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Contact mechanics issues of a vehicle equipped with partially independently rotating wheelsets

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ABSTRACT

A recently developed novel wheelset design where individual wheels are mounted on stub axles and are connected through a shaft is described. The design may include torque limiters to partially uncouple the wheels to reduce peak longitudinal forces.

The work described in this paper is based on the analysis of the running dynamics of a library vehicle to compare conventional and new wheelset arrangements to highlight the effects of the torque limiter on wear and rolling contact fatigue (RCF) damage. The comparison is performed for a wide variety or running speeds, non-compensated accelerations and adhesion coefficients, revealing that the proper setting of the torque limiters can effectively reduce both high rail RCF damages in mild radius curves and corrugation formation and growth in tight radius curves.

Practical applicability of the solution in terms of durability of the components together with the analysis of dissipated energy in the torque limiter are shown.

1. Introduction

Independently rotating wheels (IRWs) mounted on inside frame bogies are often used in trams and in all vehicles that require a low floor arrangement. This layout is very interesting as it allows to access the wheels for maintenance just lifting one side of the bogie frame at a time, without the need to lower the wheelset or to lift the carbody up as required with conventional wheelsets.

The absence of the torsional constraint between the wheels leads nevertheless to premature wear of wheel flanges, as the bogie tends to run skewed and with one or more wheel flanges in continuous contact with rail gauge corner. The gravitational stiffness prove to be insufficient to restore the central position of the wheelsets. This evidence, clear already in the 70s of the last century, explains why no IRW-equipped vehicles are used in conventional railways.

In order to overcome this drawback allowing at same time a dramatically improved running gear maintainability, the fully passive “apparently” independently rotating wheels wheelset (AIR wheelset for short) was developed and patented [1].

Although the reader is referred to another paper [2] to get a detailed description of the solution in terms of mechanical design, it can be shortly said that it consists of two wheels supported on hollow supports by a specific arrangement of the bearings, which is able to withstand both lateral and vertical loads acting on each single wheel. This function is critical, as the absence of a conventional axle does not provide any equalization of the lateral forces acting on the two wheels. The design makes use of bearings recently developed for inboard bearings high-speed vehicles (Fig. 1).

Two versions of the AIR wheelset are available, a motor one and a trailing one. In both the arrangements, the wheels are connected by a shaft passing through the hollow supports. In the case of the trailing AIR wheelset, the connection can be made through friction torque limiters that allow finite rotations between the wheels in case the torque limit set is exceeded.

About running dynamics, the introduction of a torsionally softer shaft connecting the wheels may lead to some decay in the performances of a vehicle. In particular, the critical speed may reduce by decreasing the torsional stiffness of the axle, as shown in [3]. The running dynamics behavior of a library vehicle is described in [4], where the impact on critical speed, track shifting forces and derailment ratio L/V (or Y/Q in the European practice) for both perfect and defective track and for the classical axle, the torsionally flexible axle and the “torque limited” AIR wheelset solution are analyzed. It was concluded that the effect of the axle torsional flexibility does not affect in practice the dynamic behavior of the vehicle provided that suitable anti-yaw dampers are used. The introduction of the torque limiter was shown to be beneficial in terms of increase of critical speeds and decrease of track shifting forces.

A preliminary paper on maintenance peculiarities of the AIR wheelset will be given at the WCRR2016 congress [5] and the work

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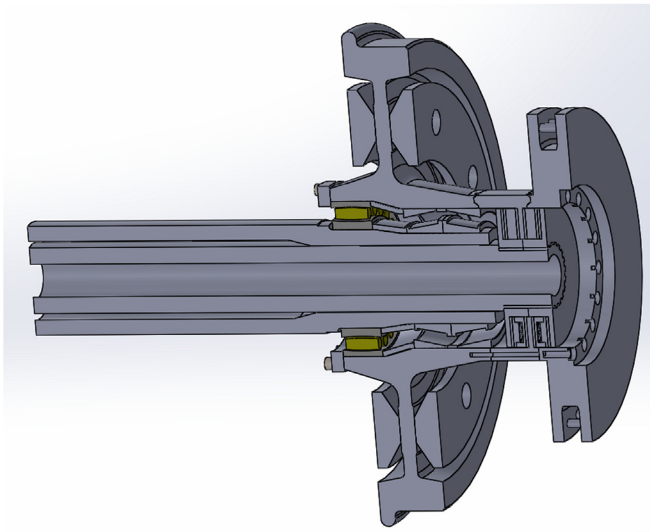

Fig. 1. Three-dimensional view of the AIR wheelset equipped with torque limiter and an optional external brake disc.

is still in progress. This activity will be developed with the help of the most important train operating company in Italy (Trenitalia SpA). It can be said at the moment that the topics that the work will concentrate on are:

- as the rotating axle "disappears", most of the conventional workshop repair activities disappear as well, as the only part subjected to maintenance is the wheel, where brake disc and bearings are fitted;
- all UT structure involved in NDT of axles (personnel, equipment, procedures) can be dismantled as well, as the stub axles are part of the bogie and will be subjected to long distance general overhaul;
- the entire logistics of the wheelset changes, as wheel change will be possible with standard and low-cost equipment in all depots without requiring the whole vehicle lift up but only the bogie frame lift up just to free the wheels flanges from the rail head;
- a centralized workshop will be able to serve many operators and there will possibly be only one main center in a country, as logistics of wheels is much easier than that of wheelsets;
- vehicle dynamics considerations force the use of oversized bearings that will very likely last "for life", similarly to street vehicles where bearings are never changed.

The present paper covers implications of torque limiters applied to the AIR wheelset on contact mechanics and wear of rail/wheel systems.

