TRAMWAY/TRACK INTERACTION: DYNAMIC ANALYSIS AND PERFORMANCE EVALUATION OF AN ARTICULATED BOGIE WITH INDEPENDENT WHEELS

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ABSTRACT

The goal of the present research is first to work out the dynamic behavior of an independent wheeled articulated bogie, by means of a 3D detailed multibody model. Previous research works have pointed out the poor dynamic behavior of the bogie on a straight track, whereas in curve it correctly deforms, leading to a noticeable reduction of the wheel/rail angle of attack and thus of wear.

Then, to improve the above-mentioned straight track behavior, we have carried out a model-based study and proposed a technically reasonable solution in order to re-stabilize the vehicle by means of slight geometrical modifications of the articulated structure. The modified vehicle behavior is compared with the original one and also with equivalent wheelset bogies in terms of mean dissipated power along a representative tramway trajectory.

1 INTRODUCTION

During the last decades, the railway industry has focused its attention on new bogie designs and secondary suspension technologies, as well in the field of high speed trains as in the field of urban tramways. The goal mainly consists in improving the vehicle rolling behavior in terms of stability and longevity, but also to enhance the passenger comfort and to reduce the inconvenience of the railway track neighborhood (noise, vibration, etc.). The use of independent wheels certainly represents one of the most ”revolutionary” innovation of the last decades. Indeed, it aims at replacing the traditional wheelset which exists for more than one century and is at the root of the bogie guidance thanks to its well-established self-steering capability. Various contributions have pointed out the advantages of bogies equipped with independent (or ”freely-rotating”) wheels such as the absence of the hunting critical speed (high speed train dynamics) or the possibility of low-floor vehicles (tramway design). On the other hand, freely rotating wheels lack the steering performances of the traditional rigid wheelsets and must rely, to steer the vehicle back into a centered position, on the wheel/track gravitational stiffness phenomenon and/or on any additional ”mechanism” to ensure a good bogie guidance (active/passive steering mechanism, left/right actuation control, steerable wheels, etc.).

1.1 The articulated bogie

As far as we are concerned, we have to analyze a light railway vehicle developed during the nineties. The main originality of this tramway, composed of three carbodies and three bogies, as depicted in Fig. 1, con-

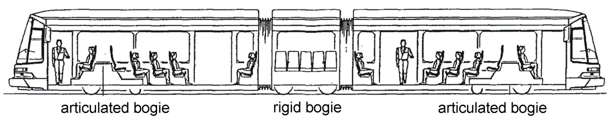


Figure 1: A light tramway equipped with bogies with independent wheels

sists of a new concept of articulated bogie with independent wheels located at the two tramway extremities. The vehicle design must satisfy the following demanding criteria [1]: a full low-floor level (0.30 meter) and the ability of negotiating curves with tight radius (down to 13 meters). This articulated bogie, depicted in Fig. 2, has already been the subject of dynamic investigations by our research team during the nineties [1], [2]: more details about this will be given in Section 2. To meet the above requirements,

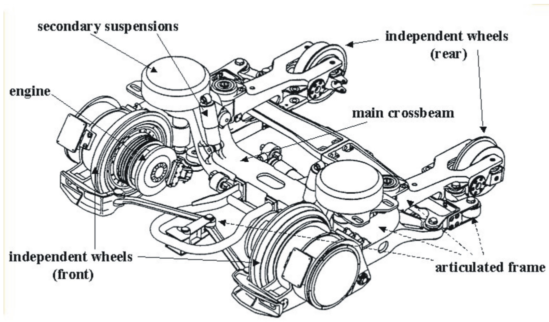


Figure 2: The articulated bogie

two important design modifications – with respect to classical bogies – have been carried out. First of all, by replacing wheelsets by independent wheels and by adequately shaping the main crossbar ("swan neck" shape, see Fig. 2), the carbody floor could be adequately lowered according to the tramway specifications. As shown in Fig. 1, the "inner"[1] wheels are smaller (radius = $195\,mm$) than the wheels located at the tramway extremities (radius = $300\,mm$). Only the latter are actuated by two independent electrical motors. However, to meet the second requirement (i.e. low radius curve negotiation), a wheel alignment mechanism was necessary in order to keep the wheel/rail attack angle as small as possible and to avoid mechanical interference when running on rail equipped with counter-rail. This has been achieved by the use of an articulated structure which naturally deforms the bogie in curve to align the wheels with the rails. Figure 3 shows some schematic pictograms of the bogie in different deformed configurations.

