient	1.08×10^4	[N.s.m^{-1}]
Secondary suspension stiffness in longitudinal direction	1.73×10^5	[N.m]
Secondary suspension stiffness in lateral direction	1.73×10^5	[N.m]
Secondary suspension stiffness in vertical direction	5.3×10^5	[N.m]
Damping coefficients in vertical direction	3.5×10^4	[N.s.m^{-1}]
Damping coefficients in lateral direction	1.5×10^4	[N.s.m^{-1}]

4. GENERAL STRUCTURE OF THE SIMULATION PROGRAM

The simulation tool was developed in MATLAB environment. The program is designed in a flexible format that allows the use of different models for the contact problem, as well as modifications to the vehicle and track configurations.

Fig. 6 presents the general flow chart of the developed computational tool for dynamic simulation. The program starts with the 'run' file, where the input information relating the type of analysis to be performed is defined as well as the running speed, integration time step and initial conditions.

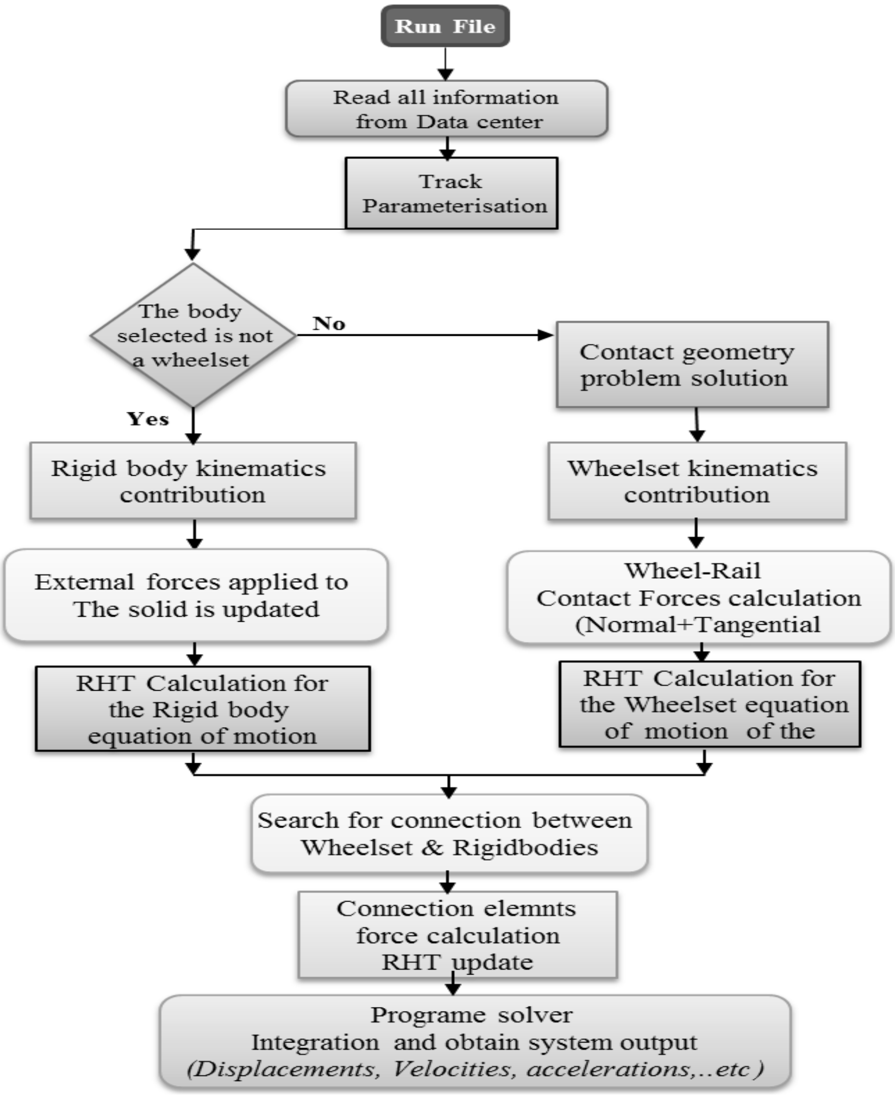

Fig. 6. Flow chart of the designed simulation tool
Rys. 6. Schemat blokowy zaprojektowanego narzędzia do symulacji