2. Forces and damage at the wheel–rail contact

The accepted parameter [6] involved in wear and rolling contact fatigue of wheel is the wear number W, also known as "Tgamma", given by Eq. (1):

$$W = T\gamma = T_x\gamma_x + T_y\gamma_y \tag{1}$$

where T is the tangential force acting on the wheel and γ is the creepage. The x and y suffixes refer to the longitudinal and lateral directions, respectively.

One potential model uses the Ekberg damage parameter [7], described by Eq. (2)

$$FI_{surf} = f' - (2AK_e)/(3T') \tag{2}$$

where T' is the vector sum of the longitudinal and lateral tangential forces T_x and T_y (Eq. (3)), A is the contact area and K_e is the shear yield strength of the wheel material. The following formula therefore holds

$$f' = T'/Q = \sqrt{T_x{}^2 + T_y{}^2}/Q \le f \tag{3}$$

where f' is the utilized friction coefficient and Q is the normal contact force. The forces at the wheel rail contact are limited by the adhesion coefficient f. Slip therefore results when the constraint is saturated, i.e. when $T' = fQ$.

The relative contribution of lateral and longitudinal forces and creepages depends in a non-linear way on the running conditions and on the architecture of the vehicle.

The use of the torque limiter in the AIR wheelset allows to manage (limit) in some way the longitudinal forces at the wheel–rail contact, leading in principle to a reduction of the T_x component and the associated γ_x creepage and therefore to a reduction of longitudinal wear number $T_x\gamma_x$. It should be said, however, that also the lateral behavior of the wheelset can be affected by this change and that different values for both lateral forces and creepages can be obtained, leading to higher $T_y\gamma_y$ wear numbers. This can be justified by the reduced steering capability of a wheelset equipped with torque limiters that leads to greater angles of attack and possibly larger lateral displacement of the wheelsets.

3. The reference case – ERRI wagon

3.1. Introduction

In order to evaluate the effects on wear and RCF of a torque-limiting device, the analysis of wheel–rail forces was conducted on a reference vehicle, i.e. the "ERRI wagon" present in the VI-Rail v. 16.0 software library [8] and used in the past as reference for a software codes benchmark [9]. It is a passenger car with two bogies equipped with anti-yaw dampers and a total of four wheelsets.

The reason and the limitations for this choice are the following:

- any possible solution found is relative to the specific vehicle chosen;
- the ERRI wagon was selected mainly as it makes possible the generation of solutions that can be easily validated and reproduced by the scientific community;
- modeling mistakes are avoided and the attention can be focused on the results, whose accuracy is indisputable;
- the ERRI wagon is representative only of a category of vehicles (long distance passenger cars) and has parameters that may differ from other category of vehicles (high speed, mass transit, metro, freight, etc.) and the results in some "extreme" situations (e.g. very tight curves with very high adhesion limit, typical of metro applications) may not be fully reliable.

Focusing on longitudinal forces T_x, the average force on the two wheels for the i-th wheelset $T_{xi,av} = (T_{xi1} + T_{xi2})/2$, i.e. the resistance to motion, has a magnitude that always remains small. Further considerations on tractive effort required in the case of standard wheelsets and on wheelsets equipped with torque limiter will be discussed later in the paper.

More interesting is the analysis of the difference of the longitudinal forces acting on the two wheels of a wheelset, $\Delta T_{xi} = (T_{xi1} - T_{xi2})/2$, as it originates:

- a torque in z direction $M_{zi}=\Delta T_{xi}\ s$, where s is the wheelset gauge, which is responsible for steering;
- a torque in y direction $M_{yi}=\Delta T_{xi}\ r$, where r is the instantaneous radius of the wheel (that for the scope of the present paper can be approximated to the nominal radius of the wheel), that torsionally loads the axle and that can be influenced by setting the torque limiters present in the AIR wheelset.

The analyses shown in this paper will be limited to the behavior of the ERRI wagon in constant radius curves, while the behavior in straight track and in transitions is described in [4]. It descends from the hypothesis that all the results presented here are to be considered as steady, i.e. they are maintained unaltered along the entire circular curve once the transition has ended.

In the following only the first two wheelsets (first bogie) of the ERRI wagon will be considered, as they represent the typically worst conditions during running in curve, the first axle having the highest angle of attack (maximum lateral forces) and the second axle running almost centered (the constraint can be saturated by longitudinal forces).

3.2. Simulation strategy

Generally speaking, the equilibrium set of forces acting on a vehicle running at constant speed in a canted curve depends on the following parameters:

- wheel–rail contact modeling, including the adhesion coefficient f;
- vehicle properties (masses, stiffness, damping, simulated as lumped parameters) and characteristic dimensions;
- resulting lateral forces, depending on kinematic parameters such as (i) curve radius, (ii) cant, (iii) speed, indicated as *non-compensated acceleration* or as *cant deficiency/cant excess*.

As it is clear that it was not possible to simulate all combinations of the aforementioned parameters, the superelevation (cant) was set in all curves at the maximum value of 160 mm in order to obtain the maximum speeds in a given radius curve. The following parameter values were therefore investigated:

- *curve radius* was varied from very tight to large (R=300, 548, 1000, 1430, 2000, 3300 m) in order to highlight the behavior related to corrugation and to RCF in the respective typical context of appearance;
- *non-compensated acceleration* was set to three classical value of running dynamics simulations (a_{nc}=1, 0, −1 m/s^2) corresponding to cant deficiencies of +153, 0 and −153 mm;
- *adhesion coefficient* was initially set to the standard value for running dynamics analysis, i.e. f=0.40, but to investigate curving in different weather and application situations, values of f=0.10, 0.22, 0.33, 0.50 and 0.60 were used as well.

