PRT simulation research

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Abstract

The paper presents analyses results of PRT vehicle driveability in a ¼ scale conducted with the application of a simulation model for a straight line driving conditions and when driving on a curve. The results of the present work will be used in the analysis of a physical motion model in a laboratory stand reflecting a railway system of the stand. The paper discusses the first stage of research in the process of virtual pre-prototyping which is to be finalized with the construction of a non-commercial vehicle prototype. In the construction of the simulation model, particular attention has been paid to three issues. First of all, a correct description of design features connected with the lack of so called centring mechanism – and not profiled tyred wheels independently embedded in the axes of the set. Secondly, a proper description of a turning mechanism with the use of a leading rollers system alongside the rail edge. Thirdly, the use of linear motor for the vehicle drive. The simulation model has been developed within MBS environment. For the description of tyred wheels, the library of TNO Delft Tyre has been used. Vehicle motion stability has been tested on the straight and curved track sections. The research has been financed within the framework of ECO mobility project.

1. Introduction

Currently developed PRT transport systems belong to the category of rail transport. In view of the assumed transport objectives (closer rather to the tasks of individual transport), the designers of these systems resign from the classic shape of the railway in favour of other solutions. In the system designed at the Transport Faculty of the Warsaw University of Technology, within the framework of ECO mobility project (presented in fig. 1 [4]), the rail track has the form of a "trough" of a flat bottom limited on both sides by vertical edges. The vehicle moves on tyred wheels set on two torsion axles. The wheels can turn independently of each other.

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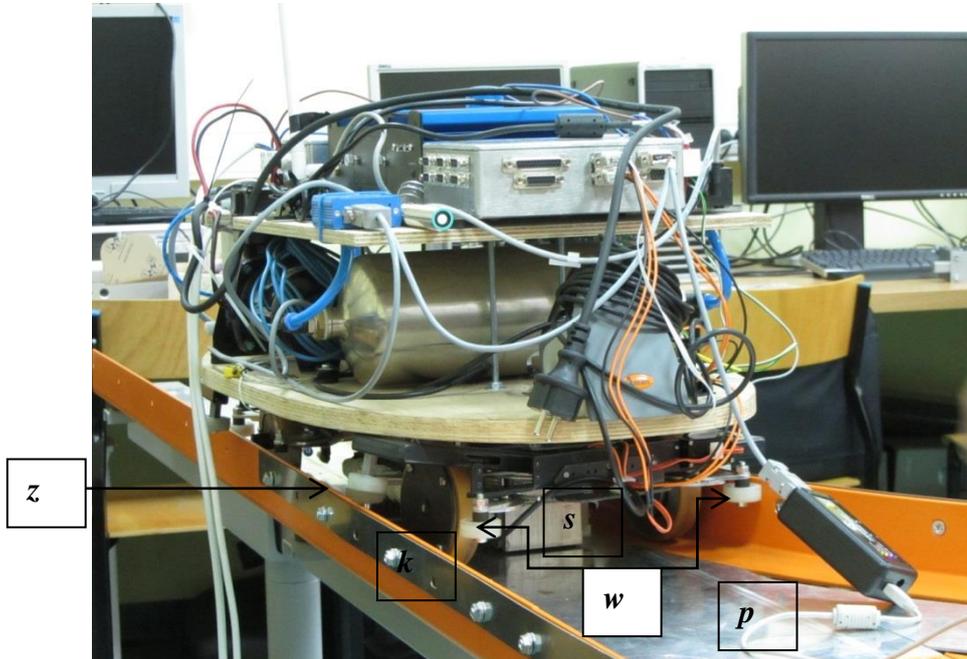
Fig. 1. State of the construction of a physical model in a ¼ scale captured in the middle of 2012.
Legend: z – outer roller, w – inner roller, k – track edge, p – track foundation, s – linear motor [4]

