Dynamic simulation of tram–train vehicles on railway track

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Abstract

"Tram–train" systems carry out the integration of an urban tramway with the surrounding railway network, by means of light rail vehicles often provided with special wheel profiles in order to fit both grooved and flat-bottomed rails. This paper aims to compare the dynamic behaviour of a typical Light Rail Vehicle (LRV) provided with these "tram–train" wheel profiles with the dynamics of the same LRV provided with an heavy railway standard wheel profile by modelling, in a multi-body simulation environment, the run on railway tracks of a virtual vehicle provided with these two wheel profiles.

Keywords: tram–train, safety, track compatibility, wheel–rail interaction, multi-body simulation.

1 Introduction

The "tram–train" is a typical example of interoperable public transport system, which allows to join city centres with suburban areas, while eliminating the necessity to change transport system and the respective waiting times, by means of urban rail vehicles adapted (e.g. Karlsruhe trams) or specifically designed (e.g. Kassel RegioCitadis LRV's) to operate both on tramway infrastructures (tramway lines or light subway lines) and on conventional railway lines.

On the other hand adapting a tramway vehicle to operate on these two different existing infrastructures requires overcoming some technical barriers (Malavasi *et al.* [1]). In particular the main geometrical issue arises from the different wheel–rail interaction between tramway, which uses grooved rails, and heavy railway where flat-bottomed (Vignole) rails with a slight inclination (1/40

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or 1/20) are used. This paper aims to analyse the above mentioned question from the point of view of safety and vehicle–track compatibility.

2 Wheel–rail interaction

Issues arising from the different rail sections often used in tramway (grooved rails) and railway tracks (flat-bottomed rails laid with an inclination of 1/40 or 1/20) can be faced by introducing in tram–train vehicles special wheel profiles able to fit both able to fit both tramway and railway track.

As an example, in the city of Karlsruhe tram–train vehicles has been provided with a special wheel profile having a narrow wheel flange to fit grooved rails and a wide tyre profile (135 mm) to let the contact between the inside edge of the wheel, higher than street surface, and the check rail in correspondence of frogs of conventional railway turnouts, which had to be raised.

However "tram–train" wheel profiles, due to their particular shapes coming from tram wheels (they have narrower and lower flanges than heavy railway wheel profiles) could cause an increase of wheel wear and, in general, a different dynamic behaviour of the vehicle in comparison with the one induced by a conventional railway wheel profile.

Therefore the study has been carry out by modelling a Light Rail Vehicle, provided with the two types of wheel profiles, and its dynamic behaviour on railway tracks by applying the multi-body system software SIMPACK®. The tram–train wheel profile chosen has been similar to the one used for Karlsruhe tram–train vehicles (GT8–100C/2S GT8–100D/2S–M series), afterwards called KVV profile. It has been compared to the nominal ORE S1002 wheel profile, widely adopted by European railway administrations, on UIC 60 rail profile with inclination of 1/40. In order to evaluate the influence of "tram–train" special wheel profiles both on solid axle wheelsets and on independent rotating wheels, the LRV multi-body model has been provided with two traditional motor bogies and with two trailer bogies having independently rotating wheels.

3 The vehicle model

In order to investigate wheel–rail interaction the benchmark vehicle has been carefully chosen to represent a typical light rail vehicle with characteristic similar to the modern "tram–train" vehicles. In particular the vehicle modelled with SIMPACK® adopts a mixed solution:

- traditional motor bogies having a pair of solid–axle wheel–sets;
- trailer bogies having independently rotating wheels.

The whole vehicle is made by five articulated body sections (two head bodies, one intermediate body and two linking platforms joined to the two trailer bogies) and four bogies (two outer motor bogies and two inner trailer bogies).

The vehicle model is not intended to represent an actual vehicle, although its modelling has been based on parts of existing vehicles.

In figure 1 a three dimensional wire frame view of the vehicle, caught from SIMPACK® simulation environment, is shown. In table 1 the main characteristics of the vehicle modelled with SIMPACK® are reported.