All simulations were performed with new S1002 wheel tread profiles on tracks with 60E1 rails inclined by 1:40 and standard gauge of 1435 mm. As known, this profile combination gives a rather good steering behavior of the wheelset. The advantages due to the AIR wheelset described in the following will be even greater with other, less steering profile couplings. Simulated speeds range from 13 km/h (a_{nc}=−1 m/s^2, R=300 m) to 296 km/h (a_{nc}=+1 m/s^2, R=3300 m), thereby describing the full range of railway conventional and high speed applications.

3.3. Results for f=0.4

As the discussion of all the results (lateral shift of the bogie center, lateral shift of the wheelsets, angles of attack, Y/Q, ΣY, lateral forces, longitudinal forces, $T\gamma$, etc.) is clearly not possible here, the attention will be focused only on those parameters that constitute a basis for the comparison with other situations.

Wear numbers W for the two wheels (11, outer and 12, inner) of the front wheelset are shown in Fig. 2. The trend is the expected one, where wear increases with reducing curve radius for any value of a_{nc}.

More interesting information can be derived from the observation of Fig. 3, where the torque acting on the first (M_1) and the second (M_2) axle are shown. It can be observed that the maximum torque for the front (leading) wheelset is not reached for the tightest curve radius, but for R=1000 m, while for the second (trailing) wheelset the torque reverses, passing from small positive values for large curves to high negative values for tight curves.

This behavior can be explained by looking at the lateral and longitudinal forces at the wheel–rail contact for the outer leading (11) and trailing (21) wheels (Fig. 4). The lateral force of the wheel 11 markedly increases when the radius is reduced, while the longitudinal force for the same wheel starts decreasing after having reached a maximum at around R=1000 m. A different behavior is observable for wheelset 2, where lateral forces for both wheels 21 and 22 are relatively low while longitudinal forces become higher for both wheels for very small radii.

As will be shown in Fig. 6 where other values of f are compared, the adhesion limit for the case a_{nc}=1 m/s^2 is reached for wheelset 1 for curve radius R=300÷1000 m, while for wheelset 2 the adhesion limit is reached only for the tightest radius R=300 m. When the adhesion limit is reached for large lateral forces reasons, longitudinal forces are therefore limited.

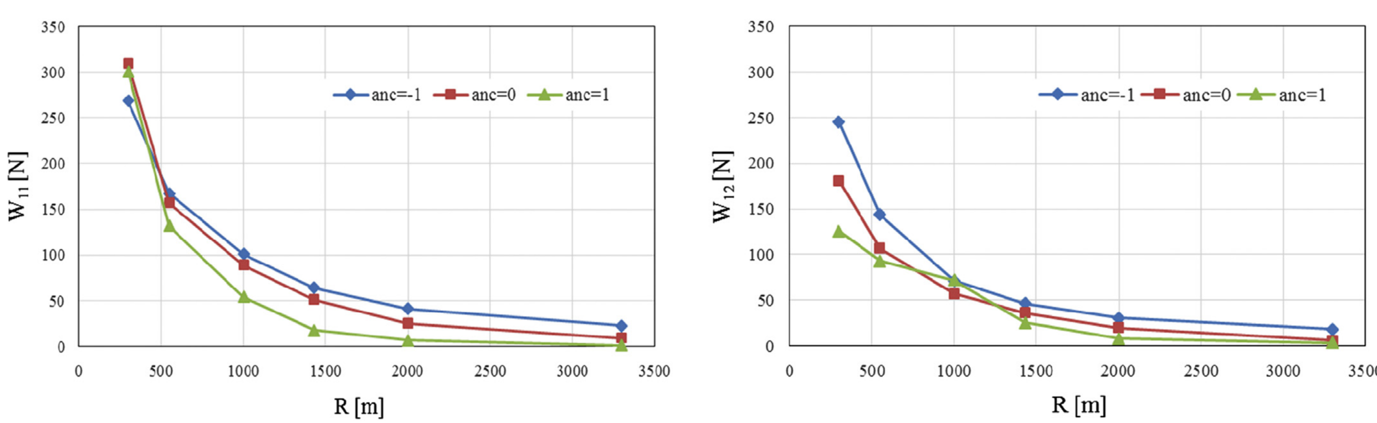

Fig. 2. Wear numbers $W=T\gamma=T_x\gamma_x+T_y\gamma_y$ for the outer wheel (11, left) and the inner wheel (12, right) of the first wheelset of the ERRI wagon for f=0.4 as a function of non-compensated acceleration (a_{nc}).

