Development of Operations of Tilting Train on Italian Network

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Summary
Investigation about the increasing of cant deficiency for tilting trains on Italian Network. Main results of the tests with the ETR470-0 train for an acceptance at 306 mm cant deficiency.

Abstract
The large experience with tilting train and the good dynamic behaviour of the Italian solutions encourages FS in developing a new programme of increasing the commercial speed on some main lines and regional lines. FS considers also the possibility of increasing the cant deficiency up to 306 mm.

Until now a fleet of 15 ETR450 tilting trains and 22 ETR460/480 tilting trains has yet run 70 millions of kilometres in commercial service on conventional lines up to a cant deficiency of 275 mm. Furthermore 9 CISALPINO ETR470 tilting trains assure a commercial service since September 1996 between Firenze-Milano and Switzerland-Germany at a cant deficiency of 275 mm and 3 ETR460P tilting trains assure a commercial service since June 1998 between Milano and Lyon, at a cant deficiency of 260 mm on French line.

After the acceptance tests of the ETR460 and ETR470 according to the basic principles of the first project of UIC 518 Code a large campaign of tests was carried out with ETR460P on French Network for acceptance at cant deficiencies both of 260 and of 280 mm. As the results were far from the safety limit values also at a cant deficiency of 280 mm, SNCF started the commercial service at a cant deficiency of 260 mm. Main results are presented.

Then, on June 1999, a large campaign of tests was carried out on FS network. The tests aimed to increase the tilting speed in the Battipaglia-Reggio Calabria main line consequently to the removing of some limitation due to the infrastructure (signalling, catenary and switches not allowing the new increased speed). At the same time a verification of the track/train system at 306 mm cant deficiency was completed. An artificial worn wheel profile was used. This last set of tests has proved some critic aspects of the train/track system regarding to the aptitude to run at 306 mm cant deficiency: Prudhomme limit, lateral force balancing between the two wheels of the same bogie, wheel profile and contact geometry, track geometric quality. A comparison with the previous results at 275 mm and 280 mm cant deficiency let us point out that an optimisation and preservation of wheel profile and preservation of the required standards for track geometric quality is necessary to respect the Prudhomme limit at 306 mm cant deficiency.

A further investigation was performed by means of a mathematical model simulating the behaviour of the vehicle in curve. The numerical results obtained are in good accordance with the experimental ones and confirm the interpretation proposed for the measurements.

The paper is completed by a discussion about the travel time reduction between 306 mm and 275 mm cant deficiency in the Battipaglia-Reggio Calabria main line and some results of a study purposed to increase the line speed by adopting tilting trains on some regional lines.

Keyword: Tilting trains, Cant deficiency, Wheel-rail forces, Wheel profile and contact geometry, Track geometric quality.
1. INTRODUCTION

A first idea to increase the speed of a railways vehicle in curve counterbalancing a part of the passenger’s lateral acceleration by tilting the car body on the internal side of the curve itself was presented by FS at a conference on 1965 in Genoa. The goal was to increase the line speed without expensive intervention in the existing infrastructure.

The development of the design of a tilting carbody technology was commissioned by FS to FIAT FERROVIARIA the following year. The car body tilting should give at higher speed in curve a passenger comfort better than conventional train at lower speed.

After laboratory tests on test beds the Italian experience passed through a first not engineered prototype ETRY0160 and the prototype train ETR401. The last one was put in commercial service between Roma and Ancona on 1976. Since the beginning a lateral active suspension system was considered and adopted. The aim of this one was to reduce the dynamic contribution in the lateral forces between wheels and rail due to the higher lateral acceleration in curve. The ETR 401 after the initial period was withdrawn from operation and used only in several tests in Italy and abroad.

The design of ETR401 was resumed at the end of 1985 with some arrangements as ETR450 trains that was put in commercial service from June 1988 between Milano and Roma allowing a significant travel time reduction by high speed in the open part of Direttissima line (250 km/h) and by increasing the line speed in the tortuous parts of the conventional lines. The maximum tilt angle of ETR450 carbody is 10°, but only a compensation of 8° is used. The maximum cant deficiency in commercial service is 275 mm.
(uncompensated acceleration at track level 1.80 m/s²) and the residual lateral acceleration for the passengers, considering the roll coefficient of the suspension, is about 0.7 m/s².

