Equivalent Conicity and Curve Radius Influence on Dynamical Performance of Unconventional Bogies. Comparison Analysis

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SUMMARY

In this paper the dynamic behaviour of several unconventional bogies is compared. The study takes into account the radius of the curve and the maximum level of wear allowed to the wheels. Ranges of conicities and curve radius in which each bogie is advantageous are studied, for both high-speed and urban transit vehicles. Simulations have been carried out using an in house software that makes it possible to solve the wheel-rail contact problem in 3D, and to simulate accurately the negotiation of very sharp curves.

1 INTRODUCTION

Unconventional bogies arise in order to improve curve negotiation of railway vehicles, forcing the wheelsets to adopt a radial position on curve. Several papers show the advantages of such bogies under certain conditions. The aim of this paper is to analyse and compare the curving behaviour of several unconventional bogies, taking into account the curve radius and the maximum level of wear allowed to the wheels. This condition is considered in this work using as a parameter the equivalent conicity of the wheels. As wheel profiles wear out, the equivalent conicity increases reducing dramatically the vehicle stability. It will be necessary in these cases to increase primary suspension stiffness in order to retrieve initial stability. Such stiffness increase, when necessary, has a negative influence on curving behaviour, and therefore an equivalent conicity should be included as a parameter affecting curving response.

Five different bogie configurations have been studied in this paper: A) Two-axle conventional bogie; B) Radial bogie, with elastic connections between wheelsets (Fig. 1 left); C) Conventional bogie in which axle boxes of the same side of the

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wheelsets are linked to an equalising bar articulated on bogie frame (Fig. 1 right). In this way, angles of attack of both wheelsets tend to be opposite and radial to the curve; D) and E) bogies are B and C bogies respectively with independently rotating wheels (IRW), only in the trailing axle [1]. Two different passenger services have been analyzed, High Speed and Urban Transit.

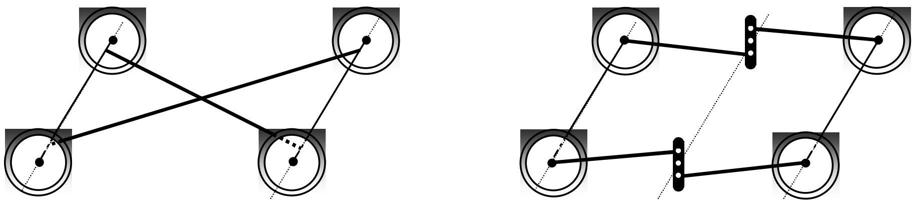

Fig. 1. On the left, radial bogie with elastic connections between the wheelsets (config. B) and on the right, bogie with longitudinal connections articulated on bogie frame (config. C).

An in house software [2] has been used to carry out all the necessary calculations. Three types of analysis can be made with this software: a) Stability linear analysis, obtaining critical speeds on straight track, b) Non-linear steady-state analysis on curves, obtaining equilibrium position, and c) Dynamic simulations, in which the non-linear equations of motion are numerically integrated.

The wheel-rail contact problem is solved in 3D. This allows taking into account the influence of the angle of attack on contact parameters, and in this way, it is possible to study the vehicle response when negotiating very sharp curves on urban transit (R<30m). Figure 2 shows three different results obtained for wear index of a bogie, when negotiating several curves, depending on the method of calculation chosen. It is very usual to obtain the wheel-rail contact point solving a 2D problem. In this way, the angle of attack is not taken into account, but it is assumed that its influence is very low. Another way to solve the problem is to linearize the wheel and rail profiles around the contact point, and estimate the influence that the angle of attack has on the location of this point. As seen in Figure 2, linear estimation gives excellent results for large and medium curve radii. However, differences with 3D analysis become more significant when very sharp curves are computed (approximately radius of 15 m). Regarding the 2D method, it is clear that is not valid if sharp curves of radius below 125 m. have to be studied.

In order to obtain creep forces, FASTSIM [3] algorithm has been used, both in quasiestatic and dynamic analysis. There are no simplifications regarding low angles or secondary accelerations in the formulation of the equations of motion and equilibrium.

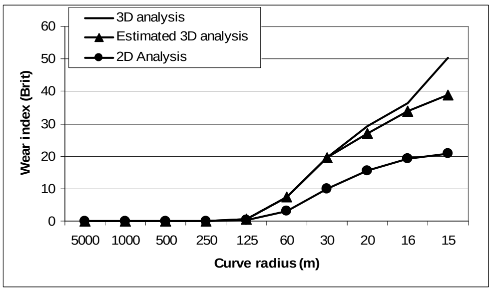

Fig. 2. Wear index differences depending on the type of method used to solve wheel-rail contact problem.