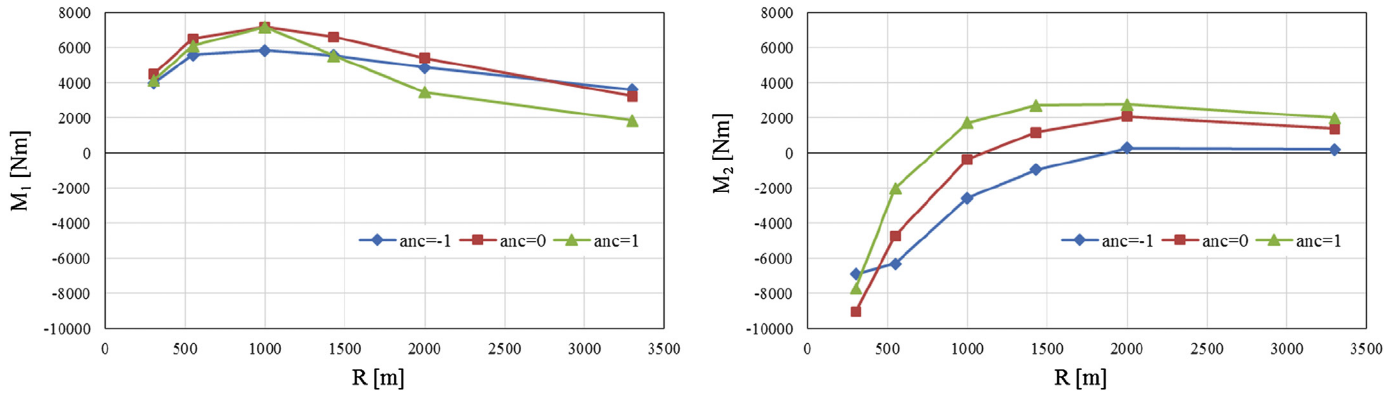

Fig. 3. Torque acting on the first two wheelsets of the ERRI wagon for f=0.4 as a function of non-compensated acceleration (a_{nc}).

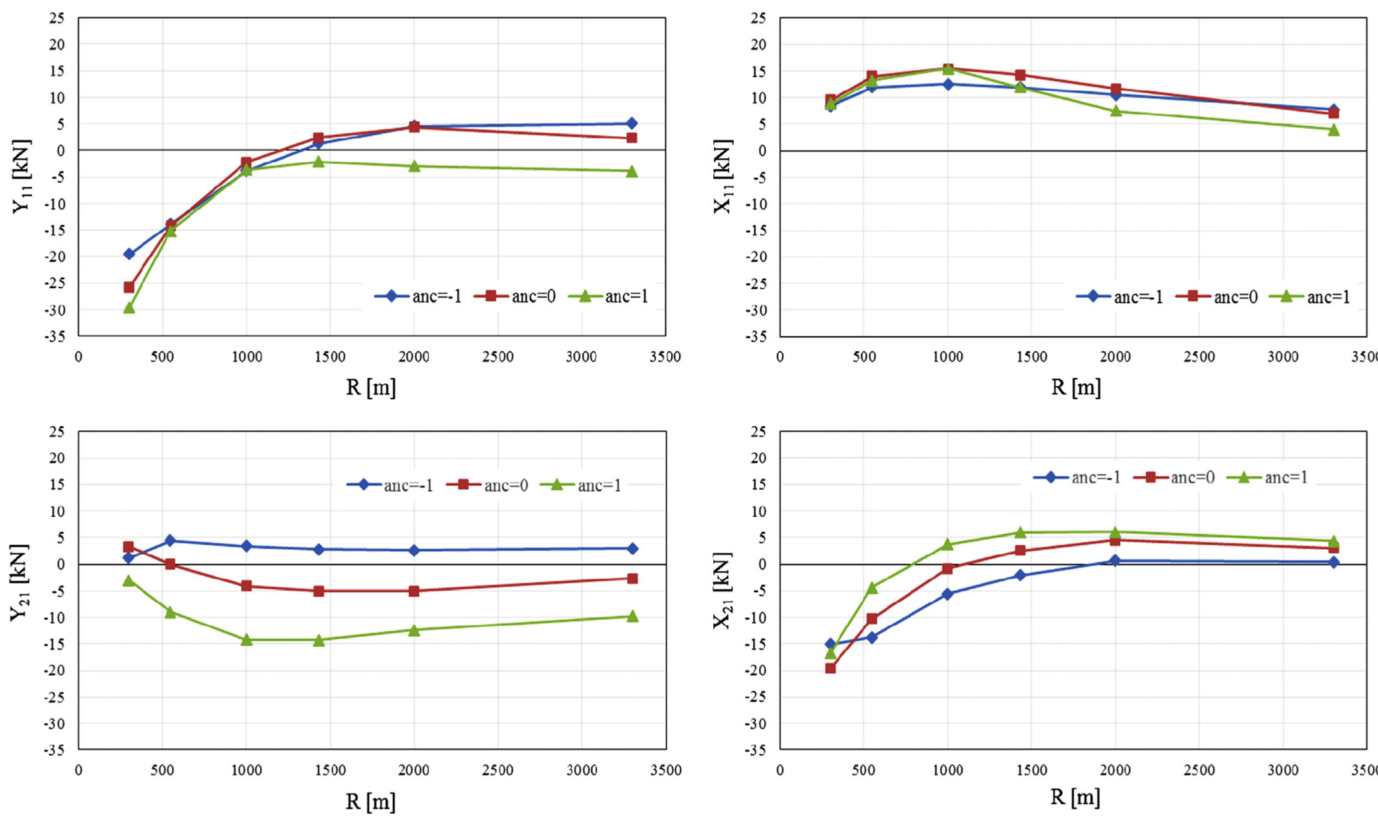

Fig. 4. Lateral forces (left) and longitudinal forces (right) for the leading (top) and trailing (bottom) outer wheels of the first bogie of the ERRI wagon.

All these diagram amply justify the observation of both extensive RCF defects and lateral wear on the high rail in mild radius curve and the presence of corrugation on low rail in tight curves.

3.4. Results for lower and higher f values

As a confirmation of the trend described above, a set of simulations with the adhesion limits shown in par. 3.2 was performed. About the selected adhesion coefficients, the following considerations can be made:

- f=0.10 is typical of low-adhesion situations (light rain, dust or leaves on the rails);
- f=0.22 is intermediate between 0.10 and 0.33 and is a value rather common in normal operations [10];
- f=0.33 is the adhesion limit at zero speed from the classical Curtius and Kniffler equation;
- f=0.40 is the adhesion limit conventionally used in running dynamics simulations;
- f=0.50 is intermediate between 0.40 and 0.60;
- f=0.60 is typical of high-adhesion situations (dry and clean rails, metro tunnels, etc.).