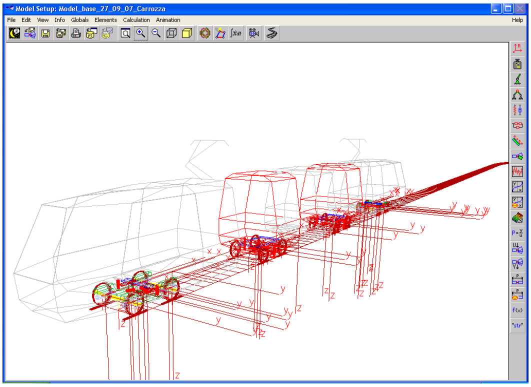


Figure 1: Wire frame view of the vehicle caught from SIMPACK® simulation environment.

Table 1: Main characteristics of the vehicle model.

Wheels arrangement	Bo-2-2-Bo	Height of low floor area	350 mm
Tare weight	40 t	Height of high floor area	880 mm
Total length	31.250 mm	Boogie wheelbase	1.750 mm
Width	2.400 mm	Wheel diameter, new	740 mm
Height without trolley	3.560 mm	Track gauge	1.435 mm

4 Wheel profiles geometrical analysis

By the geometrical analysis of wheel–rail interaction, carried out in SIMPACK® simulation environment, the following characteristics of interaction between the two wheel profiles considered (KVV and S1002) and the standard on UIC 60 rail profile with an inclination of 1/40:

- wheels rolling radii (difference between right and left wheel) as a function of the relative lateral position of the wheelset with respect to the track;
- wheels contact angles (difference between right and left wheel) as a function of the relative lateral position of the wheelset with respect to the track;
- “equivalent conicity” (defined as the ratio of the difference r_1-r_2 between left and right wheel radius to the double of the relative lateral displacement of the wheelset);
- the distribution of contact points.

The aim of the above mentioned analysis is to investigate the possible consequences of the singular interaction between a “tram–train” wheel profile and a standard rail profile both on wear issues and on the dynamic behaviour of the vehicle, with particular regard to trailer bogies having independently rotating wheels. In fact, one of the main problems of independently rotating wheels is the self-centring action on straight track, which for a conventional wheelset is allowed by conicity, whereas for independently rotating wheels the only way to obtain the self-centring action is using the gravitational stiffness caused by the possible superelevation of the track.

Generally wheel profiles are defined by two main parameters: the difference between rolling radii and the difference between contact angles in function of the relative lateral position of the wheelset with respect to the track.

For a conic wheelset profile (e.g. the one used for rolling stock running on Italian railway network) diagrams of the above mentioned parameters in function of the wheelset lateral displacement are straight lines and easy to interpret both in correspondence of the wheel running surface and of the wheel flange.

For a non conic profile the variation of these parameters in function of the lateral displacement is not linear; therefore the angle of the interpolator straight line, called “equivalent conicity”, is considered.

If an independently rotating wheelset is provided with a conic wheel profile, with a null difference of the contact angles near the rolling circle, it isn’t possible to obtain any force towards the centre of the track due to the gravitational stiffness. Hence it is necessary to provide independently rotating wheels with a profile characterised by a variable conicity (like S1002 “distributed wear” profile), which is able to generate a difference of contact angles between the two wheels.

In the light of previous considerations it is clear the importance of the geometrical analysis of KVV wheel profile, in comparison to S1002 profile, in order to evaluate its influence on the dynamic behaviour of bogies having independently rotating wheels. Therefore, as first step of the analysis, in table 2

Table 2: Main geometrical differences between KVV wheel profile and S1002 wheel profile.

Wheel profile / Characteristics	KVV	S1002
Wheel profile width [mm]	135	135÷140
Distance between inside faces of wheel profiles in correspondence of upper rail surface [mm]	1374 (*)	1360
Distance between inside faces of wheel profiles at 10 mm under the nominal rolling circle [mm]	1378	1360
Distance between outside faces of wheel flanges [mm]	1426	1425
Wheel flange height [mm]	28	30

(*) The standard European value of 1360 mm is assumed in KVV profile at 9,5 mm above the nominal rolling circle.

the main geometrical characteristics of KVV and S1002 profiles are reported. The comparison of the two wheel profiles confirms that, as said before, KVV has a narrower and lower flange than S1002 profile.