The role of road edges is to keep the direction of vehicle motion along the longitudinal track axis. Contact forces needed for this purpose are generated within special systems of rollers with which the vehicle is equipped. Vehicle drive is provided by a linear motor. The above dynamic features distinguish the PRT vehicle described, both from the classic rail vehicle and from a motor car. Due to the lack of profiled wheels and their independent installation on the axes of the set, the modelled PRT vehicle is devoid of so called centring mechanism typical for the classic rail. This dynamic feature distinguishes the PRT vehicle from a railway carriage. The PRT vehicle considered, has two torsion axles (front and rear). Turns of the wheels axes are forced by the torque from contact forces with the track edge, and not by the steering wheel (conversely to the car). Trailing wheels negotiate turns at negative values of thrust angles. These features of the dynamics distinguish a PRT vehicle from a motor car where a driving direction controller is the steering wheel. The above remarks indicate that the analysis of PRT model driveability can prove difficult. It is relatively easy to define ideal requirements for driveability which a PRT vehicle should meet at a substantial level. These requirements are in principle the same as for the classic rail vehicles. Geometrical centre of a vehicle should always move along the longitudinal axis of the track, and the turn axes of vehicle wheels should always be perpendicular to the track edge. Meeting these requirements means that in the conditions of straight line motion, they should move centrally in the track axis, and in the conditions of driving on a curve – additionally place themselves radially to the edge of the track curvature. Therefore,

basic simulation research tasks can be formulated in a similar way as in the analyses of driveability of a railway carriages. These tasks comprise analysis of straight line motion, analysis of cornering, choice of structure and parameters of the wheel turning axis mechanism system in order to ensure the best motion stability of the model, and indication of driving wheels slip facilitating the assessment of future track wear.

In the process of developing the simulation model, the multi-body simulation analysis MBS has been used [1], [5]. The simulation program has been implemented in the calculation environment: Matlab, Simulink, SimMechanics. For correct dynamics description of the tyred wheels, the software from TNO Delft Tyre library has been used [4]. The tyre has been described by the minimal number of parameters (defined independently by means of "TNO express" file), among which the most important is the value of modulus of rigidity of a tyre assumed based on the laboratory measurements.

When interpreting simulation research results, it should be indicated that they relate to the model in ¼ scale. Their reference to the real measurement model will additionally require solving the problem of the results of scaling up. Description of this problem's solution which is omitted in this present paper, has been presented in the reference book [2].

2. Model of the vehicle

The basic structure of a nominal model is presented in fig. 2. The vehicle consists of the bodywork (marked in blue) with the centre of gravity in point B, two axes of driving wheels (front α_1 and rear α_2 marked in red) with centres of rotation in points A and C, outer rollers 2 and 5, inner roller arms (marked in green and additionally with Roman numerals I - VIII), inner rollers 1 3 4 6 7 8 9 10 and four driving wheels $K_1 - K_4$.
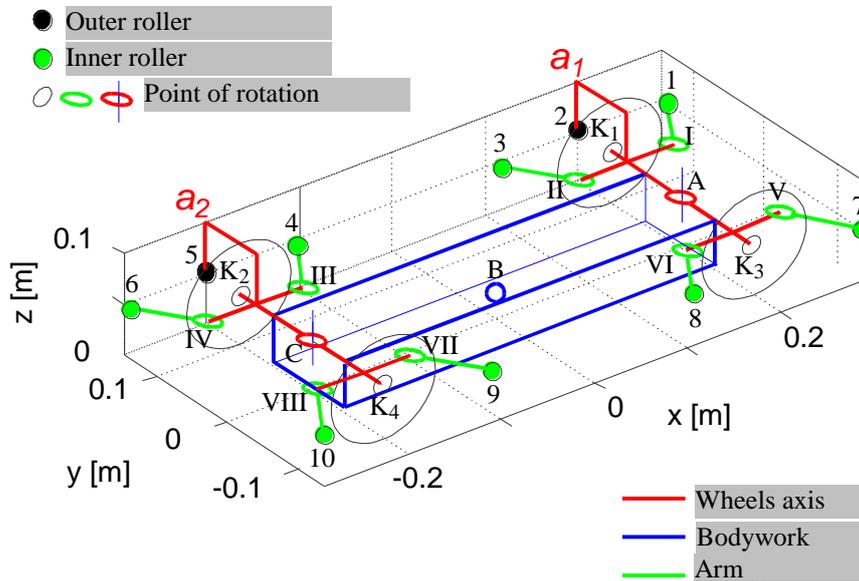
Fig. 2. Structure of dynamic model of PRT vehicle: 1 3 4 6 – left inner rollers, 7 8 9 10 – right inner rollers, 2 5 – left outer rollers, A – centre point of the front wheels axis, B – centre of bodywork, C – centre point of the rear wheels axis, I II III IV – points of rotation of the left arms, V VI VII VIII – points of rotation of the right arms, K_1 K_2 K_3 K_4 – centres of rotation of the driving wheels, α_1 α_2 – driving wheels axes
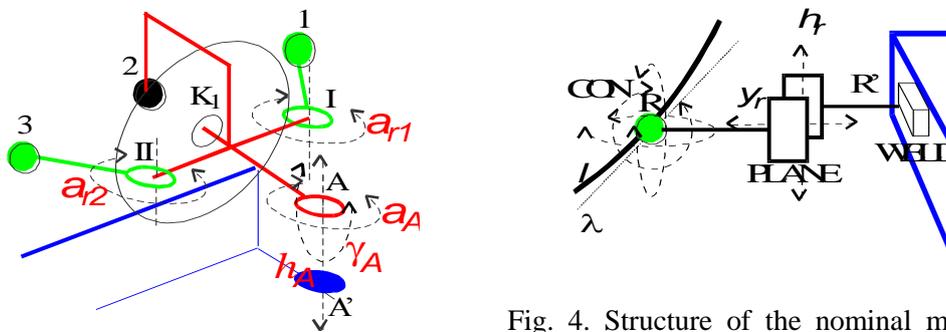
Fig. 3. Structure of the nominal model of the outer driving rollers set (close up of the front left quarter of a vehicle): Indications: h_A – distance A-A', α_A, α_r – rotation angles in YOX plane of the bodywork, γ_A – rotation angle in YOZ plane of the bodywork