2 METHODOLOGY AND PARAMETERS DESCRIPTION

For each configuration, linearized stability analyses are computed, and primary suspension is optimized according to the conicity value adopted. Generally, the aim of the analysis is to determine a longitudinal stiffness as low as possible compatible with stability criteria and the conicity adopted each time. A low value of longitudinal stiffness allows the bogie to negotiate curves more easily, because each wheelset has more freedom to become radial to the curve.

Once the primary suspension is defined, an exhaustive curving performance is studied for each bogie configuration, each conicity and each curve radius. In order to compare the curving behaviour of the bogies and to determine which configuration is advantageous against the others, it is necessary to compute representative parameters of curve negotiation. In this paper, four different parameters have been considered:

a) Wear index: This is the most important index, due to its direct influence in costs of maintenance, safety and comfort levels. In this work, wear index is computed according to the expression [4]: $W=T*\gamma /A$ (N/m^2), where $T*\gamma$ is the scalar product of friction force and the creepage and A is the contact area. Another way to calculate wear index is according to [5] as $W=0.005\ T*\gamma$ for $T*\gamma < 160$ N and $W=0.025\ T*\gamma$ for $T*\gamma > 160$ N. Actually the results are very similar for both cases.

b) Lateral force distribution among wheelsets: When negotiating a curve, a total lateral force appears in each wheelset in order to balance the whole centrifugal force of the bogie. The optimum situation will occur when both lateral forces, the leading wheelset's one ($H\ell$) and the trailing wheelset's one (Ht) are balanced ($H\ell$-Ht=0). In this way, the maximum value will be the lowest possible, and the difference with Prud d'Homme limit will be maximum. Lateral forces difference let us estimate the level of aggression of the vehicle to the track.

c) Angle of attack: In general, as the curve radius becomes smaller, the angle of attack of the leading wheelset increases. This is unfavourable, since it increases the risk of derailment, the wear index and the acoustic emissions. It is intended to obtain as low a value as possible.

d) Risk of derailment: It is estimated using Nadal coefficient, Y/Q , evaluated in the outer wheel of the leading wheelset.

3 URBAN VEHICLES

3.1 Linearized analysis

In general, urban transit bogies reach maximum speeds of 80 Km/h, so it will be a necessary condition that the critical speed is above 80 Km/h, with a minimal damping ratio of 10%. Curve radii that can appear in this case are very small. The analysis has taken into account curve radii from 5000m to 15m. Conicities analysed vary from 0.05 (which simulates new wheel profiles) to 0.40 (which simulates extremely worn wheel profiles).

Once the vehicle model is linearized, stability analyses are made in order to obtain critical velocity for a wide range of siffnesses K_x (longitudinal primary suspension stiffness) and K_y (lateral primary suspension stiffness). The maximum stiffness value considered has been $2x10^7$ N/m in all cases. In this way, stability maps are calculated for each configuration and for each equivalent conicity studied. Through the analysis of these maps, it is intended to determine the optimum couple of K_x and K_y for a good curving behaviour, among all the possible values that achieve a critical speed higher than 80 Km/h. Table 1 summarizes the couples chosen for each bogie configuration and conicity.

Table 1. Chosen couples of longitudinal stiffness (K_x) and lateral stiffness (K_y) for each configuration and conicity value for urban service (N/m).

Conicity	Config. A	Config. B	Config. C	Config. D	Config. E
0.05	$1.1x10^6/2x10^7$	$7.3x10^5/5x10^5$	$7.5x10^5/2x10^7$	$9x10^6/1x10^6$	$3x10^6/1x10^7$
0.10	$1.7x10^6/2x10^7$	$1.1x10^6/5x10^5$	$1.2x10^6/2x10^7$	$1x10^7/1x10^5$	$3x10^6/1x10^7$
0.15	$2.3x10^6/2x10^7$	$1.4x10^6/4x10^5$	$1.6x10^6/2x10^7$	$2x10^7/1x10^5$	$3x10^6/1x10^7$
0.20	$2.9x10^6/2x10^7$	$1.6x10^6/4x10^5$	$1.9x10^6/2x10^7$	$2x10^7/2x10^5$	$3x10^6/1x10^7$
0.25	$3.4x10^6/2x10^7$	$1.9x10^6/4x10^5$	$2.3x10^6/2x10^7$	$2x10^7/2x10^5$	$3x10^6/1x10^7$
0.30	$4x10^6/2x10^7$	$2.0x10^6/6x10^5$	$2.6x10^6/2x10^7$	$2x10^7/2x10^5$	$3x10^6/1x10^7$
0.35	$4.5x10^6/2x10^7$	$2.3x10^6/1x10^6$	$2.9x10^6/2x10^7$	$2x10^7/2x10^5$	$3x10^6/1x10^7$
0.40	$5.1x10^6/2x10^7$	$2.4x10^6/8x10^5$	$2.9x10^6/2x10^7$	$2x10^7/2x10^5$	$3x10^6/1x10^7$