Figure 2 shows geometrical interaction between both wheel profiles (KVV and S1002) and UIC 60 rail profile laid at 1/40, in correspondence of the nominal rolling circle.

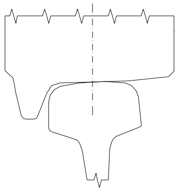
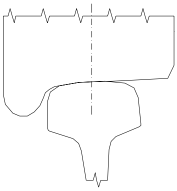
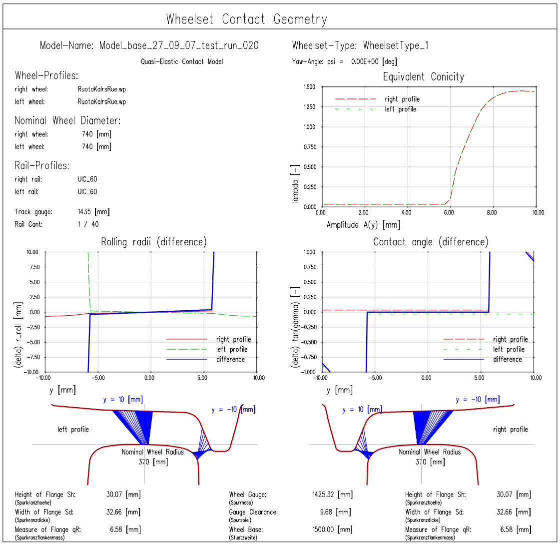
KVV – UIC60	S1002 – UIC60
	

Figure 2: Geometrical interaction between both wheel profiles (KVV and S1002) and UIC 60 rail profile with an inclination of 1/40, in correspondence of the nominal rolling circle of the wheel.

In figures 3 and 4, both for KVV and S1002 wheel profiles, the distribution of contact points and the diagrams of "equivalent conicity", rolling radii difference and contact angle difference as a function of the lateral displacement of the wheelset, obtained by means of SIMPACK®, are reported. These diagrams have been obtained for a wheel diameter of 740 mm and a UIC 60 rail profile with an inclination of 1/40.



Wheelset Contact Geometry

Model-Name: Model_base_27_09_07_test_run_020
Quasi-Elastic Contact Model

Wheelset-Type: WheelsetType_1
Yaw-Angle: psi = 0.00E+00 [deg]

Wheel-Profiles:
right wheel: RuotaKalrsRue.wp
left wheel: RuotaKalrsRue.wp

Nominal Wheel Diameter:
right wheel: 740 [mm]
left wheel: 740 [mm]

Rail-Profiles:
right rail: UIC_60
left rail: UIC_60

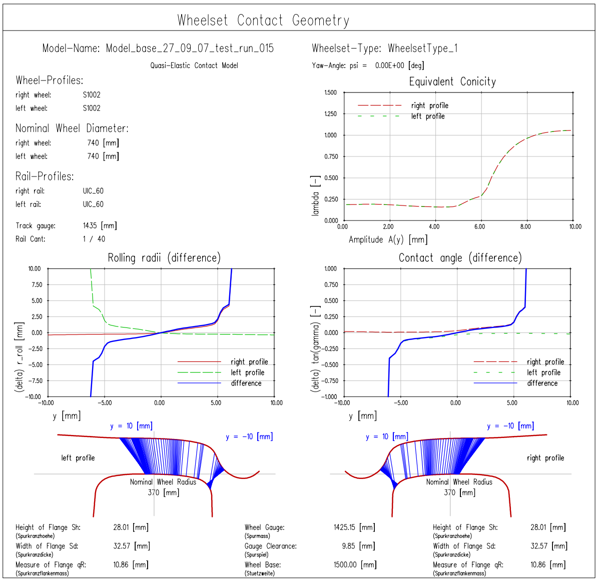
Track gauge: 1435 [mm]
Rail Cant: 1 / 40