Let us point out that due to the articulated structure, left and right independent wheels are no longer mounted on a common — even virtual – axle. On the basis of this figure, one can already imagine that the deformed configurations in curve (left pictograms) should have a positive effect on the bogie curve dynamics (ex. wheel/rail contact dissipated power). On the contrary, the bogie configuration on a straight track, that one would wish undeformed, could be such as those depicted in the right pictograms, that is a so-called "left curve" or "right curve" configuration. This last remark is important for the present work; indeed, the final design was mainly the result of *geometrical* specifications (curve inscription, wheel/rail interference, left/right wheel gauge conservation, etc.). In fact, the dynamic aspects of the bogie have been probably underestimated in view of its stability performances on a perfect track as already pointed out via modal analyses in our previous studies. Roughly speaking, this unconventional bogie clearly meet the original system specifications from a geometrical point of view (low-floor, curve negotiation, — and this was obviously a real challenge — but, as we shall see, exhibits some stability problems that a lonely dynamic analysis could reveal.

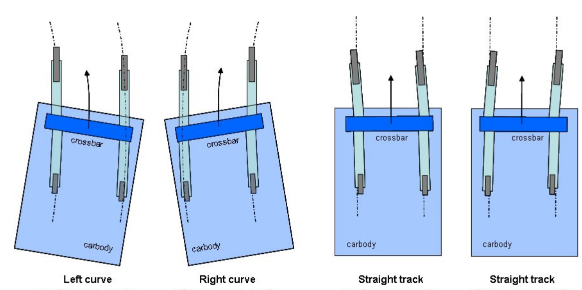


Figure 3: The bogie in different deformed configurations

[1] that is the wheels which are closer to the tramway center

1.2 Aim of the research

The goal of the present research work is first to confirm, by means of a multibody model of the tramway, that the front[2] bogie is unstable on a straight track. Since this lateral instability generates costs, it is now attempted to re-stabilize it via geometrical modifications of the bogie structure to make it stable or at least "less unstable". Due to the complexity of the system (the bogie structure consists of more than 15 articulated bodies, wheels and motors excluded) and of its dynamics (railway dynamics is not trivial, all the more in case of independent wheels mounted on an articulated frame), we have carried out a model-based study to propose a "technically cheap" solution in order to re-stabilize the vehicle, by conferring on it a rather similar behavior as the one of a classical bogie with wheelsets.

2 MULTIBODY APPROACH

Whereas classical railway vehicles could be modeled in a rather straightforward manner[3] thanks to the very small motions around a given nominal configuration, the articulated bogie, from the modeling point of view, is more like a 3D mechanism than a railway bogie and its deformation make a linear model unrealistic for the envisaged trajectories. This justifies the use of a multibody approach (and software) to model the system. Moreover, the nature of the system is really suitable for a relative coordinate approach (the bogie frame is composed of 15 articulated bodies + the wheels). This is the reason why we have used the SIMPACK multibody programs [4] to perform the numerical investigations. As regards the independent wheel model, it is based on the approach proposed in [2], which was latter on at the root of the SIMPACK corresponding module.

[2]The tramway being able to run in both direction is "left-right symmetric": thus, there is always a "front" and a "rear" articulated bogie.

[3]even without using a multibody program, the linearized kinematics being rather simple

2.1 The bogie: a constrained multibody system

According to Fig. 4, the bogie contains five kinematic loops: two at the front closed by connecting rods, the same at the rear, closed by two small connecting rods, a central loop involving the two crossbars and an "hidden" loop at the right extremity of the main crossbar (point A) where the joint:

- can rotate around a vertical axis (yaw) to allow the yaw deformation of the mechanism;
- can rotate around a transverse axis (pitch) to allow a relative pitch motion between the left and right sides which is indispensable to run over cross level-type track irregularities;
- is locked around a longitudinal axis (roll) via a small connecting rod (⇔ fifth loop) to ensure the mechanical robustness against vertical loads.