A fleet of 15 ETR450 allowed particularly high speed in the Italian network but an extended operation of the tilting technology was possible starting on 1995, when 7 new generation trainsets ETR460 was put into commercial service. The maximum tilt angle of the ETR460 carbody is 8°, and the maximum cant deficiency in commercial service is 275 mm as ETR450. The maximum 8° tilt angle allows to increase the width of the ETR460 carbody as regards to ETR450. The new generation was completed in 1996 with 3 two-voltage ETR460P for a commercial service between Italy and France, with 9 two-voltage ETR470 CISALPINO trainsets for commercial service between Italy and Switzerland and, in 1998, with 15 3 kV ETR480 trainsets for domestic routes. The tilting speed was then extended to several routes.

Up to now the Italian tilting train’s fleet, including the CISALPINO tilting trains, consists in 48 sets, and the extent of the routes concerned by tilting speed is about 4000 km. More than 70 millions of kilometres are covered by the Italian tilting trains.

2. TRAINSETS MAIN FEATURES

The Italian tilting trains are manufactured by FIAT FERROVIARIA, and the basic choice is distributed power EMU’s.

The ETR450 set is 8 motored cars and 1 trailer, located in the set’s middle. This solution allows a low axle load: 13 tonnes.

The second generation of tilting trains ETR460/ETR470/ETR480 adopts always the distributed power, but each set consists of nine cars, divided into three traction units, each one formed by two motored cars and one trailer car. The maximum axle load is 12.5 tonnes for trailer cars and 14.5 tonnes for motored cars.

The main features of ETR460/ETR480 are listed in table 1.

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<tr>
<th>Technical Data</th>
<th>Unit</th>
<th>BAC motored</th>
<th>BB, BA motored</th>
<th>RA, RB, RH trailer</th>
<th>Train Set</th>
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<td>Length over buffer</td>
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<td>26.75</td>
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<td>[m]</td>
<td>19</td>
<td>19</td>
<td>19</td>
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<tr>
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<td>FIAT 72412/3</td>
<td>FIAT 72414</td>
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<tr>
<td>Bogie wheel base</td>
<td>[m]</td>
<td>2.70</td>
<td>2.70</td>
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<td>----</td>
</tr>
<tr>
<td>Torque couple body-bogie</td>
<td>kNm/°</td>
<td>4.79 (R.O.)</td>
<td>4.61 (N.L.)</td>
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</tr>
<tr>
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<tr>
<td>Bogie masse</td>
<td>[t]</td>
<td>7.785</td>
<td>7.530</td>
<td>7.335</td>
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<td>[mm]</td>
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<td>[°]</td>
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<td>2 (car body suspended)</td>
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<td>Wheel profile</td>
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<td></td>
<td>ORE S 1002</td>
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Table 1 – Main features of ETR460/ETR480
3. ON TRACK TESTS

After the acceptance tests of the ETR460 and ETR470 according to the basic principles of the first project of UIC 518 Code a large campaign of tests was carried out with ETR460P on French Network for acceptance at operating limit speed \( V_{\text{lim}} = 200 \text{ km/h} \) and two permissible cant deficiency \( I_{\text{adm}} = 260 \text{ mm} \) and \( I_{\text{adm}} = 280 \text{ mm} \) (respectively uncompensated acceleration at track level 1.70 m/s² and 1.83 m/s²). The test condition comply by far the general requirements of UIC 518 Code and the collected results were meaningfully representative of the running parameters. Test acceptance was conducted with a naturally worn in service wheel profile, representative of mean profile of the fleet of ETR460 trains. As the results were far from the safety limit values also at a cant deficiency of 280 mm, the ETR460P was admitted on French network at a cant deficiency of 260 mm since may 1998.

Meanwhile was increasing the adoption of the tilting technology in Europe and in the World so a far-reaching discussion begun in UIC to harmonise the running conditions and the test acceptance criteria. This discussion is still opened and one of the dialled points is the reference value of the cant deficiency. The general opinion seems to converge at \( I_{\text{adm}} = 300 \text{ mm} \) (uncompensated acceleration at track level 1.96 m/s²) when and where the safety and comfort criteria are complied.