Height of Flange Sh: (Spurkranzhoehe) 30.07 [mm]
Width of Flange Sd: (Spurkranzdicke) 32.66 [mm]
Measure of Flange qR: (Spurkranzflankenmass) 6.58 [mm]

Wheel Gauge: (Spurmass) 1425.32 [mm]
Gauge Clearance: (Spurspiel) 9.68 [mm]
Wheel Base: (Stuetzweite) 1500.00 [mm]

Height of Flange Sh: (Spurkranzhoehe) 30.07 [mm]
Width of Flange Sd: (Spurkranzdicke) 32.66 [mm]
Measure of Flange qR: (Spurkranzflankenmass) 6.58 [mm]

Figure 3: Geometrical parameters of the interaction between KVV wheel profile and UIC 60 rail profile with an inclination of 1/40.



Wheelset Contact Geometry

Model–Name: Model_base_27_09_07_test_run_015

Quasi–Elastic Contact Model

Wheelset–Type: WheelsetType_1

Yaw–Angle: psi = 0.00E+00 [deg]

Wheel–Profiles:

right wheel: S1002

left wheel: S1002

Nominal Wheel Diameter:

right wheel: 740 [mm]

left wheel: 740 [mm]

Rail–Profiles:

right rail: UIC_60

left rail: UIC_60

Track gauge: 1435 [mm]

Rail Cant: 1 / 40

Height of Flange Sh: 28.01 [mm]
(Spurkranzhoehe)

Width of Flange Sd: 32.57 [mm]
(Spurkranzdicke)

Measure of Flange qR: 10.86 [mm]
(Spurkranzflankenmass)

Wheel Gauge: 1425.15 [mm]
(Spurmass)

Gauge Clearance: 9.85 [mm]
(Spurspiel)

Wheel Base: 1500.00 [mm]
(Stuetzweite)

Height of Flange Sh: 28.01 [mm]
(Spurkranzhoehe)

Width of Flange Sd: 32.57 [mm]
(Spurkranzdicke)

Measure of Flange qR: 10.86 [mm]
(Spurkranzflankenmass)

Figure 4: Geometrical parameters of the interaction between S1002 wheel profile and UIC 60 rail profile with an inclination of 1/40.

Figure 3 shows that for KVV wheel profile (like for a conic profile) diagrams of rolling radii and contact angles differences in function of wheelset lateral displacement are straight lines; whereas figure 4 shows that for S1002 "distributed wear" profile, which is a variable conicity profile, the variation of these parameters in function of wheelset lateral displacement is not linear; therefore the angle of the interpolator straight line, called "equivalent conicity", is considered.

Therefore providing independently rotating wheels with KVV, which is a profile with a very low difference between rolling radii near the nominal rolling circle, it is no possible to obtain any force towards the centre of the track due to the gravitational stiffness and hence it is no possible to realize the self-centring action on straight track. This fact implies that independently rotating wheels provided with KVV profile cause an increase of rail and wheel wear compared to traditional wheelsets.

On the other hand S1002 profile besides providing an high gravitational stiffness, it also has an elevated equivalent conicity, which at high speeds could cause instability of the traditional wheelsets.

At last, regarding the distribution of contact points, graphics for KVV wheel profile show two zones at high contact points density: the first zone in correspondence of the nominal rolling circle (lateral displacement of wheelset between ±1 mm) and the second in the contact zone between rail and wheel flange (lateral displacement between ±5 and ±6 mm). Contrary to what happens for S1002, these high concentrations of contact points for KVV profile can cause severe localized wear in correspondence of the rolling circle and of the inside face of wheel flange, which could require to be often reprofiled due to its narrow design.

5 Wheel profiles dynamic analysis

To be able to study the dynamic behaviour of a tram–train vehicle moving on railway tracks (comparing the kinetics of KVV wheel profile with the one of the standard S1002), 20 runs have been made, selecting, in each run, only the steady-state behaviour while the vehicle's curving. The simulations data input were:

- curve radius at the end of initial transition length: 20, 50, 100, 150, 200, 250, 400, 600, 800, 1000 m;
- track gauge: 1435 mm;
- rail profile: UIC60;
- rail inclination: 1/40;
- cant deficiency: 0,16 m;
- friction coefficient: 0,15;
- start-run speed: 10 m/s;
- maximum simulation time duration: 40 s.