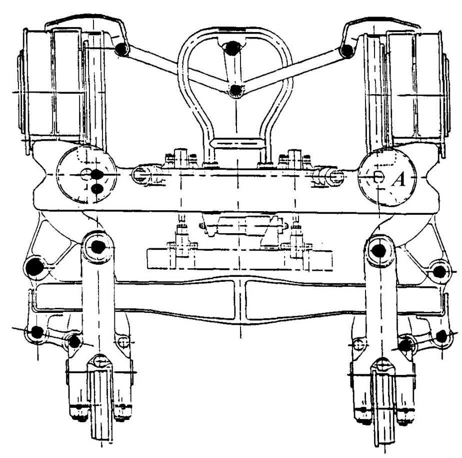


Figure 4: The closed morphology of the bogie: top view

It is clear that in view of the structure, the dynamic modeling of the vehicle is advantageously carried out via a multibody formalism using *relative* joint coordinates, as used by SIMPACK. The multibody equations of motion are obtained via a recursive formulation which are considered as the most efficient for large systems.

For a $n-$ d.o.f. tree-like multibody system, the configuration only requires n generalized coordinates q. The well-known "Order-N" formalism is used by SIMPACK to computes with an $\mathcal{O}(\mathcal{N})$ complexity the generalized accelerations $\ddot{q}$ via three recursions:

$$\ddot{q} = f(q, \dot{q}, \delta, g, f_{ext}, t_{ext}) \tag{1}$$

in which q are the n generalized joint coordinates, δ denotes the dynamic body parameters (masses, centers of mass and inertia properties), f_{ext} and t_{ext} respectively represent the contributive internal/external forces and torques – barring gravity – applied to the system. Considering the closed structure of the bogie which involve five kinematic loops as explained above, the classical Lagrange multiplier technique is used to deal with the corresponding kinematic constraints denoted $h(q)$. The global system of equations reads (using a semi-explicit formulation for clarity purpose):

$$\begin{aligned} M\ddot{q} + c(\delta, f_{ext}, t_{ext}) &= Q + J^t\lambda && (2)\\ h(q) &= 0 && (3)\\ \dot{h}(q,\dot{q}) &= J\dot{q} = 0 && (4)\\ \ddot{h}(q,\dot{q},\ddot{q}) &= J\ddot{q} + \dot{J}\dot{q} = 0 && (5) \end{aligned}$$

in which M stands for the system mass matrix, h denotes the m kinematic constraints between the n generalized coordinates, J ($= \frac{\partial h}{\partial q}$, size mxn) stands for the constraint Jacobian matrix and λ are the m Lagrange multipliers associated with the constraints. Let us point out that, in addition to the closed-loop constraints, wheel/rail constraints can be considered to impose the wheel/rail contact in the normal[4] direction: the latter constraints will be part of the vector h and will be numerically treated in the same way as the loop constraints, for their solution.

DAE's solvers are used in SIMPACK to time integrate the full system (2–5), the constraint solution at position, velocity and acceleration levels being rigorously done within the integrator algorithm. As regards time simulation, SIMPACK exhibits impressive capabilities, also in terms of track description and graphical post-processing (3D animation including wheel/rail forces visualization).

[4]assuming a regular contact

2.2 Independent wheel model

For decades, the wheel/rail contact models have only considered rigid wheelsets, the reason being that independent wheels were absolutely not popular for railway bogies. As far as we are concerned, we have thus developed a new wheel/rail model for independent wheels [2] which has been exploited and enriched afterward by other research groups. The specificity of this model consists in the fact that, contrary to a wheelset, each wheel has to be considered individually without considering any direct connection with the wheel located on the other side. In view of the bogie design, it is easy to understand that between a left and a right wheel, various articulated bodies exist which make the "wheelset"[5] assumption completely erroneous.

Let us briefly recall the geometrical and kinematical feature of this model that the reader can find in [2]. In view of Fig. 5, in the context of constrained contact model, a single profiled wheel on a profiled rail has five degrees of freedom which could be naturally described by:

- the lateral and longitudinal displacement of the wheel center of mass G;
- the yaw and roll angle of the wheel;
- the rotation angle around its axis of symmetry.