The procedure followed by program includes the following steps:

- Storing the track model, vehicle model as well as the contact model as special class parameters in the data centre; they can be recalled by the program when necessary at each time step of the simulation;
- Parametrising the track centre line, in which the position, velocity and acceleration are calculated at each time step as a function of the distance covered by the vehicle;
- The program distinguishes between the dynamic analysis of the wheelsets and any other generic body like the bogie frame and the car body. In case of the program detects that the analysis is for a wheelset then it directly starts to calculate the contact forces applied at each wheelset at the wheel-rail interface and update the differential equations of the body under study with the new values of the applied contact forces;
- Computing the contribution of the kinetic energy for each body used in analysis and providing the obtained values, alongside the external forces as inputs into the formulated equation of solid bodies' motion;

- At each time step corresponding to a new location, the relative distance between each of the bodies connected by force elements is calculated;
- The new values of the forces generated by the force elements are used to update the system equations of motion;
- Solving the developed differential equations of motion in the program solver in order to obtain the outputs for analysis.

5. SIMULATION RESULTS

The dynamic behaviour of a vehicle model in different operation scenarios was analysed using the developed multibody program, for testing and validating the functionality of the simulation tool, and evaluate the obtained results.

5.1. Stability analysis of a vehicle negotiating a curved track

The simulation condition for the vehicle model can be primarily defined by the description of the track geometry as presented in section (3.1). The fixed frame of reference presenting the observer of the body is located at the point of the beginning of the transition curve. The vehicle model (Fig. 5) includes two bogie frames and four wheelsets. The vehicle is initially located on the track without any initial misalignments or rotations that may develop disturbance in the results. The vehicle running speed is adjusted to 20m/s.

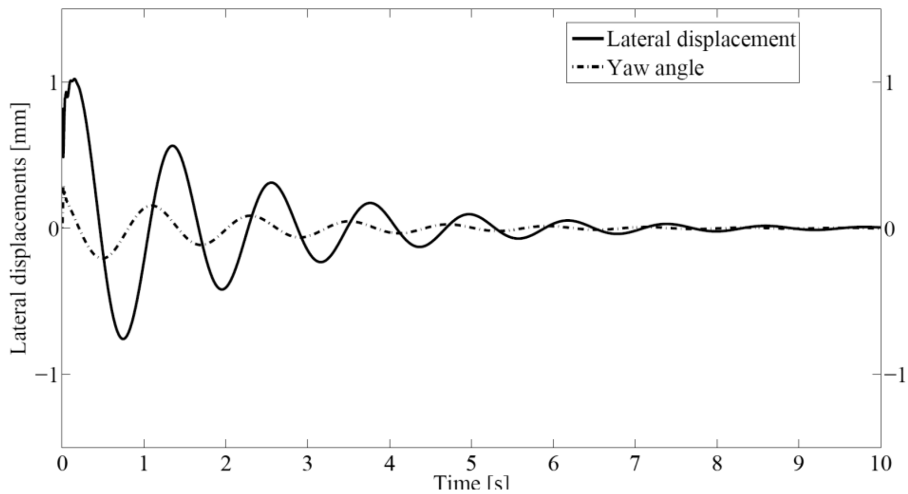

Fig. 7. Lateral displacement and yaw angle of front wheelset
Rys. 7. Boczne przemieszczenie i kąt odchylenia przedniego zestawu kołowego

A dynamic analysis has been made for studying the dynamic response of the bogies firstly moving through the straight line section. The model exhibits stable response during the motion when it is moving with a velocity of 20 m/s. Fig. 7 shows the lateral displacement and the yaw angle of the first wheelset of the vehicle under study. An initial lateral misalignment with a value of 1mm is given to the first wheelset in the lateral direction towards the inner rail. It is noted that the system returns to its stable position after 10 seconds.