The main aim of this study is analysing the transversal kinematics of the wheelsets (displacements) and the resultant of contact slip forces in longitudinal and in transversal directions, with respect to the rail track reference frame.

It is to note that the dynamic analysis of the vehicle do not consider track irregularities, therefore the results have to be read as steady-state results, that is the maximum values of each parameter on full curve, without analysing the movement of vehicle on transition arcs.

Data records for the first motor bogie and for the first trailer bogie have been collected, allowing the study of the effects of changing wheel profile, both for traditional bogies and for bogies with independently rotating wheels.

5.1 Longitudinal resultant T_x of slip forces

Extracting maximum values on full curve of the longitudinal resultant T_x of the contact slip forces for each test run made, always at same velocity (10 m/s), in SIMPACK® simulation environment, it has been possible to obtain the variation of the steady-state values of T_x as a function of the curved track radius both for the first motor bogie (with traditional wheelsets) and for the first trailer bogie (with independently rotating wheels).

Figures 5 and 6 show the variation of T_x as a function of the curved track radius on the first motor bogie (with traditional wheelsets), respectively for S1002 and KVV wheel profile.

The analysis of the traditional motor bogie shows that the use of KVV profile eliminate the presence of a turning curve radius for the value of longitudinal resultant T_x, acting on the guiding wheelset, while this effect can be seen in case of S1002 profile (T_x value turning curve radius: 220 m).

At last for trailer bogie, with independently rotating wheels, both in case of KVV profile and S1002 profile the analysis highlights the almost absence of the longitudinal resultants for the slip forces, confirming that the born of longitudinal guiding forces is a phenomenon belonging only to standard wheelsets, whatever the wheel profile is.

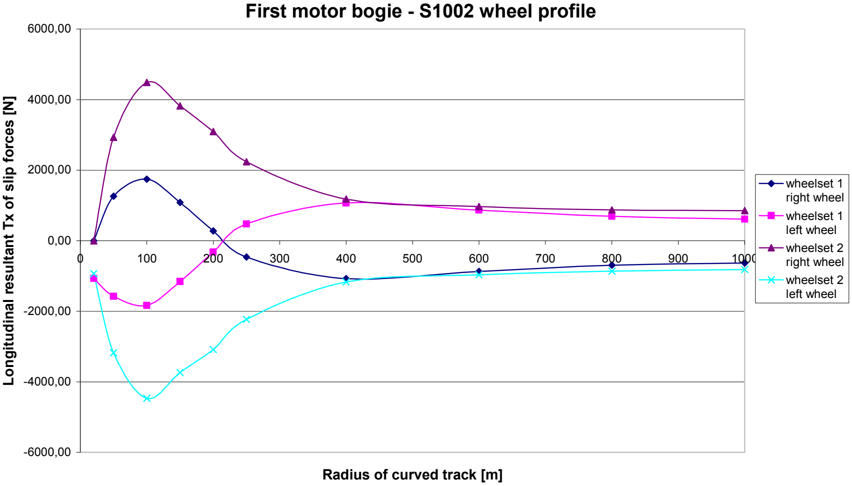


Figure 5: Longitudinal resultant T_x of slip forces on motor bogie with traditional wheelsets (S1002 profile).