This set of coordinates – which will be replaced by relative coordinates in our case – however require to solve the following nonlinear geometrical problem which comes from the fact that both surfaces are profiled : each wheel tread, at each time step configuration, has a regular contact with the rail, that is a common contact point[6] and a common contact plane. This problem requires to introduce two auxiliary variables per wheel to locate the contact, in addition to the generalized coordinates locating the wheel in space (see Fig. 5):

- w, the lateral position of the contact point on the wheel axis;

[5]even with a virtual axle

[6]being the center of the contact ellipse

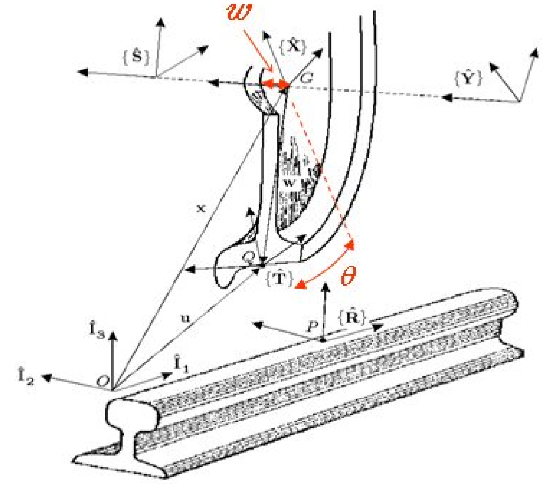


Figure 5: A single wheel on a rail - auxiliary variable w and θ

- θ, the pitch angle, locating the contact point on a wheel axial section circumference (the wheel axial rotation being ignored);

In view of Fig. 5, to satisfy the regular contact of a wheel on a rail, three geometrical constraints have to be satisfied: The first one is a position constraint and states that the wheel geometrical point Q must belong to the rail surface:

$$h_1(q, w, \theta) = u_3 - \mu(u_2) = 0 \tag{6}$$

where u_2 and u_3 are the lateral and vertical components respectively of the absolute position of point Q (vector $\mathbf{u}$) and μ is the rail profile defined in the track reference frame $\{\hat{\mathbf{I}}\}$.
Two additional orientation constraints are necessary to ensure a regular tangent contact at point Q:

$$\begin{aligned} h_2(q, w, \theta) &= \hat{\mathbf{T}}_3.\hat{\mathbf{R}}_1 = 0 & (7) \\ h_3(q, w, \theta) &= \hat{\mathbf{T}}_3.\hat{\mathbf{R}}_2 = 0 & (8) \end{aligned}$$

The frames $\{\hat{\mathbf{T}}\}$ and $\{\hat{\mathbf{R}}\}$ have been defined for the "non-rolling" wheel and the rail respectively. Frame $\{\hat{\mathbf{T}}\}$ is such that its (x, y) unit vectors are tangent to the wheel surface at point Q, $\hat{\mathbf{T}}_3$ thus being normal to the tangent plane (see Fig. 5). Equivalently for the rail, frame $\{\hat{\mathbf{R}}\}$ is such that $\hat{\mathbf{R}}_1$ is parallel to the rail (straight track) and $\mathbf{R}_3$ is normal to the rail surface. These constraints, which can be highly nonlinear due to the wheel/rail profiles and difficult to make converge because for some wheel/rail combinations, the profiles are close to conformity. For instance, a robust method is proposed in [3] to combine a dichotomic method, which finds potential contact points Q by "scanning" the wheel/rail profiles, with the standard Newton-Raphson iterative method applied to the set of constraints (6–8).

Let us point out two important remarks.

- With this modeling approach, an independent wheel on a rail has – as it should be ! – five d.o.f. since three constraints apply to a set of eight variables : six absolute coordinates to locate the wheel in space plus two auxiliary variables (w and θ) to locate the contact point Q.

- In previous works issuing from the author's Research group (ex. [2]), it is demonstrated that Lagrange multipliers associated with the two orientation constraints (7) and (8) equal zero. Indeed, from a physical point of view, each of them imposes an orientation condition between two bodies *in point contact*: obviously the latter cannot transmit – through a contact point – any pure torque along any axes located in the tangent contact plane. This allows us to completely disregard the contribution of these constraints in the dynamic equations (2) (term $J^t\lambda$) which represents a non negligible computational saving. The Lagrange multiplier associated with the first constraint represents the vertical contact force on the wheel from which the normal force – required by the tangent creep force models (ex. [5]) can be deduced from simple considerations.