In this scenery the FS Infrastructure Manager asked to verify the possibility of increasing the cant deficiency on FS network. The opportunity was offered by the tests required to increase the tilting speed in Battipaglia-Reggio Calabria main line. The increasing of tilting speed was taken into consideration according to the removing of some limitations due to the infrastructure (signalling, catenary and switches not allowing the new increased speed). The tests were carried out using the FIAT tilting train ETR470-0, prototype of CISALPINO, and with the same dynamic characteristics of ETR460 and ETR480 train. To reach extremely severe conditions an artificial worn wheel profile was used for the bogie fitted with measurement equipment. As running parameter an operating limit speed \( V_{\text{lim}} = 200 \text{ km/h} \) and two permissible cant deficiency \( I_{\text{adm}} = 275 \text{ mm} \) and \( I_{\text{adm}} = 306 \text{ mm} \) (respectively uncompensated acceleration at track level 1.80 m/s² and 2.00 m/s²) was considered.

This last campaign of tests pointed out some critic aspects of the train/track system regarding the aptitude to run at 306 mm cant deficiency. The Prudhomme limit was exceeded in the zone with large radius curve.

To better understand the behaviour of ETR470-0 a comparison of test conditions and main results between the last one and the previous campaign of test is necessary.

A first look to the wheel profile is important In figure 1a the wheel profiles used in the two campaigns of test are shown coupled with theoretical UIC60 rail profile, while the characteristics of the same wheel profiles coupled with a rail UIC60 worn profile are shown in figure 1b. The actual rail profiles wasn’t available, so worn rail profiles was measured on similar line. Particularly the \( r_1-r_2 = f(y) \) characteristics may be a decisive factor in the steering of the wheelsets and of the bogies. The higher \( r_1-r_2 = f(y) \) characteristics of the worn artificial profile may turn out the ETR470-0 bogie more steering than the ETR460 bogie with natural worn profile.
Figure 1a – S1002 theoretical wheel profile and ETR460/ETR470 worn wheel profiles coupled with UIC60 theoretical rail: Characteristics $r_1-r_2 = f(y)$ and $\tan \gamma_e = f(y)$
Figure 1b – S1002 theoretical wheel profile and ETR460/ETR470 worn wheel profiles coupled with UIC60 worn rail: Characteristics $r_1 - r_2 = f(y)$ and $\tan \gamma = f(y)$

Now a look to the graphs summarising the “line” track geometric quality and the results for the safety quantities for the tests ETR460 on SNCF lines (figures 2a and 2b) and for ETR470-0 on FS lines (figure 3a and 3b). The “line” track geometric quality graphs mean the actual distribution as % of recommended distribution, according to Appendix D of UIC 518 Code. The $\Sigma Y$ and $Y/Q$ safety quantities are computed according to UIC 518 Code and means the computed values as % of limit value. The mean value of safety quantities means the mean of the statistical quantities $x(F_1)$ or $x(F_2)$, grouped in the test zone, $F_1$ and $F_2$ being the centiles corresponding to the statistical quantities for frequencies $F_1 = 0.15\%$ and $F_2 = 99.85\%$ of these distribution functions, according to UIC 518 Code.

Figure 2a - ETR460 Tests on SNCF Lines - Zone with large-radius curve
Graphs summarising “Line” and “Safety” Assessment Quantities
The results for ETR460 with natural worn profile on SNCF lines show the safety computed values far to the limit. In small-radius curve $250m \leq R < 400m$ for a permissible cant deficiency $I_{adm} = 280$ mm the margin of safety is reduced due to the “line” quality that is worse than the recommended by UIC518 Code for the new increased speed.