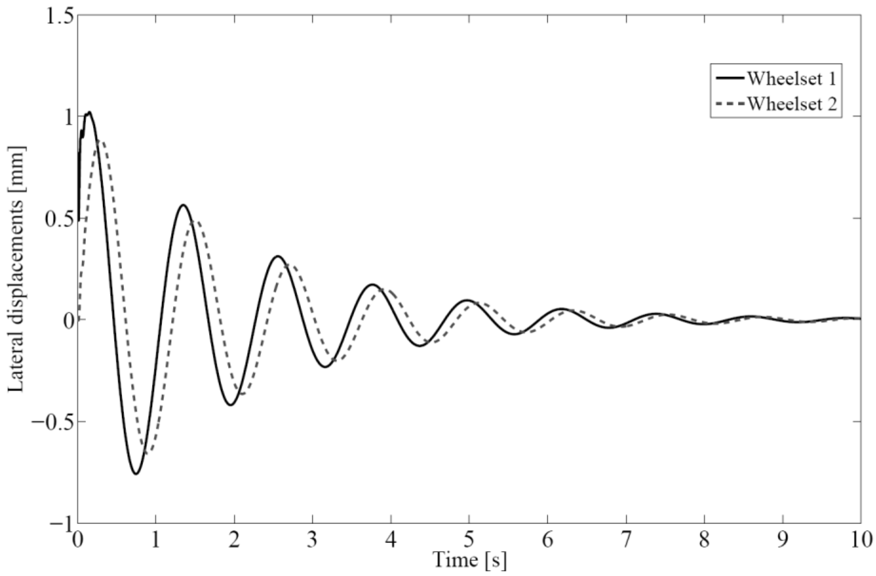

Fig. 8. Lateral displacement of the 1st and 2nd wheelset attached to the front bogie
Rys. 8. Boczne przemieszczenie 1 i 2 zestawu kołowego przymocowanego do przedniego wózka

Fig. 8 presents the lateral displacements of front and rear wheelsets. It can be seen that the lateral displacement of the rear wheelset is shifted from the frontal one with an amount of the distance between the centre of mass of the front wheelset and the rear wheelset.

5.2. Quasi static curving analysis of the vehicle model

The second simulation scenario was defined for the vehicle moving through a curved track. The transition curve stage connecting the tangent track to the constant radius circular track had to be defined. The transition curve stage in the modelled track is taking the form of a Clothoid curve with the length of 200m. The transition curve in the current work is designed to connect the tangent track to a canted curve with a constant radius equal to 1000m. The cant was designed here for a velocity of 100m/s and the equilibrium cant angle φ_{eq} [21], which can be defined as a function of the running speed as shown in the following equation:

$$\varphi_{eq} = \arctan\left(\frac{V^2}{R\,g}\right) \tag{5}$$

where V is the running speed; R is the curve radius and g is the gravitational acceleration.

Fig. 9 shows that the leading wheelsets displaced toward the outer rail during the motion of the vehicle through the transition curve stage. The wheelsets systems return to the stability positions after they enter the constant radius circular curve stage. The rear wheelset for the front and rear bogie frame is shifted by a lower amount than the front wheelset toward the outer rail during the motion in the quasi static curving stage trying to make the bogie centred to the track to stabilise the motion in curved sections of the track.