Fig. 4. Structure of the nominal model of a roller. Indications: R – material point of roller marker on the track edge described by line constraint of motion (CON – "line constraint"), R' – material point of the roller rigidly connected to the arm rigid body (WELD – "welded connection"), PLANE – plane of freedom of motion of the points R R', y_r – distance RR', l – track edge

Fig. 3 presents the structure of the nominal model of driving rollers set (using the example of the front left quarter of a vehicle). The outer driving roller is rigidly connected to the vehicle axis. The point of the wheels axis centre has three degrees of freedom in relation to the vehicle's bodywork: linear motion along the axis A − A' described by the distance h_A, rotation in the YOX plane of the bodywork described by angle α_A, rotation in the YOZ plane of the bodywork described by angle γ_A. Each point of connection of the arms has one degree of freedom of rotating motion in the plane YOX of the bodywork described by angle α_r. In all points of freedom there are resilient and shock-absorbing elements placed. Fig. 4 presents the nominal model of a roller. Indications: R − material point of the roller marker on the track edge described by line constraint of motion (CON − "line constraint"), R' − material point of the roller rigidly connected with the arm rigid body (WELD − "welded connection"), PLANE − plane of freedom of motion of points R R', y_r − distance RR', l − track edge. Material point of marker R' can move linearly only on the curve l describing the track edge. This point can simultaneously rotate in the three degrees of freedom as in a spherical joint. The roller is rigidly connected to the arm in point R'. In order to compensate potential mutual deflections between points R − R', the joint "In plane" has been used. In this case marker R is always located in the place of orthogonal projection of the roller R' onto the track edge. The force affecting roller R' is modelled by means of a non-linear motor whose force is dependent on the distance y_r between the roller and the rail edge. The motor operator models the phenomenon of elastic collision of the roller with the track edge. With the positive values of the distances there is no contact force. With negative distances, the force increases in proportion to the strain edge − roller, based on the elastic force. Additionally, in this moment the force of resistance to the motion of the turning roller is being applied. Parameter values of the model have been set up in the reference book [1].