In the case of a conventional bogie designed for an equivalent conicity of 0.05, and negotiating a curve with a radius of 30 m, the curving behaviour according to the lateral stiffness K_y for three parameters: wear index, angle of attack and risk of derailment are represented in Figure 3b. Each K_y value has its corresponding K_x value that provide the required critical speed of 80 Km/h (Fig. 3a). In config. A, B and C, as seen in Fig. 3b, the lower K_x (larger K_y), the better curving performance.

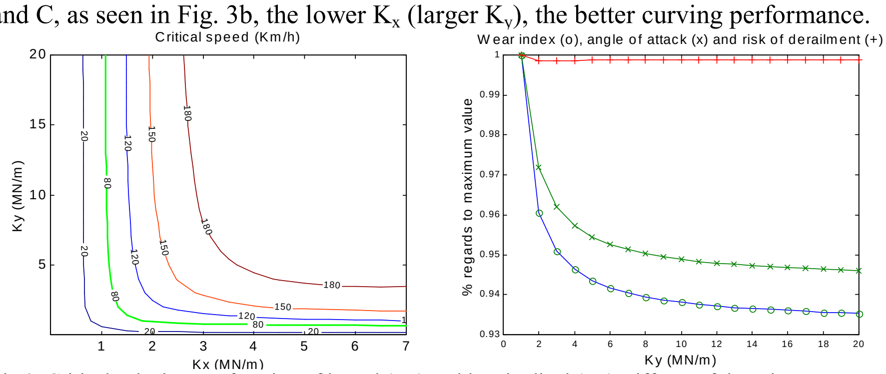

Fig 3. Critical velocity as a function of lateral (Ky) and longitudinal (Kx) stiffness of the primary suspension of an urban conventional bogie with 0.05 equivalent conicity (left), and influence that chosen stiffnesses have on curving behaviour for the same vehicle (right).

Regards to config. D, analysing the curving performance for a representative curve radius and for several values of K_x and K_y, one can see that, on the contrary, wear index and the other parameters decrease very lightly as K_x increases (Fig. 4). The differences are only about 6%. Then, the couples of stiffnesses values are chosen in order to have a good stability, and if possible a high K_x value at the same time, as K_y hardly has influence. Config. E shows a similar behaviour, again with very small differences, and couples of K_x and K_y will be chosen mainly in order to increase stability.

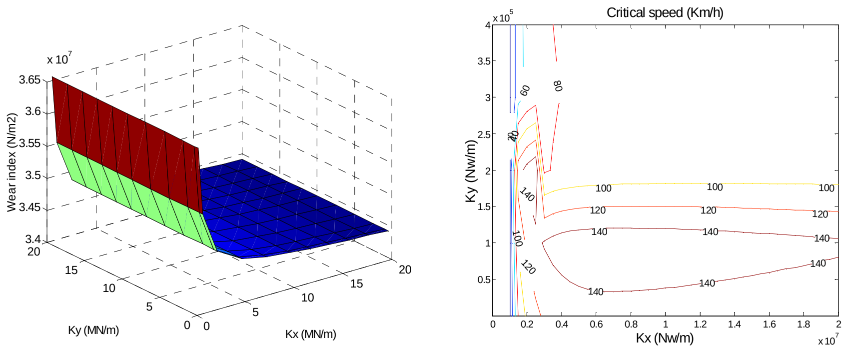

Fig 4. Wear index (N/m^2) according to the primary suspension stiffness of config. D in a 30 m. radius curve (left) and stability map (right) for an equivalent conicity of 0.10.

3.2 Curve steady-state analysis

At this point, the curving performance of all the vehicle configurations described has to be studied, for a wide range of curve radius and conicities. Once all the primary suspension values are determined for each configuration and conicity, steady-state analyses are computed with curve radii from 5000 to 15m.