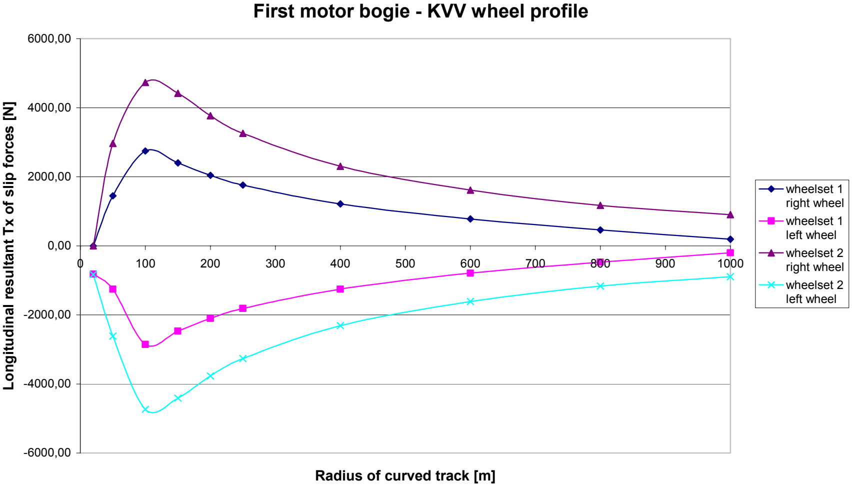


Figure 6: Longitudinal resultant T_x of slip forces on motor bogie with traditional wheelsets (KVV profile).

5.2 Transversal resultant Ty of slip forces

As seen before for longitudinal forces, also for transversal forces it has been possible to obtain the variation of the steady-state values of the resultant force T_y as a function of the curved track radius both for the first motor bogie (with traditional wheelsets) and for the first trailer bogie (with independently rotating wheels). Diagrams show that, both for the traditional motor bogie and for the trailer bogie with independently rotating wheels, the transversal forces reach higher values with the adoption of KVV profile with respect to S1002 profile, whereas the trend of transversal forces with the curved track radius is almost the same for the two wheel profiles, except for the force acting on the left wheel of the second wheelset which has opposite signs in the two cases. As an example figure 7 shows the variation of T_y as a function of the curved track radius on the first motor bogie (with traditional wheelsets) for KVV wheel profile (diagram related to motor bogie for S1002 profile and diagrams related to trailer bogie are not reported because very similar). In these diagrams also the variation of non compensated curving acceleration as a function of curve radius is reported.

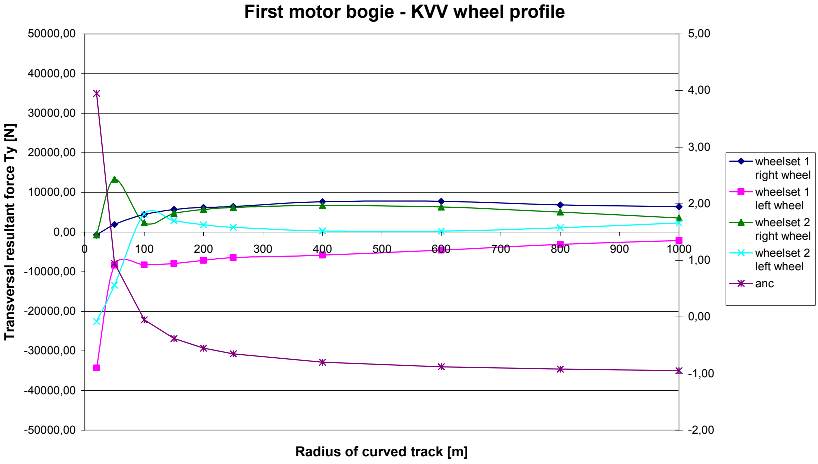


Figure 7: Transversal resultant T_y of slip forces on motor bogie with traditional wheelsets (S1002 and KVV profile).

5.3 Lateral displacement of wheelsets

Figure 8 shows the variation of the maximum lateral displacement of the wheelsets in full cuve (steady-state values) as a function of the curved track radius both for the first motor bogie (with traditional wheelsets) and for the first trailer bogie (with independently rotating wheels) respectively for S1002 and KVV wheel profile.

Diagrams show that at the increase of curve radius with the S1002 the motor bogie centres itself on the track, whereas with KVV profile this phenomenon doesn't occur and the bogie places itself on the outside of the curve. Trailer bogie places itself always on the inner of the curve more markedly adopting KVV profile.