The torque acting on the wheelsets of the front bogie for the case with a_{nc}=1 m/s^2 is shown in Fig. 5. The trend of the torque acting on the front wheelset changes noticeably and exhibits the maximum torque (steering) at different curve radii as a function of the adhesion (f=0.10, R=2000 m; f=0.22÷0.50, R=1000 m; f=0.60, R=548 m). For the trailing wheelset the maximum torque (anti-steering) is always at R=300 m but values for higher curve radius are always relatively small as the wheelset tends to run centered.

The black dashed lines define the range where the torque limiter does not intervene (between the lines) keeping the wheels

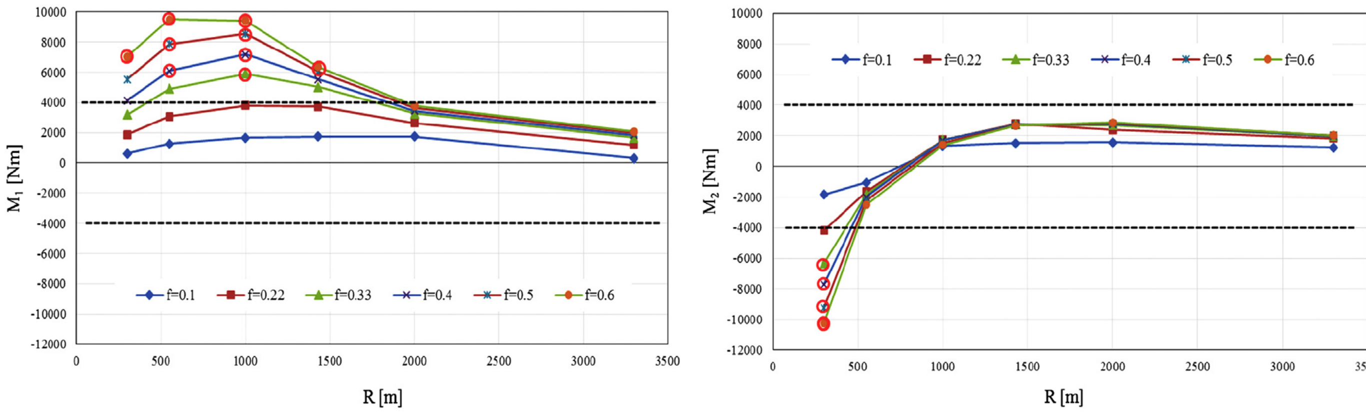

Fig. 5. Torque acting on the leading wheelset M_1 (left) and trailing wheelset M_2 (right) for different f values for the standard ERRI wagon for $a_{nc}=1$ m/s^2. Black dashed lines define the range of intervention of the torque limiter, while red circles highlight the running conditions where the reduction of torque will be greater than 33% (see paragraph 4). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