The best bogie configurations depending on curve radius and conicity are represented in the following pictures, regarding wear index (Fig 5a) and risk of derailment (Fig 5b). Graphs regarding H/Ht and angle of attack are similar to Figure 5a. It is clear that if a conventional bogie is designed with an optimized primary suspension, its performance when low conicities and not very sharp curves are analysed is not only as good as unconventional's ones, but even much better (curve radius of 150 m approximately), as proved in [6]. Only if the risk of derailment is studied, config. B is the best option in this area, nevertheless the differences being little significant.

Config B also arises as the best option in wear index when curve radius becomes lower than 150 m, specially with high conicities. With extremely small radii, config. D appears as the advantageous option for all type of conicities. It can be seen that in urban service, there are no significant areas where config. C is the best option. On the other hand, config. E only shows improvement in large curves, and if the wheels are allowed to wear out much.

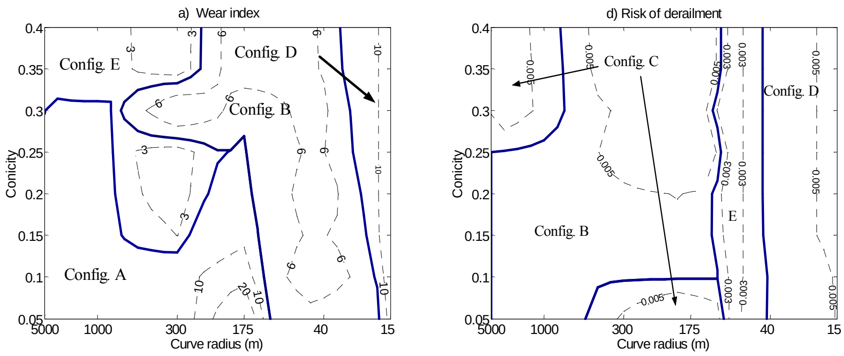

Fig 5. Best bogie configuration according to a) wear index (N/m^2 x 10^5) and b) risk of derailment. Dotted lines show the improvement between the best configuration and the second best configuration in absolute value for both cases.

Figures 6 and 7 show a more specific analysis of configurations B and D, comparing them directly to the conventional bogie. They show the ranges of curve radii and conicities in which their response is better than conventional bogie's one. As said, radial bogies improve curve response in sharp curves, and it can be observed with regards to wear index that config. B is advantageous in a larger area than config. D, but when radii are large config. D behaviour is better, more clearly shown by H/Ht graphs. For this reason, both of them can be a good option if very sharp curves are likely to appear in the railway line.

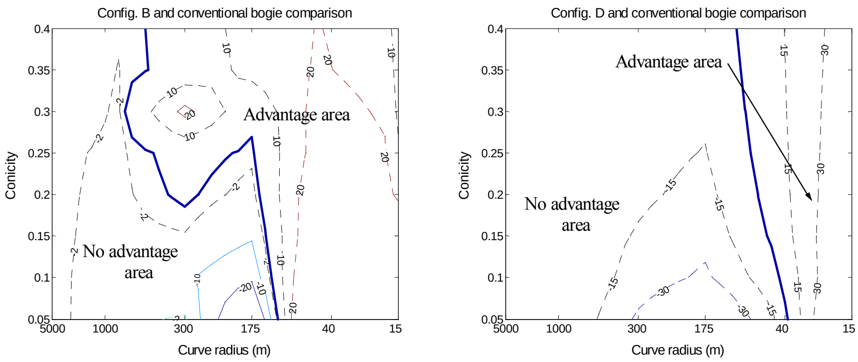

Fig. 6. Differences in wear index of config. A and config. B (left) and config A and config. D (right) in $N/m^2 \times 10^5$. Dotted lines show the difference in absolute value.

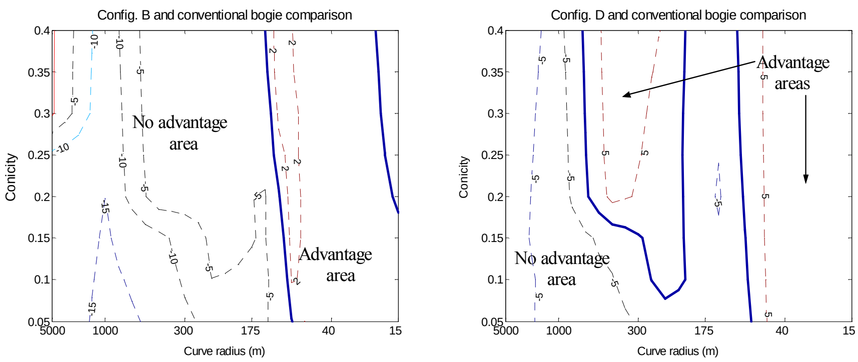

Fig. 7. Differences in lateral forces distribution of config. A and config. B (left) and config A and config. D (right) in KN. Dotted lines show the difference in absolute value.