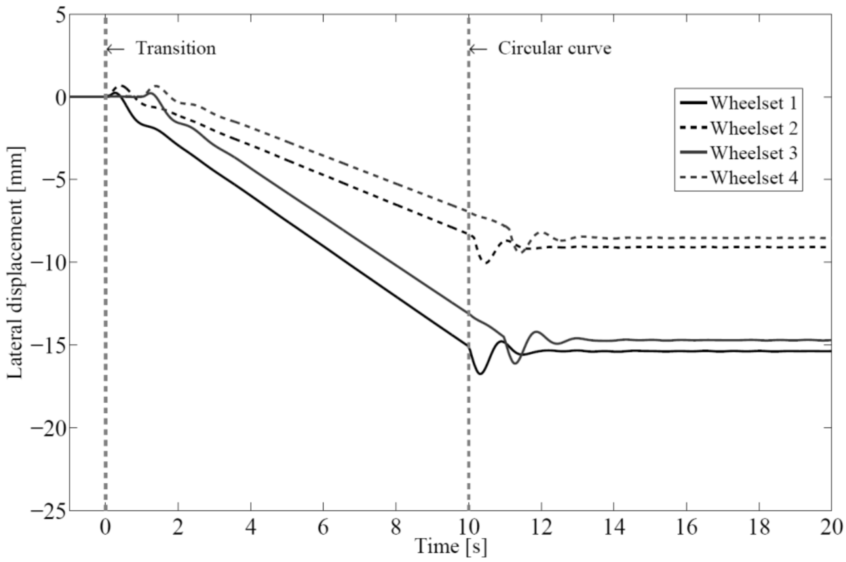

Fig. 9. Lateral displacement of the wheelsets attached to the front and rear bogie frames
Rys. 9. Boczne przemieszczenie zestawów kołowych dołączonych do przednich i tylnych ram wózków

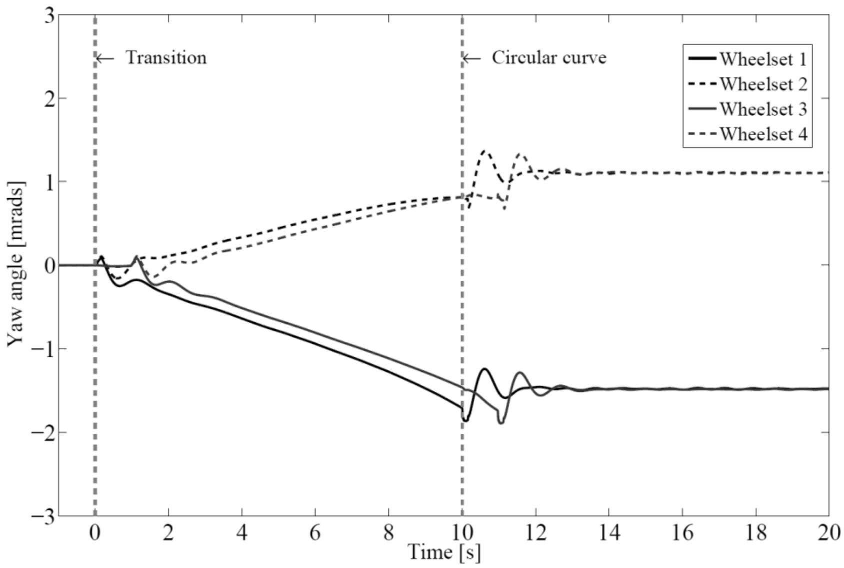

Fig. 10. Yaw angle variation of the wheelsets attached to the front and rear bogie frame
Rys. 10. Odchylenia zmienności kąta zestawów kołowych dołączonych do przedniej i tylnej części ramy wózka

Fig. 10 depicts the change in yaw angle of the leading and trailing wheelsets during the motion in the curved tracks provided by the used track segments in this work. The behaviour of the 1st wheelset of the front bogie exhibits similar behaviour with the 3rd wheelset which is attached to the rear bogie frame. Both wheelset number 2 and wheelset number 4 of the vehicle show similar behaviour in transition as well as quasi-static stages of the track.