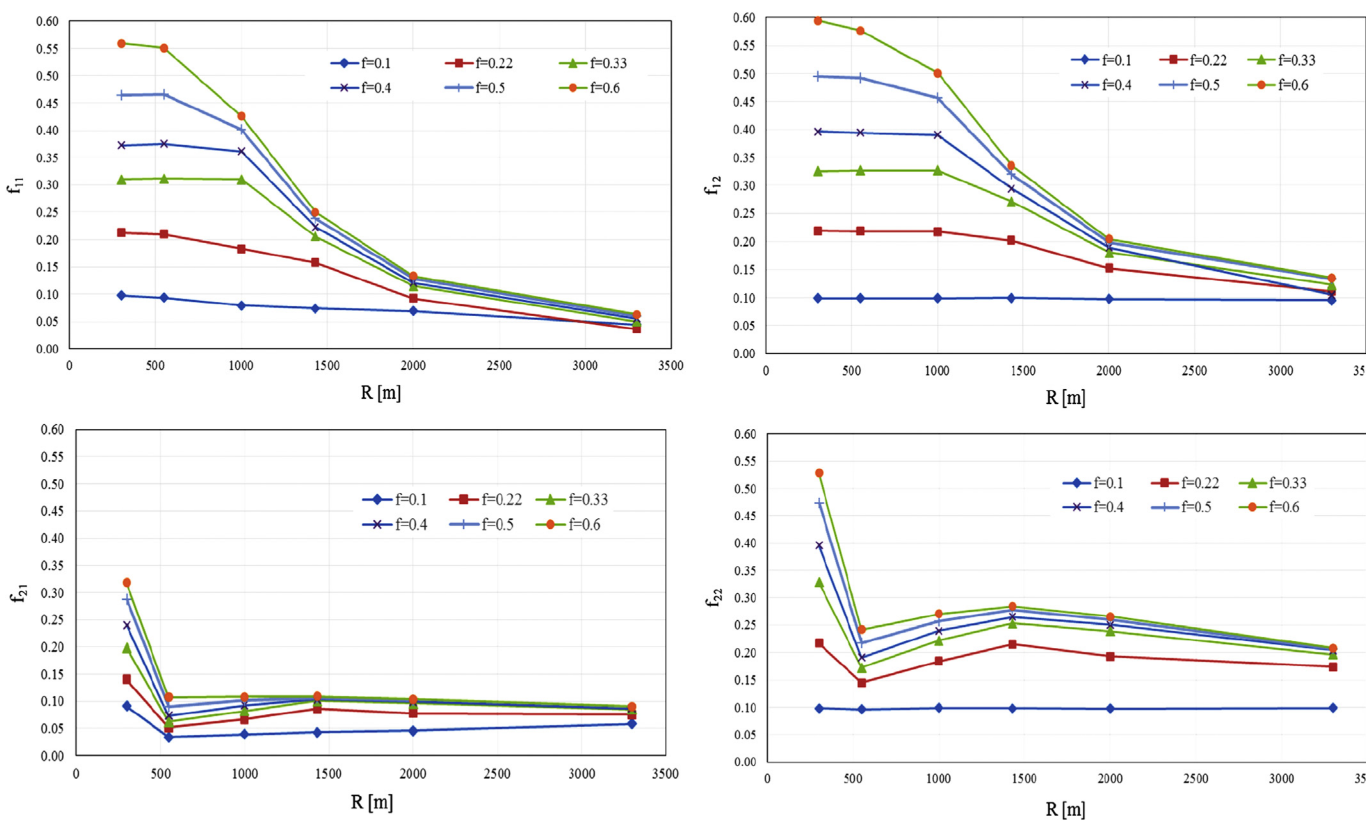

Fig. 6. Utilized adhesion for the four wheels of the leading bogie of standard ERRI wagon for $a_{nc}=1$ m/s^2.

connected. In these conditions, the behavior of the wheelset is identical to that of a conventional wheelset.

Outside this range the wheels can perform relative rotations, while keeping the maximum torque continuously applied. This feature has distinctive advantages on wheel and rail damages and will be described in detail in the next paragraph.

An even more interesting analysis can be conducted on the adhesion coefficients for the four wheelsets of the front bogie (Fig. 6), again for $a_{nc}=1$ m/s^2. Front wheels are in full slip up to around $R=1000$ m for $f\leq 0.40$, while only at higher f values slip is not reached until $R\leq 500$ m. Rear outer wheel 21 never reaches saturation for any f value, while rear inner wheel 22 reaches saturation (slip) only for $f=0.10\div 0.40$ for $R=300$ m.

4. Torque limited to 4000 Nm

4.1. Introduction

The possibility of limiting the longitudinal forces using a torque limiter is beneficial to both the wheel and the rail, although in the authors' opinion the maximum benefit can be obtained on the rail. This is related to the tendency of low rails in tight curves to corrugate. Corrugation is extensively observed around the world, while its counterpart (wheel polygonization) is relatively rare and of much lower importance. Once a rail starts to corrugate, wheel–rail dynamic forces dramatically change in the sense that they tend to exacerbate the problem leading to higher corrugation levels.

Although useless on the wear deriving from lateral forces, the introduction of a torque limiter allows finite rotation between the wheels avoiding the stick–slip phenomena arising from the longitudinal forces. It also introduces some damping in the wheelset, which can be of extreme importance to limit the amplitude of the vibrations arising from the rapidly changing dynamic forces at the wheel–rail contact such as those that appear during negotiation of a highly corrugated rail.

The definition of the setting of the torque limiter is not trivial, as its intervention should fulfill the following requirements:

- it should provide an effective "protection" against too high longitudinal forces that can damage the rails;
- for such reason, it should not intervene in the case of low adhesion (i.e. rainfall) as longitudinal forces are naturally low;
- on the contrary, it should intervene in case of high adhesion coefficient f even for larger curve radius;
- its intervention should be in any case limited at the maximum to avoid premature wear of the limiter generating high unwanted costs;
- it should not too much disturb the running dynamics of the vehicle at high speed and large curve radius as its behavior is nonlinear.

The torque limiter is modeled as sign function multiplied by the desired maximum torque. Therefore, wheels are rigidly connected up to the limit value and then they can perform relative rotations under the maximum torque still applied.

For reasons linked to running dynamics that are partially described also in [4], the torque limit was set to $M_{lim}=4000$ Nm as shown in Fig. 5. With this selection the limiter never intervenes for $f \le 0.22$ (i.e. standard case for the majority of service conditions) while intervenes in curves of radius $R < 2000$ m for other adhesion limit values. It is clear that its effect will be larger the higher the adhesion limit found in the curve.

Full protection can never be achieved, as the torque is not totally canceled. This should be seen as a positive feature, as it leaves some steering capability of the wheelset that would be lost in case of the use of "fully disengaging" torque limiters. Fig. 5 shows the points (highlighted by red circles) were a reduction in the transmitted torque (i.e. the reduction of the longitudinal forces) is greater than 33%. In some extreme situations (front wheelset $f=0.60$, $R=548 \div 1000$ m; rear wheelset $f=0.50 \div 0.60$, $R=300$ m), the reduction in the maximum torque reaches approximately 60%. These cases are those in which the maximum rail damage normally occur.

The shape of the torque curves indicates that the torque limiter effect will be somewhat limited for the front wheelset M_1 for very tight curve radius, where in most of the cases the torque limiter will never intervene ($f=0.10 \div 0.40$). As previously explained, this is due to the prevalence of lateral forces that saturate the contact. The torque limiter intervene instead in mild curves, i.e. for $R=548 \div 1430$ m. This area is the one where the presence and growing of RCF defects is normally observed due to the practical absence of wear phenomena [11].

An interesting behavior is observed for the rear wheelset, where the reduction of the torque M_2 is always greater than 33% for $f \ge 0.33$ reaching, as already said, the value of 61% for $f=0.60$. This suggests that the effect of the torque limiter in metro vehicle could be very effective to reduce longitudinal forces on the trailing wheelset, where the maximum forces (responsible for corrugation) are observed.