Figure 2b - ETR460 tests on SNCF lines - Zone with small-radius curve
Graphs summarising “Line” and “Safety” Assessment Quantities

Figure 3a – ETR470-0 tests on FS lines - Zone with large-radius curve
Graphs summarising “Line” and “Safety” Assessment Quantities
The results for ETR470-0 with artificial profile on FS lines show the safety computed values are generally close to the limit or over. In the zone with large radius curve $900 \, \text{m} < R$ the “line” is a little better than recommended, but the $\Sigma Y_2$ is close to the limit due to the steering effects of the wheel profile. In the zone with large radius curve $600 \, \text{m} < R \leq 900 \, \text{m}$ the “line” is worse than recommended by UIC518 Code for the new increased speed and the $\Sigma Y_2$ is over the limit. In the zone with small radius curve $400 \, \text{m} \leq R \leq 600 \, \text{m}$ the “line” is about as recommended and the $\Sigma Y_2$ is quite far to the limit. In the zone with small radius curve $250 \, \text{m} \leq R < 400 \, \text{m}$ the “line” is worse than recommended by UIC518 Code for the new increased speed and the $\Sigma Y_1$ is close to the limit for a permissible cant deficiency $I_{\text{adm}} = 306 \, \text{mm}$.

The increasing of $\Sigma Y$ appears generally weighty linked to the increasing of the “line” conditions.

To better understand the behaviour of the bogies the distribution of $\Sigma Y_{\text{qst}}$ forces as function of cant deficiency on the axles of the front bogie are shown in the graphs of figure 4 for ETR460 tests and of figure 5 for the ETR470-0 tests.
In Figure 4 the distribution of $\Sigma Y_{qst}$ forces shows the front bogie of ETR460-28 in SNCF lines oversteered in the zone with large-radius curve 900 m < $R$, whereas in the zone with small-radius curve is about tangent for 400 m ≤ $R$ ≤ 600 m and understeered for 250 m ≤ $R$ < 400 m.

Figure 5 – ETR470-0 tests on FS lines distribution of $\Sigma Y$ forces on the axles of the front bogie.
In figure 5 the distribution of $\Sigma Y_{qst}$ forces shows the front bogie of ETR470-0 in FS lines oversteered in the zone with large-radius curve for $900 \text{ m} < R$ and more for $600 \text{ m} < R \leq 900 \text{ m}$, whereas in the zone with small-radius curve is quite oversteered for $400 \text{ m} \leq R \leq 600 \text{ m}$ and about tangent for $250 \text{ m} \leq R < 400 \text{ m}$.

The curve radius for which the ETR470-0 front bogie is oversteered is lower than in the case of ETR460-28 front bogie. Due to the fact that the ETR460-28 and the ETR470-0 have the same type of bogie this result is mainly caused by the different wheel profile (see figure 1).

The steering effect of the wheel profile determine in the ETR470-0 the $\Sigma Y_2$ close to the limit for $900 \text{ m} < R$.

The combined effects of the “line”, worse than the recommended by UIC518 Code for the new increased speed, and the steering effects of the wheel profile determine in the ETR470-0 the $\Sigma Y_2$ over to the limit for $600 \text{ m} < R \leq 900 \text{ m}$.

An investigation on the steering effects of the wheel profiles and further consideration are carried out in the next section.

**4. NUMERICAL SIMULATIONS**

A mathematical model of an ETR470 train running along a curved track was used to obtain a better comprehension of the steering effect evidenced in the measurements. The model was developed at Politecnico di Milano [6] and, as the result of previous researches, it was thoroughly validated by comparison with line measurements [7].

The mathematical model includes a full schematisation of the vehicle, including carbody, bogies and wheelsets (see figure 6). A rigid body model is adopted for the carbody and the bogies, while for the wheelsets at least the effect of torsional deformability is considered, besides the effect of rigid motion. Primary and secondary suspensions are modelled by means of linear and non-linear elastic and damping devices.

As to the description of wheel-rail contact, the most important part of the model, a multi-elliptic approach is used, allowing to treat the presence of multiple contacts between one single wheel and the rail. The model can also include track deformability, using a finite element model for the track, which includes the
rails, sleepers and ballast deformability reproduced by equivalent springs. Nevertheless, in the simulations presented in this section, a rigid track model was assumed.