Once the three above constraints are satisfied (for each wheel of the vehicle), the next steps – not detailed here – of the model are the following (see [2] for instance):

- computation of the constraint derivatives (4, 5), including the Jacobian matrix $J(q)$ and the quadratic term $\dot{J}\dot{q}(q,\dot{q})$;

- computation of the creepages at each contact point Q: this can be straightforwardly achieved via the multibody system kinematics;
- computation of the creep forces on the basis of a well-known model (ex. Kalker [5]) whose degree of refinement will depend on the wheel/rail profiles and relative configurations (ex. conformal profiles or not, flange contact with high spin or not, etc.).

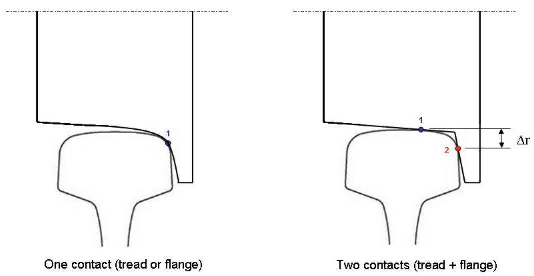


Figure 6: Flange wheel/rail intermittent contact

Finally, as regards the flange contact problem, two situations have been considered for the bogie and are depicted in Fig. 6.

1. First, for the case of new profiles (close to S1002 on UIC60 rails), a "rather smooth" transition from tread to flange contact and conversely is used as depicted in Fig. 6_{left} and this can be modeled by a "single point" of contact approach.
2. Since worn wheel/rail profiles are more representative of the actual situation[7], an intermittent "double contact" model has also been considered. In such model (see Fig. 6_{right}), the flange contact may be intermittent and is not treated as a (unilateral) constraint but as a constitutive force based on the wheel/rail lateral flexibility.

One could question about the choice between these two models for the present bogie. In fact, as soon as it is mostly an instability problem on straight track which is at the root of the present study, flange contacts, can be seen as mechanical lateral "bumps" whose contribution is mainly to avoid derailment and not to guide the bogie.

[7]as it is certainly the case for tramways in most of the cities

3 VEHICLE DYNAMIC BEHAVIOR

3.1 The "half tramway model"

In view of Fig. 1, the vehicle is symmetric with respect to a vertical transverse plane located at the center of the intermediate carbody (carried by a classical bogie), the tramway being designed to run in both direction. Since the focus is put here on the articu-

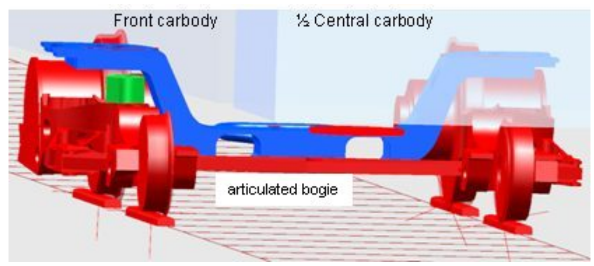


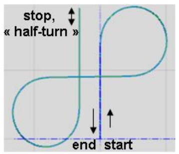
Figure 7: A half-tramway model (Simpack)

lated bogie behavior – the central bogie being stable – a so-called half-tramway model is sufficient to carry out the dynamic analyses. According to Fig. 7, this consists of:

1. half a carbody carried by a perfect[8] bogie (the classical bogie model would needlessly complexify the multibody model and analysis);
2. a full carbody carried by an actuated articulated bogie carrying the half carbody.

Full tramway models and simulations have been performed in the nineties with our own multibody sofware ROBOTRAN [1], the results of which allow us to justify the use of this half-tramway model which is able to "capture" the most significant phenomena. For transient response analyses, a reference trajec-

[8]by perfect it is meant that the bogie is assimilated to a rigid body which perfectly follows the track center.



	ST1	RC	ST2	LC	ST3	Tot. [m]
15 km/h	125 m	75 m	60 m	75 m	325 m	800 m
25 km/h	125 m	200	100 m	200 m	135 m	900 m
50 km/h	200 m	435	200 m	435 m	1210 m	2500 m

Figure 8: Tramway simulation: proposed trajectory

tory represented in Fig. 8 has been defined to be representative of a real tramway network: a first straight track (ST1) followed by a right curve (RC), another straight track (ST2), a left curve (LC) and a final straight track (ST3). Simulating the half-tramway model on this track in both direction (i.e. "go and back" simulation) allows to observe some interesting bogie behaviors:

1. *straight track behavior*: the unstable mode – revealed by previous modal analysis – on a straight track has been confirmed by nonlinear simulations, obviously for validation purpose but mainly for the subsequent investigations aiming at re-stabilize the bogie.