The effect of the torque limiter on a metro vehicle will be discussed in detail in a future paper. It should not be forgotten that the ERRI wagon is a long distance passenger car, with rather stiff primary longitudinal suspensions and a rather long wheelbase (2560 mm). It is easy to expect that the balance of lateral and longitudinal forces will be completely different on a softer and shorter bogie arrangement. The best effect should be obtained on passively or actively steered wheelsets, where lateral forces are minimized.

4.2. Results for $M_{lim}=4000$ Nm, $a_{nc}=0$ and $f=0.4$

The effect of the limitation of the axle torque on the longitudinal wear number $T_x\gamma_x$ is shown in Fig. 7. This is different from the torque (or the longitudinal force itself) as it takes into account also the longitudinal creepage.

As expected, the effect on the wear number for the front wheelset is maximum on the outer wheel 11 for radii larger than 300 m, with a consistent reduction in the range $-58\% \div -67\%$ for curve radii $R=548 \div 1430$ m, where RCF defects normally appear. Even larger relative effects can be obtained on the inner wheel 12, with reductions in the range $-65\% \div -72\%$ for the same curve radii.

On the rear wheelset the effect is negligible for radii $R \ge 548$ m but is dramatic for $R=300$ m, where the reduction in $T_x\gamma_x$ is at least -86%. This result, together with the observation that the lateral wear number results $T_y\gamma_y \cong 0$, confirms that wear due to rear wheelset vanishes almost completely.

The analysis of total wear numbers W on both the wheels of the front wheelset (Fig. 8) shows that the overall effect of the torque limiter will nevertheless be limited. This is not surprising because, as already mentioned, forces at the wheel–rail contact are mainly lateral and the arrangement with the torque limiter does not sensibly affect the situation. Lateral wear number in fact slightly increase, due to the lower steering effect resulting from lower longitudinal forces. This drawback is limited and negligible in practice.

No information about the results with higher adhesion coefficients are given here for space reasons and as they are substantially similar.

5. Torque limiter description

The applicability of the AIR wheelset requires maintenance targets in line with common practice, i.e. the torque limiter should last long enough to cover the same mileage between overhaul of conventional wheelsets.

The limit torque selected $M_{lim}=4000$ Nm is well within the range of devices available on the market, that for similar size can accommodate torques up to 10.000 Nm. Important parameters to evaluate durability are the number of interventions of the limiter in typical service and the related dissipated power.

If nothing can be said about the first one, being it specific to the network severity and the service, some calculations were performed on the frictional power dissipated in the torque limiter for all non-compensated acceleration values for $f=0.4$ and $M_{lim}=4000$ Nm.

Fig. 9 shows that the dissipated power for the leading wheelset is lower than 2.5 kW in the worst situation, i.e. $R=1000$ m, $a_{nc}=1$ m/s^2, $v=163$ km/h. At this speed, the already limited thermal power is easily dissipated by the airflow around the AIR wheelset end where the torque limited is located. For the trailing wheelset the torque limiter intervenes only at $R=300$ m with extremely low speeds and consequently limited power.

It is worth highlighting that basic energy consideration lead to the conclusion that this dissipated power can only be a fraction of the total energy that would be dissipated at the wheel–rail contact due to the friction associated to the energy lost during longitudinal force creeping. Tractive effort and resistance to motion remain therefore basically unchanged.