4 HIGH-SPEED VEHICLES

4.1 Linearized analysis

High-speed bogies reach maximum speeds between 200 and 350 Km/h, so it will be necessary to achieve a critical speed of at least 350 Km/h with a damping ratio of 0%, because anti-yaw dampers are usually installed, improving stability. In this case curve radii are generally very large, of approximately 3000 m., although at some points of the railway line radii could be smaller, being necessary to negotiate them at lower speeds. The analysis has taken into account conicities from 0.05 (new wheel profiles) to 0.35 (worn wheel profiles), and curve radii from 5000 m. to 180 m.

In the same way as shown in urban vehicles, Table 2 summarizes the chosen couples K_x/K_y for each case.

Table 1. Chosen couples of longitudinal stiffness (K_x) and lateral stiffness (K_y) for each configuration and conicity value for high-speed service (N/m).

Conicity	Config. A	Config. B	Config. C	Config. D	Config. E
0.05	$2.1x10^6/2x10^7$	$1.2x10^6/2x10^6$	$1.1x10^6/1x10^6$	---	$1.5x10^6/2x10^7$
0.10	$3.8x10^6/2x10^7$	$2.0x10^6/1x10^6$	$1.4x10^6/1x10^6$	---	$1.0x10^6/1x10^7$
0.15	$4.0x10^6/2x10^7$	$2.7x10^6/1x10^6$	$1.8x10^6/2x10^6$	$4.0x10^6/1x10^6$	$1.3x10^6/1x10^7$
0.20	$6.4x10^7/2x10^7$	$3.2x10^6/2.5x10^6$	$2.7x10^6/2x10^6$	$2.5x10^6/2x10^6$	$1.5x10^6/8x10^6$
0.25	$7.0x10^7/2x10^7$	$3.6x10^6/3.5x10^6$	$3.0x10^6/2x10^6$	$3.5x10^6/2.5x10^6$	$1.8x10^6/6x10^6$
0.30	$8.0x10^7/2x10^7$	$4.1x10^6/4x10^6$	$3.3x10^6/2x10^6$	$4.0x10^6/3x10^6$	$2.1x10^6/6x10^6$
0.35	$9.0x10^7/2x10^7$	$4.5x10^6/4x10^6$	$3.5x10^6/2x10^6$	$5.0x10^6/5x10^6$	$2.3x10^6/2x10^6$

Config. D is not able to achieve a critical speed of 350 Km/h for low conicities, disregarding it for subsequent studies. Stiffnesses selected for config. E reaches values up to 1000 Km/h, proving to be a very stable vehicle on straight track. For A, B and C configurations, a critical speed of 350 Km/h is obtained with a damping ratio of 0%.

4.2 Curve steady-state analysis

Figure 8 shows vehicle responses in terms of wear index and angle of attack against curve radius, for the case of a 0.05 conicity. Config. C minimizes these parameters for a wide range of curve radii, while config. E shows a very deficient response in sharp curves. For this reason, config. E will also be disregarded unless there are only large curves in the railway line.

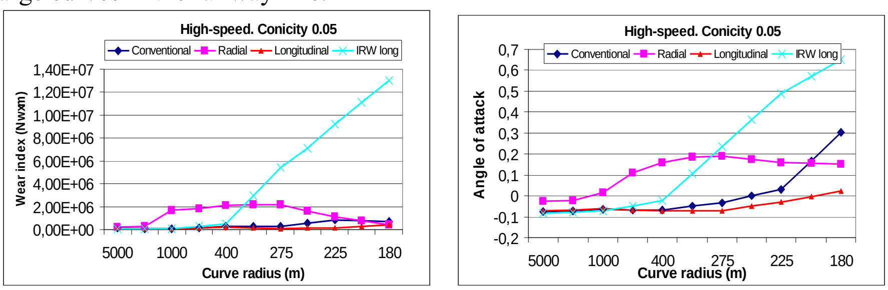

Fig. 8. Wear index (left) and angle of attack (right) versus curve radius, according to four of the analysed bogie configurations (conicity 0.05).