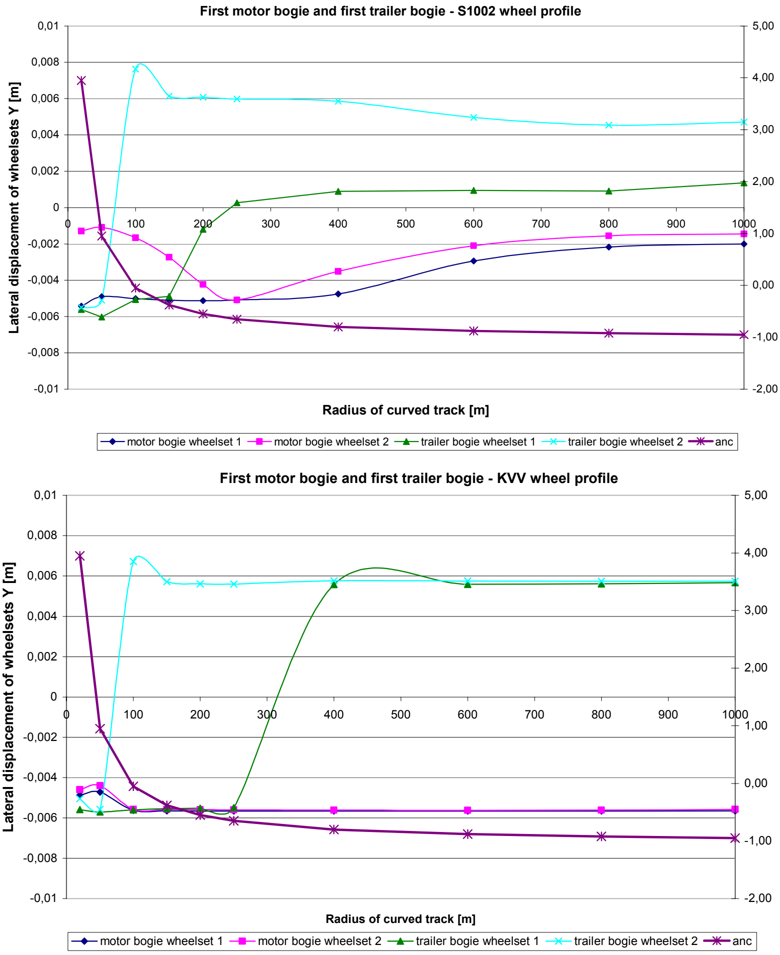


Figure 8: Lateral displacement of the wheelsets of motor bogie with traditional wheelsets and of trailer bogie with independently rotating wheels (S1002 and KVV profile).

6 Conclusions and further developments

The present paper has summarised the results of a study on the possible influence of a special "tram–train" wheel profile on the dynamic behaviour of a typical Light Rail Vehicle running on conventional railway tracks.

The study has been carry out by modelling, in a multi-body simulation environment, a Light Rail Vehicle, provided with the tram–train wheel profile KVV, and comparing its dynamic behaviour on railway tracks with the dynamic behaviour of the same LRV provided with an heavy railway standard wheel profile ORE S1002.

About geometrical wheel–rail interaction, contrary to what happens for S1002, tram–train wheel profile KVV presents high concentrations of contact points, which can cause severe localized wear in correspondence of the rolling circle and of the inside face of wheel flange. Therefore providing independently rotating wheels with KVV, which is a profile with a very low difference between rolling radii near the nominal rolling circle, it is no possible to obtain any force towards the centre of the track due to the gravitational stiffness and hence it is no possible to realize the self-centring action on straight track. This fact implies that independently rotating wheels provided with KVV profile cause an increase of rail wear compared to traditional wheelsets.

About dynamic analysis the study of a Light Rail Vehicle curving on conventional railway track has highlighted that the use of a tram–train wheel profile changes the dynamic behaviour of both bogies with traditional wheelsets and with independently rotating wheels in comparison with the same bogies provided with the standard wheel profile ORE S1002.

At last a possible development of the research is the analysis of the influence of “tram–train” wheel profiles on the dynamic behaviour of Light Rail Vehicle running on singular points of the tracks, like conventional railway turnouts, in correspondence of which “tram–train” wheel profiles, due to their narrow flange, could cause remarkable differences compared to a conventional railway standard wheel profile.

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