5.3. Validation and comparison with commercial simulation packages

A comparison has been made between results obtained by developed tool (Vehicle track interaction Analysis-VIA) and SIMPACK programs for TGV001 vehicle in order to test the validity of the developed simulation tool. The selected contact model in SIMPACK is a multipoint contact model that permits the definition of all possible contact points. The standard wheel profile S1002 was used in combination with the standard rail profile 60E1 with inclination 1:40. Finally the evaluation of the contact problem is selected to be on line evaluation to be in agreement with the procedure followed by VIA program.

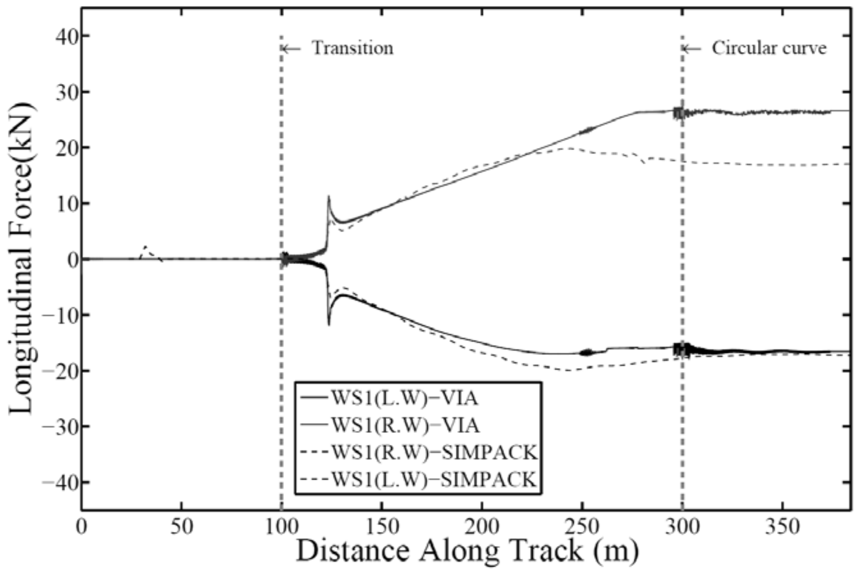

Fig. 11. Longitudinal creep forces on the left wheel (L.W) and right wheel (R.W) of the leading wheelset for a forward velocity of 25.6m/s, using VIA and SIMPACK simulation tools

Rys. 11. Pełzanie wzdłużne siły na lewym kole (L.W) i prawym kole (R.W) wiodącego zestawu kołowego, do prędkość 25,6 m/s, przy użyciu narzędzia do symulacji VIA i SIMPACK

Fig. 11 depicts the longitudinal contact forces on the left and right wheelset of the leading wheelset. The results are in g agreement with obtained results for the simulation carried out by SIMPACK package. The longitudinal forces affecting the right wheel has the highest value as the outer wheel is always subjected to higher creep values during the curve negotiation. The results demonstrate an agreement between both analysis achieved by the simulation tools VIA and SIMPACK.

6. CONCLUSIONS AND FUTURE WORK

The reported research developed a computational tool for the dynamic analysis of railway vehicle–track systems using multibody system formulations. The simulation tool was tested and validated through dynamic analysis of railway systems. Independent coordinates have been used to define the general motion of a three dimensional rigid body forming a component of the multibody system. The equations of motion of the multibody system were obtained for non-constrained systems by means of Lagrange's principle which is used to determine the equation of motion of a rigid body. The solution of the algebraic set of equations has been avoided, as there are no kinematic constraints applied to the multibody system. The developed simulation tool has been applied to run simulations using a complete vehicle model, in order to test its functionality, as well as to determine the suitability of the proposed methodology for different types of railway system analyses. The adopted model can be successfully used in the dynamic analysis of low and medium frequency ranges.

Further steps will include the verification of the obtained results against the output results from different commercial simulation packages, alongside the implementation of different contact models and the use of flexible track structure.