Figure 7 – Results of the numerical simulation: steady state values of values of $\Sigma Y$ forces on the two axles of front and rear bogie and $Y_{1e}$ force on the leading axle of the front bogie for cant deficiency of 336.6 and for different values of curve radius and for different wheel profiles.
The simulations presented in this section concern the behaviour of the vehicle in full curve, for different values of curve radius. In each simulation, the running of the vehicle into a curve of specified radius is studied, and the forward speed of the vehicle is changed from one case to the other in order to keep a constant value of 336.6 mm cant deficiency. After the vehicle has traversed the entry spiral, the simulation is continued for some seconds, until a steady state condition is reached, and finally the steady state value of the total lateral forces are reported as function of curve radius. Figure 7 reports the $\Sigma Y$ forces on the four axles and the $Y_{1e}$ force (guiding force on the outer wheel of the first axle).

Some observations can be made, which are directly related to the experimental findings reported in the previous section:

- very different values of lateral forces take place depending on the radius of the curve, though the sum of the forces on the two axles of each bogie is the same for all simulations, as cant deficiency is kept constant;
- a different behaviour can be observed for the two bogies: as to the front one, the $\Sigma Y$ force is higher on the leading wheelset for small curve radius, and is higher on the trailing axle for $R>400$ m; on the rear bogie the $\Sigma Y$ force is always greater for the trailing wheelset;
- finally, different values of contact forces are obtained as function of the wheel profile; this fact was expected as a consequence of the different steering effect of the profiles considered.

These points will be discussed in detail below.

During curve negotiation, the leading wheelset moves outwards, and flanging contact occurs on its outer wheel (see figure 8). As a consequence of the increase in the rolling radius due to flange contact, a longitudinal creep force in forward direction takes place on the outer wheel and, for the torsional force balance of the wheelset (supposed not subjected to braking or tractive couples) a corresponding force pointing backwards appears on the inner wheel. These two longitudinal forces generate, as shown by figure 8, the steering effect mentioned in the previous section.

It is clear from these figures, that due to the yawing force balance of the bogie, the steering couple will cause a different value of the lateral forces on the two axles, the force on the trailing axle being the largest one. On the front bogie, the steering effect due to the longitudinal forces is counteracted by the elastic moment generated by the secondary suspensions, as a consequence of bogie yaw rotation with respect to the carbody. On the rear bogie, the elastic moment has opposite direction, and therefore tends to increase the difference between the $\Sigma Y$ forces on the two axles.

It is clear that this non-uniform distribution of lateral forces is unfavourable for the vehicle, because what is relevant for the purpose of Prudhomme limit verification is the largest force taking place on the different axles, and therefore the most favourable situation is that the total centrifugal force acting on the vehicle be subdivided into equal components on the four axles.

Nevertheless, the bogie shows a different curving behaviour when travelling in curves of different radius, and therefore the steering effect can be more or less pronounced. In curves with small radius, the leading wheelset has a large angle of attack (figure 8), causing high values of lateral creep forces on the two wheels. Therefore, being the total tangential contact force limited by friction, the amplitude of the longitudinal “steering” force is relatively small. In the same time, the trailing wheelset travels almost centred on track centreline, so that the rolling radius variation on its wheels is small and cannot compensate for the different distance travelled by the two wheels. Consequently, longitudinal forces pointing in the opposite direction than those on the leading wheelset appear: these give a “countersteering” effect, which tends to balance the $\Sigma Y$ force.

For larger radius curves, the angle of attack is small and the steering moment on the leading wheelset is more pronounced; moreover, also the trailing wheelset moves outwards and generates a steering couple, though smaller than on the leading axle. This explains why the steering effect has a greater influence for curves with large radius, as reported in section 3.

Concerning the results obtained for the guidance force on the first axle $Y_{1e}$, the lower diagram in figure 7 shows that this force component is higher for small radii of the curve. In fact in this condition, due to the
high angle of attack of the first axle (see figure 8), the lateral creep forces are large and point outwards the
curve. Consequently, a large flange force is required to ensure the equilibrium of the wheelset in lateral
direction.

Finally, some considerations about the effect of wheel profile. As shown by figure 7, as the amount of
wheel profile wear increases, the steering effect becomes more important. This happens because the
rolling radius variation on the outer wheel becomes greater, as shown by the \( r_1 - r_2 = f(y) \) diagram reported
in figure 1b. In particular, the artificially worn profile used in the tests on the Battipaglia-Reggio Calabria
line shows the largest steering effect, which is much more pronounced than for a new wheel profile.