2. Simulation results

Fig. 5 defines the most important state variables describing the course of motion of the model. These are the three distances between the points of geometrical centres of the vehicle rigid body and the track axis (for the rigid body of the vehicle bodywork, front and rear wheels axes indicated in the following way: y_0 − bodywork, y_1 − front wheels axis, y_2 − rear wheels axis) and three deviation angles of axes of these rigid bodies from normal to the centre track line (indicated: ψ_0 − bodywork, ψ_1 − front wheels axis, ψ_2 − rear wheels axis). The model presented in the figure has inner left rollers set active and the right ones non active (which corresponds to indicating the left rail edge with a continuous blue line). The preset vehicle trajectory consists of three parts: a straight line segment of entry of 2–metre length, a curve of intersection angle of 45° on a line segment of 2–metre length and a straight line exit segment of 2–metre length. It has been assumed that at the initial moment of simulation, geometrical centre of the model is at the beginning of the coordinate system, the model has the coaxial location in relation to the track axis and moves at the linear speed of 1 m/s. In the further stage of simulation, the model moves at the speed equal to

the preset initial speed. Fig. 6 presents the temporary functions of distances between centres of rigid bodies and the track axis: a) crosswise deviations indicated by y, b) angular displacements from normal indicated by ψ, wheels axes turning angles indicated by δ.
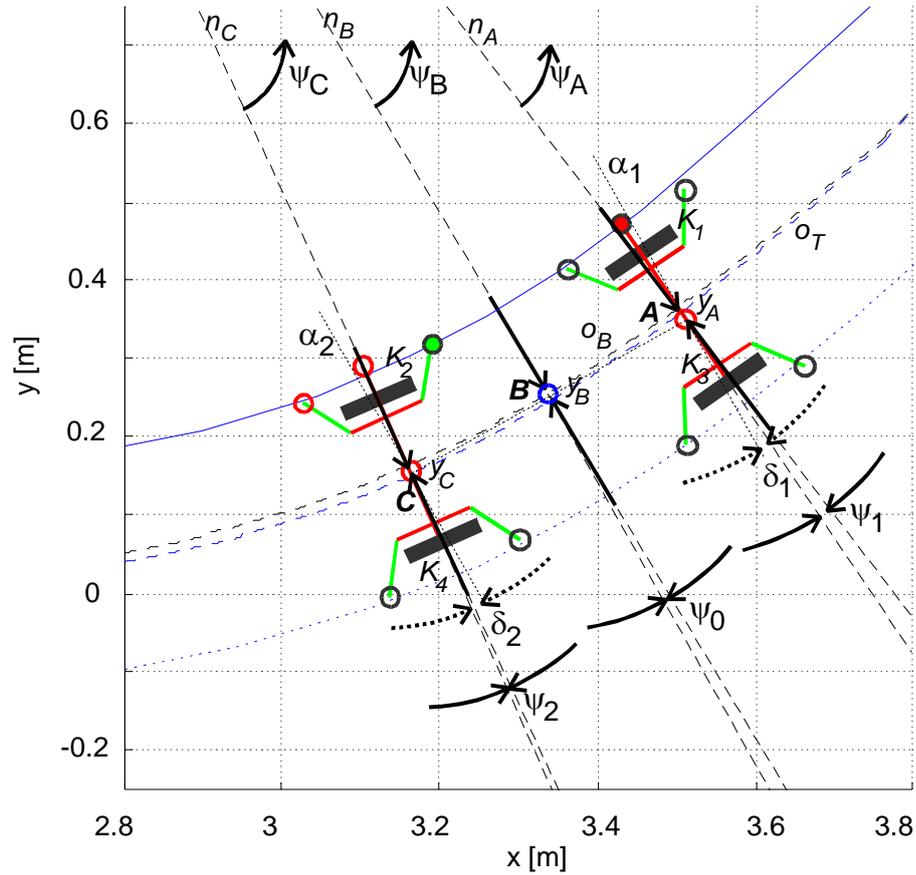
Fig. 5. State variables describing the course of motion of the model. Indications: n_A n_B n_C – normal to the track curvature (transition curve is a clothoid), y_0 y_1 y_2 distances between points of geometrical centres of rigid bodies and the track axis, ψ_0 ψ_1 ψ_2 deviations of rigid bodies axes from normal to the track curvature, ψ_A ψ_B ψ_C – intersection angles of normal, δ_1 δ_2 – axis turning angles