The following graphs show which bogie configurations (A, B or C) is the most advantageous in terms of wear index (Fig. 9a) and lateral forces distribution (Fig. 9b). Differences between configurations in terms of risk of derailment and angle of attack are not significant. Config. E, initially disregarded for its bad behaviour in medium and sharp curves, however shows excellent results in the distribution of lateral forces when large curves are negotiated.

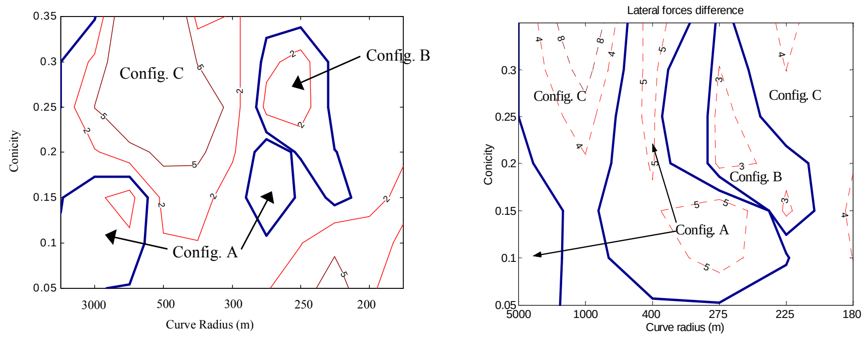

Fig. 9. Best bogie configuration according to a) wear index (N/m^2 x 10^5), and b) lateral forces distribution (KN). Dotted lines show the improvement between the best configuration and the second best configuration in absolute value.

It can be seen in these figures that conventional bogie is good enough when curves have large radius and wheel profiles are not allowed to wear in excess. In other cases, config. C arises as the best option. Regarding the H/Ht parameter, conventional bogies are also advantageous in curves of medium radius, while config. C is still the best option for a wide range of radii, specially with high conicities.

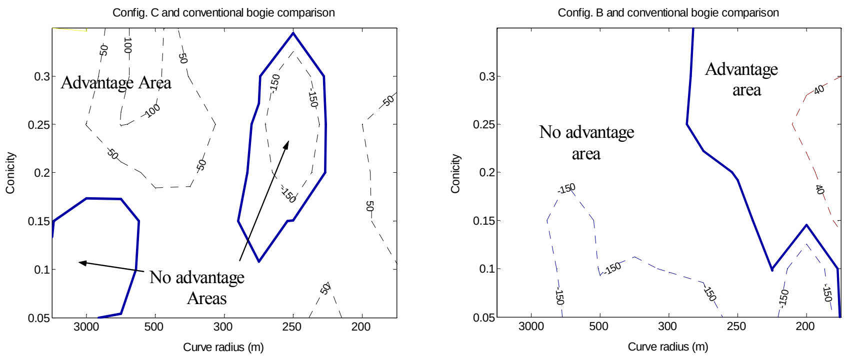

Fig. 10. Differences in wear index of config. A and config. C (left) and config A and config. B (right) in N/m^2 x 10^4. Dotted lines show the difference in absolute value.

Figure 10 shows the improvement obtained with config. C (Fig. 10a) and config. B (Fig. 10b) in comparison to the conventional bogie, in terms of wear index. It can be seen that config. C is to be preferred for a wide range of conicities and curve radii, being the improvement more important if high conicities and large curves are considered. On the other hand, it can be observed that configuration B is advantageous in sharp curves in comparison with the conventional bogie, specially with high conicities. When conicities are small (wheel profiles not worn), config. B hardly shows advantageous areas. Moreover, for a wide range of curve radii, not very small (larger than approximately 300 m), its behaviour is much worse than the conventional bogie's one. For this reason, the election must be between conventional and config. C bogies.

5 CONCLUSIONS

In the analysis presented in this paper, it can be concluded that a conventional bogie adequately optimized is good enough or even better than unconventional bogies, when the curve radii are not very short, and the wear level of the wheels profiles is not high. This is more significant in urban service rather than in high-speed vehicles. Nevertheless, if urban vehicles are to negotiate very sharp curves, radial bogies B and D are to be preferred. When high-speed vehicles are analysed, config. C offers a good curving performance for a wide range of conditions. Advantages compared to the conventional bogie are more significant if high conicities or small curve radius are simulated. Config. B does not improve in general conventional bogie response, and when conicity is small, its performance is significantly worse.

6 ACKNOWLEDGEMENTS

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