This means that lower values of safety coefficients could be obtained in the line tests if different, less
worn profiles were used instead than the artificially worn ones. This conclusion should anyway be
considered as only qualitative, because many unknown factors like wheel-rail adhesion coefficient, track
geometry and irregularities have a big influence on the results of the tests. Moreover, also the profile of
the rails has a great importance: in this case the rail profiles of the line were not known, and therefore
worn rail profiles measured on a similar line were used instead.

As to the effect of wheel profiles on the \( Y_{le} \) guiding force, the steering effect slightly reduces this force
component and therefore the guidance force on the first axle \( Y_{le} \) is higher for the new profile than for the
worn ones.

Front bogie, small radius curve     Rear bogie, small radius curve

Front bogie, large radius curve     Rear bogie, large radius curve

Figure 8 – Steady state curving forces on front and rear bogies, for different values of curve radius
Figures 9 and 10 report the results of the simulations performed considering different values of cant deficiency. The trends obtained in these graphs are in good accordance with the corresponding ones obtained in line tests, reported in figure 4. It can be observed that the value of lateral forces grows almost linearly with the cant deficiency.

For large values of curve radius (R=900 m) the force in the trailing wheelset is always greater than on the leading one, and also the gradient of the force with respect to the cant deficiency (graphically, the “slope” of the line) is greater for the trailing wheelset. This trend is in very good accordance with the one shown in figure 4 for the curves with large radius (R > 900 m).

On the contrary, for the radius of 300 m (figure 10) the leading axle shows the higher values of $\Sigma Y$ force. The trend with cant deficiency corresponds well to the experimental results shown in figure 4 for small radius curves (250 < R < 400 m).
Figure 9 – Results of the numerical simulation: steady state values of $\Sigma Y$ forces on the two axles of front and rear bogie and $Y_{1e}$ force on the leading axle of the front bogie for curve radius of 900 m and for different values of cant deficiency.
Figure 10 – Results of the numerical simulation: steady state values of $\Sigma Y$ forces on the two axles of front and rear bogie and $Y_{1e}$ force on the leading axle of the front bogie for curve radius of 300 m and for different values of cant deficiency.
5. DEVELOPMENT OF OPERATION

As mentioned in the Chapter 1, a significant increasing of the operation of tilting technology started on 1995 with the introduction in commercial service of the ETR460, followed by ETR460P, ETR470 CISALPINO and ETR480. After Milano-Roma-Napoli and Roma-Bari main lines the tilting speed was extended in order to reduce journey times in several routes. At the present the Italian tilting trains’ fleet, including the CISALPINO, consists in 48 trainsets. The extent of domestic routes concerned by tilting speed is 3816 km, see map in Figure 11a and the sharing in Figure 11b.

![Figure 11a – Map of routes](image)

![Figure 11b – Routes and tracks: length & sharing](image)

Tilting trains run also in some sections not concerned by tilting speed, in such cases obviously at conventional speed. More than 70 millions of kilometres are covered by the Italian tilting trains. The 2001 summer timetable involves the use of 35 sets that cover 27351 km per day on domestic routes and 5304 km per day on foreign routes. That means 9,983,115 km per years covered on domestic routes and 1,936,960 km per year covered on foreign routes.

Further development in the extent of the lines concerned by tilting speed will include the completion of some routes and some regional routes under study.
Furthermore, the increasing of cant deficiency from 275 mm to 300 mm might be possible. With regard to this in the following table the real journey time of ETR460 is compared as function of the cant deficiency rate in the Battipaglia-Reggio Calabria section, 374 km length. Two situations has been considered: present tilting speed, limited by Permanent Speed Restrictions (PSRs), due to signalling, catenary and switches not allowing the new increased speed, and tilting speed without PSRs. ETR460 tilting train at 275 cant deficiency with PSRs reduce the journey time of 10.7%. Without PSRs ETR460 at 306 mm cant deficiency reduce journey time of 17.4%. The results are summarised in the table 2 and in the graph of figure 12.