References

1. Andersson, C. & Abrahamsson, T. Simulation of interaction between a train in general motion and a track. *Vehicle System Dynamics*. 2002. Vol. 38. No. 6. P. 433-455.
2. Andersson, E. & Berg, M. & Stichel, S. *Rail Vehicle Dynamics: Fundamentals and Guidelines: Railway Technology*. Railway technology. 1999.
3. Baeza, L. & Roda, A. & Nielsen, J.C.O. Railway vehicle/track interaction analysis using a modal substructuring approach. *Journal of Sound and Vibration*. 2006. Vol. 293. No. 1. P. 112-124.
4. Baumgarte, J. Stabilization of constraints and integrals of motion in dynamical systems. *Computer methods in applied mechanics and engineering.* 1972. Vol. 1. No. 1. P. 1-16.
5. de Jalón, J.G. & Bayo, E. *Kinematic and dynamic simulation of multibody systems.* Mechanical Engineering Series, Springer, New York. 1994.
6. Eich-Soellner, E. & Führer, C. *Numerical methods in multibody dynamics*. Springer. 1998.
7. Escalona, J. & Hussien, H. & Shabana, A. Application of the absolute nodal co-ordinate formulation to multibody system dynamics. *Journal of Sound and Vibration*. 1998. Vol. 214. No.5. P. 833-851.
8. Esveld, C. *Modern railway track*. Zaltbommel, Netherlands: MRT-productions. 2001.
9. Fisette, P. & Samin, J. *Symbolic modeling of multibody system*. Kluwer Acad. Pub. 2003.
10. Iwnicki, S.D. & Wickens, A.H. Validation of a MATLAB railway vehicle simulation using a scale roller rig. *Vehicle System Dynamics*. 1998. Vol. 30. No. 3-4. P 257-270.
11. Kortüm, W. Review of multibody computer, codes for vehicle system dynamics. *Vehicle System Dynamics*. 1993. Vol. 22. No. S1. P. 3-31.
12. Lichtberger, B. *Track compendium*. Hamburg. Eurailpress, Tetzlaff-Hestra GmbH & CO. KG 2005. P. 309-332.
13. Nikravesh, P.E. Computer-aided analysis of mechanical systems. Prentice-Hall, Inc. 1988.
14. Polach, O. & Berg, M. & Iwnicki, S. Simulation. In: *S. Iwnicki ed. Handbook of railway vehicle dynamics*. CRC press. 2006.
15. Pombo, J. & Ambrósio, J. & Silva, M. A new wheel–rail contact model for railway dynamics. *Vehicle System Dynamics.* 2007. Vol. 45. No. 2. P. 165-189.
16. Pombo, J. & Ambrósio, J.A. General spatial curve joint for rail guided vehicles: kinematics and dynamics. *Multibody system dynamics.* 2003. Vol. 9. No. 3. P. 237-264.
17. Schiehlen, W.O. *Multibody systems handbook*. Springer. 1990.
18. Shabana, A. & Chamorro, R. & Rathod, C. A multi-body system approach for finite-element modelling of rail flexibility in railroad vehicle applications. *Proceedings of the Institution of Mechanical Engineers, Part K: Journal of Multi-body Dynamics*. 2008. Vol. 222. No. 1. P. 1-15.
19. Shabana, A.A. *Dynamics of multibody systems*. Cambridge university press. 2013.
20. Shabana, A.A. & Sany, J.R. A survey of rail vehicle track simulations and flexible multibody dynamics. *Nonlinear Dynamics*. 2001. Vol. 26. No. 2. P. 179-212.
21. Shabana, A.A. & Zaazaa, K.E. & Sugiyama, H. *Railroad vehicle dynamics: a computational approach*. CRC Press. 2010.
22. Wickens, A. *Fundamentals of rail vehicle dynamics*. CRC Press. 2005.

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