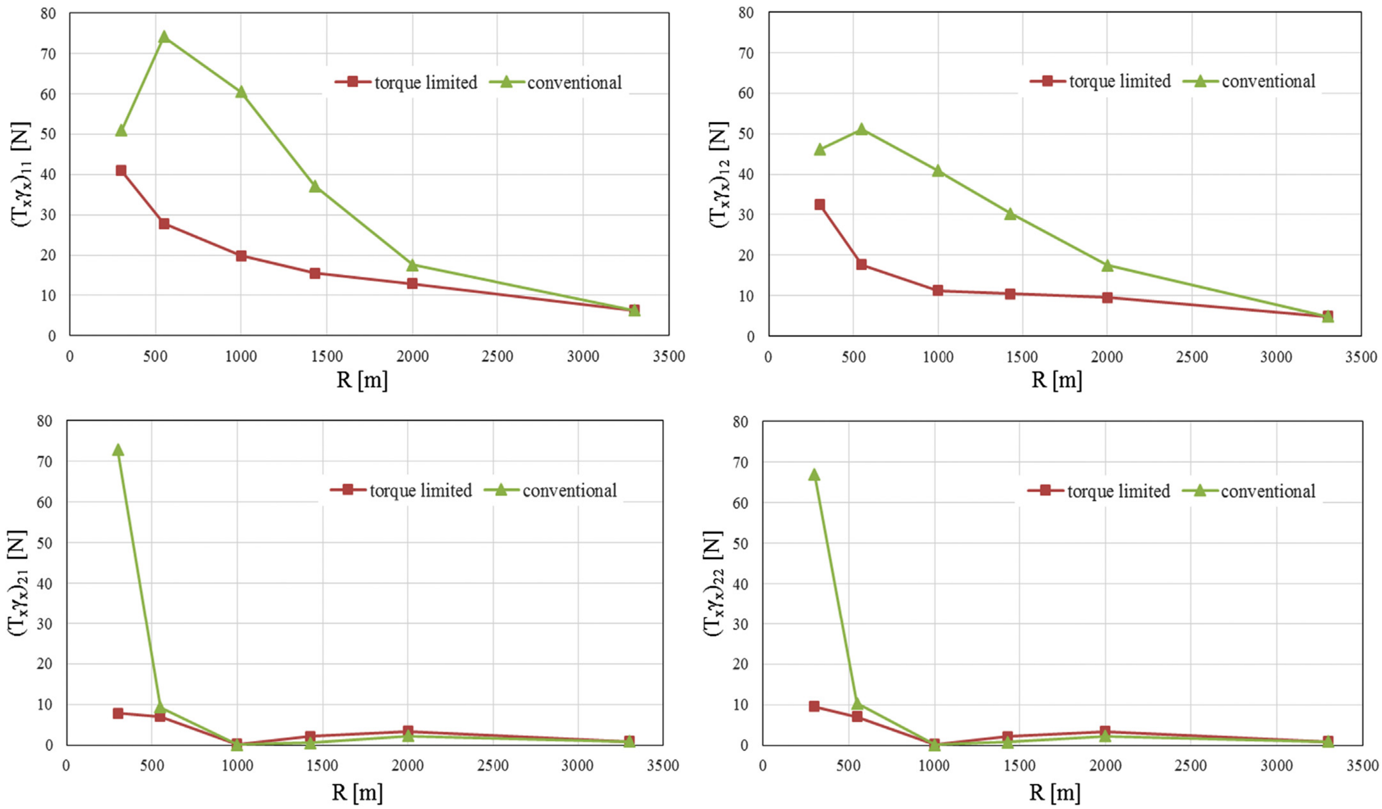

Fig. 7. Longitudinal wear number $T_x\gamma_x$ for all the wheels of the ERRI wagon in the original configuration and with the torque limited to 4000 Nm.

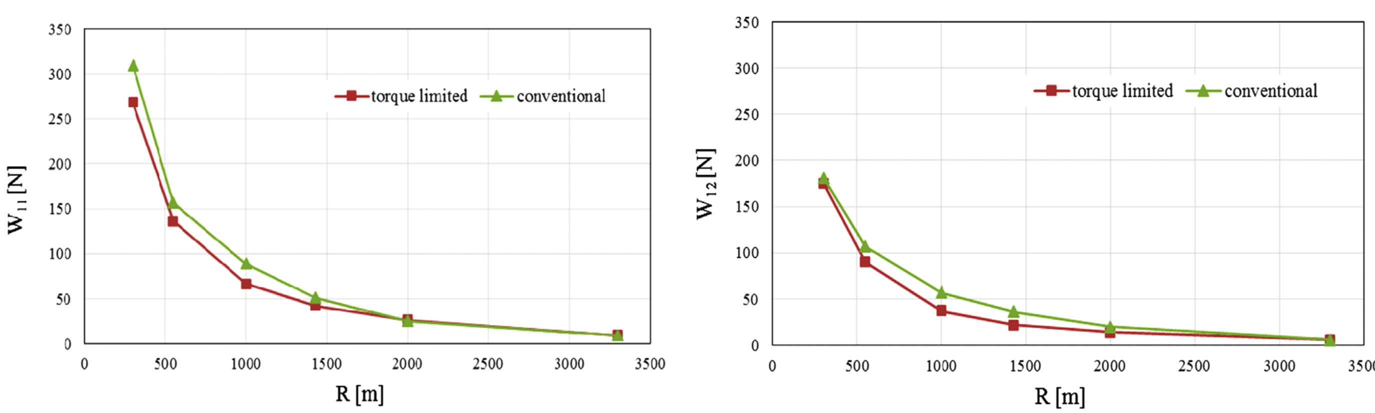

Fig. 8. Total wear number $W=T_x\gamma_x+T_y\gamma_y$ for the front wheels 11 and 12 of the ERRI wagon in the original configuration and with the torque limited to 4000 Nm.

The practical details of the design of the torque limiter lie outside the scope of this paper and are described in another paper [12].

6. Conclusions

The AIR wheelset is a promising design of a novel wheelset that has distinct advantages in maintenance and life cycle cost. The effect on contact mechanics parameters of a torque limiter applied to the AIR wheelset has been analyzed in this paper.

Starting from the analysis of the curving characteristics of the ERRI wagon library vehicle, the implications of the reduction of the longitudinal forces due to the application of a torque limiter set to a predetermined value has shown noticeable reduction of both wear and RCF damages in revenue service.

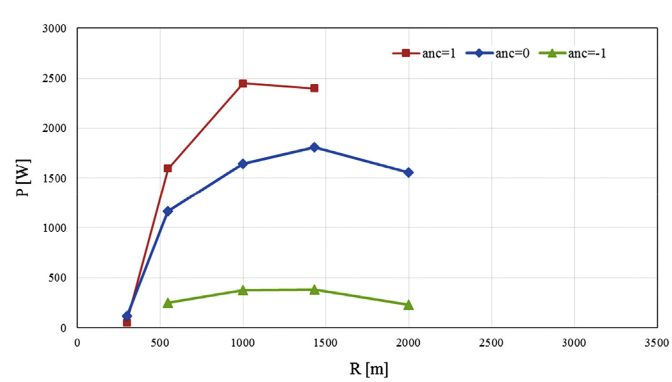

Fig. 9. Power dissipated in the front wheelset (torque limiter set to $M_{lim}=4000$ Nm) for different non-compensated acceleration (a_{nc}) conditions and $f=0.4$.

In particular, the torque limiter is particularly effective on the front wheelset reducing longitudinal forces on the outer wheel in mild curves where RCF defect usually appear; a similar and even more pronounced effect is shown on the inner wheel of the rear wheelset where longitudinal forces responsible for corrugation are reduced up to 90%.

The application of the torque limiters seem therefore a feasible and low-cost opportunity to reduce adverse wheel–rail contact mechanics effects in all operational situations.

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