<table>
<thead>
<tr>
<th>Route</th>
<th>Distance [km]</th>
<th>Stops [n°]</th>
<th>Journey time [minute]</th>
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<td></td>
<td></td>
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<td>with PSRs</td>
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<td>Battipaglia-Reggio C.</td>
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<td>-11.63%</td>
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<td>-1.87%</td>
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<tr>
<td>Difference/Journey Time 150 mm with PSRs</td>
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<td>----</td>
<td>-1.87%</td>
</tr>
</tbody>
</table>

Table 2 – Battipaglia-Reggio Calabria route: Journey time with or without PSRs for different values of cant deficiency.

Figure 12 – Battipaglia-Reggio Calabria route: graph summarising Journey time

Significant journey time saving are possible on some regional lines where the permissible cant deficiency is now 122 mm. As example in the following table are resumed the results of a study on an extent of 330 km of the main Sardinia routes. For the study a hypothetical diesel tilting train has been considered (2 vehicles, maximum speed of 160 km/h, power at the wheels 800 kW, compensation of cant deficiency until 8°). Also in this case two situations has been considered: present tilting speed, limited by Permanent Speed Restrictions (PSRs), due to recanting of some curves, track renewals, platforms, unmanned or automatic closing level crossings, and tilting speed without PSRs. In this case the maximum journey time reduction is 8.8% with PSRs and 10.4% without PSRs. The economic impact of PSRs removing is very modest, comparable to the cost of one trainset. The results of journey time saving are summarised in the table of table 3 and in the graph of figure 13.
### Table 3 – Routes Cagliari-Olbia and Cagliari-Sassari: Journey time with/without PSRs for different values of cant deficiency

<table>
<thead>
<tr>
<th>Route: Cagliari-Chilivani-Olbia</th>
<th>Distance [km]</th>
<th>Stops [n°]</th>
<th>Journey time [minute]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>122</td>
<td>150</td>
<td>275</td>
</tr>
<tr>
<td></td>
<td>with PSRs</td>
<td>without PSRs</td>
<td>with PSRs</td>
</tr>
<tr>
<td>CAGLIARI-CHILIVANI-OLBIA</td>
<td>284</td>
<td>3</td>
<td>178.77</td>
</tr>
<tr>
<td>Difference/Journey Time 122 mm</td>
<td>----</td>
<td>-2.81%</td>
<td>-8.78%</td>
</tr>
<tr>
<td>Difference/Journey Time with PSRs</td>
<td>----</td>
<td>-0.16%</td>
<td>-0.92%</td>
</tr>
<tr>
<td>CAGLIARI-CHILIVANI-SASSARI</td>
<td>260</td>
<td>3</td>
<td>167.33</td>
</tr>
<tr>
<td>Difference/Journey Time 122 mm</td>
<td>----</td>
<td>-2.69%</td>
<td>-8.06%</td>
</tr>
<tr>
<td>Difference/Journey Time with PSRs</td>
<td>----</td>
<td>-0.65%</td>
<td>-0.80%</td>
</tr>
</tbody>
</table>

### Figure 13 – Routes Cagliari-Olbia and Cagliari-Sassari: Graps summarising Journey

### 6. CONCLUSIONS

The discussion presented in this paper allows concluding that an increase of cant deficiency up to 306 mm is possible for tilting train service on the Italian Network. To this end, it is necessary that a proper preservation and control of wheel profiles be performed, in fact, excessive wear of the profiles determines a relevant steering effect, which has a negative impact on the assessment of safety with respect to Prudhomme limit.

Moreover, also track quality has a very large impact on the safety assessment results, and therefore plays a fundamental role in determining the possibility to operate the trains at higher cant deficiency.

The work also reports some results of numerical simulations that are in good agreement with measurements. Besides providing an explanation for the steering effect, the mathematical model can be useful for parametric analysis finalised to point out the effect of wheel profiles and other parameters, and therefore can be of help to the experimentation.

The difference in journey time between tilting trains and conventional trains is minus 8 to 12%. The removing of some restrictions due to infrastructure, generally with modest economic impact, combined with the increasing of cant deficiency at 306 mm can allow to cut journey time up to more than 18%.

### BIBLIOGRAPHY