a)

b)

c)
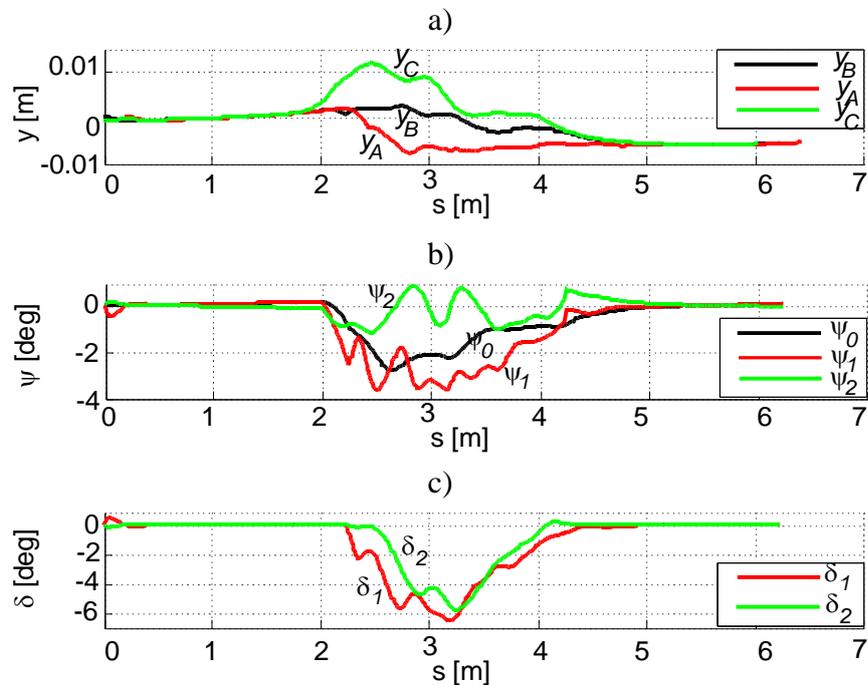
Fig. 6. Functions of the variables characterizing the way of setting vehicle axes in relation to the track centre: a) crosswise deviations y, b) angular displacements from normal ψ, c) turning angles δ.

Simulation results indicate that in driving conditions on a straight line segment, a vehicle has a tendency to drive along the track (it stays adjacent to the track edge). If the straight line segment is at the beginning of vehicle motion, then the vehicle may turn to the right or to the left edge of the track (it has been tested that the direction of turn may be dependent on minimal changes of initial parameters values – such a situation is typical for the phenomenon called deterministic chaos). On a straight line segment of the track which ends a curve, the vehicle always becomes adjacent to the track edge which constitutes the inner edge of the curve. Entering the curve starts with a short-term impulse of contact force of the outer roller. This impulse forces the turn of the vehicle body in the direction of the track curvature, however, without a simultaneous turn of front and rear wheels. The turn of front and rear wheels occurs with a certain time delay. Then, dampened oscillations of turning angles are visible, which lead to achieving quasi steady state for this phase of motion. Quasi steady state of motion in a curve is characterised by the lack of radial positioning of a vehicle. The vehicle moves being deflected from the track axis (in the case discussed it is about 3.75°), which results in establishing non-zero values of the wheel slip angles. As a result of this, the whole centrifugal force within an arc is only balanced by the contact force of the first outer roller. This phenomenon is undesirable. In the future, it may contribute to the increase of exploitation wear of wheel track and rail edge.

3. Summary

Simulation research results have shown various features of motion connected with the lack of centring mechanism. These features are, among the others, front wheels torsional vibration in the initial stage of turn, driving on a curve with vehicle bodywork deflected in relation to the tangent to the central line of track, "adjacency" to track edge after finishing the turning stage. Such behaviour was observed in the trial runs of a physical model in scale carried out in the laboratory of the Faculty of Transport. Further research facilitating formal verification of the model will be conducted in the laboratory of the Institute of Electrical Machines of the Faculty of Electrical Engineering. Construction of the test track has not been completed yet.

Acknowledgements

References

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