2. *left/right curve behavior*: in addition to its apparent complexity, the bogie is not left/right symmetric; an eccentric mechanism located at the left cross bar extremity "enlarges" the bogie to keep the wheel gauge approximately constant when the bogie deforms in curve.

3. *curving behavior*: the articulated structure being specifically designed for that purpose, it was crucial to check for curving performances in dynamic situations.

4. *out of curve behavior*: being deformed in curve, the bogie mechanism should recover an undeformed configuration on the subsequent straight track ... which is not obvious in view of its instability problem (see below).

3.2 Tramway dynamics : Simulation results

To improve the above-mentioned straight track unstable behavior, we have carried out a model-based

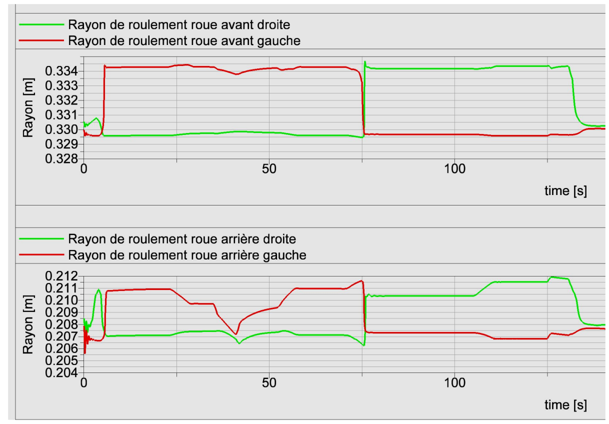


Figure 9: Original tramway on straight track: flange + tread contact

Figure 10: Modified tramway on straight track: tread contact only

study and proposed a "technically reasonable" solution in order to re-stabilize the tramway, by only slightly modifying the articulated bogie geometry: multibody analyses show that, in terms of lateral stability, this modified bogie exhibits a behavior which is quite similar to a classical one with wheelsets. This was rather challenging due to the complexity of the bogie and of its unstable behavior (railway dynamics is not trivial, all the more in case of independent wheels mounted on an articulated frame!).
In Fig. 9 for instance, the wheel radii time history are plotted for the first half of the trajectory (of Fig. 8), for which the bogie is such that its large wheels are at

the front and the small at the rear. The upper plot refers to the front wheels and the lower for the rear wheels (left in red, right in green). One can easily observe that even on the straight track segments ST1, ST2, ST3 (see Fig. 8), the flanges must participate to the tramway guidance.
With the modified design (see Fig. 10), the problem disappears: the tread contact is sufficient to keep the tramway centered on the track, even after the curve: the dynamic behavior is similar to a classical bogie with wheelsets, although the lateral wheel/rail stiffness be significantly lower with the articulated bogie (not shown here).

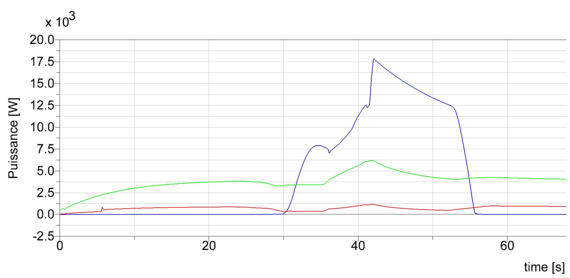


Figure 11: Contact dissipated power comparison between three bogies: blue - classical bogie with wheelsets; red - original articulated bogie with independent wheels; green - modified articulated bogie with independent wheels.

In terms of wear, Fig. 11 compares the – instantaneous – wheel/rail contact dissipated power of three front bogies (multibody models) for a trajectory composed of straight and curved segments. We can observe that the bogie with rigid wheelsets has a perfect behavior on straight track but dissipates quite a lot in curve (the latter occurs between $t = 30\,\mathrm{s}$ and $t = 50\,s$ in Fig. 11), while the versions with independent wheels exhibit a less contrasting behavior. Of course, beside this wear-type criteria, other important performances like bogie stability, steady-state curving configuration, vehicle/track lateral stiffness, etc. are also considered in the global dynamic evaluation of the tramway, underlying the present work.

4 ACKNOWLEDGEMENTS

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