New developments with the Italian solution for tilting trains: optimization of tilting system on new generation of Pendolino trains

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Abstract

Tilting trains can be classified into different categories according to the features of their tilting system. On every types of tilting trains the tilting systems shall perform three main functions: first, they have to identify accurately and without delay the initial position of curve transitions, then they have to tilt the car body according to the tilting algorithm provided for the system and finally they have to verify that the provided amount of tilt corresponds to the tilt demand.

With the “Italian solution” applied on Pendolino trains curves are recognized by some dynamic signal measured by sensors located on the bogies such as the bogie lateral acceleration and roll rate. On these tilting trains, the type of algorithm controlling the angle of tilt has been defined in order to compensate a fixed percentage of total lateral acceleration which is constant for all curves. In order to achieve that, the tilting system evaluates the same signals used to identify curves and produces a tilt request proportional to the lateral acceleration on the bogie. Finally, on Pendolino trains a simple loop allows to verify the effectiveness of the tilting control comparing the requested tilt angle and the actual angle applied and measured on the car body.

The most significant advantage of this solution is that tilting trains can be operated on all types of lines and infrastructures at higher speed than the other trains without the necessity to equip any kind of devices on the infrastructure. The corresponding disadvantage is that the system identifies the curve entrance with a time delay on the head of the train causing a proportionate amount of discomfort beyond a certain threshold, even if the gyroscopes allow to reduce this delay to a minimum.

The paper develops a simple analytic approach which is useful to investigate the main design parameters of tilting systems and tilting trains based on the “Italian solution”. This approach shows that Pendolino tilting systems can be fully described at last by only two independent parameters while all the other ones depend on the two selected variables. With this approach the Pendolino type tilting systems are described in terms of compensation coefficient (that is the ratio between the acceleration compensated by the system and the acceleration of a non tilting train on the same curve and at the same speed) and the residual acceleration on the car body at the maximum tilting angle of the system.

This section of the paper is completed by the analysis of the relationship between the design parameter of the tilting system and maximum speed and curve radius of a line in order to show that the benefits of multipurpose tilting trains such Pendolino trains are not only connected to the increase in operational speed with respect to conventional trains and, as a consequence, on the increased capacity of the infrastructure. In fact, when in the design phase of new railway lines, an operation model with tilting train is an essential option to investigate to reduce the curve radius of the lines without decreasing speed and thus achieving a lower cost of the infrastructure (e.g. reducing number and length of tunnel).

The paper includes the description of the main features of the new generation of Pendolino ETR600 as well as of architecture and features of its tilting system. The effects of the tilting system degraded modes on operations are analyzed, focusing the methodology and results of the safety analysis and FTA that have been carried on the tilting system.

Finally the paper presents the results of the dynamic behavior tests carried out on 2007 for the approval of Pendolino new generation ETR600. Measurements of dynamic parameters carried out both on high speed lines and conventional lines with small radius curves are presented and analyzed focusing the results achieved for passenger comfort. Examples of results achieved in the ride comfort analysis according ENV 12299 are provided focusing on $P_{CT}$ index on curve transitions.
1. Introduction

The need of reducing the traveling time on railways has found two different solutions. High speed lines and trains represent the solution already established all over the world for passenger traffic on medium-long distance in the countries where funds are available to build new lines and high speed systems.

The second solution is the use of tilting trains on conventional line allowing to increase train speed and to reduce traveling time without any adjustment requested to the railway infrastructure. Such a result is achieved equipping trains with active systems which tilt the carbody of vehicles and allow to negotiate the curves of existing lines at increased speed without reducing travel safety or passenger comfort. This solution can not produce the same reduction of travel time compared to a high speed line, but permit to exploit the conventional existing network at its maximum performances with no investment on a new line or on existing infrastructure. So this solution is the only one available when the reduction of traveling time shall be achieved on the conventional existing network.

Trenitalia, the Italian State owned train operator, has developed both approaches and its fleet includes both high speed trains and four series of tilting trains, nicknamed Pendolino. Since the conception of the first series of Pendolino trains, Italian approach to the design of tilting trains was driven by to main ideas. The first one is that tilting system has to be controlled completely on-board in order to allow operations of tilting trains on all lines without the need of any device located on the infrastructure. The second one is that tilting trains are not finalised just to conventional lines but they are multipurpose train both for conventional and high speed systems. As a result, all series of Pendolino trains are high speed tilting trains with a maximum operational speed of 250 km/h and which can negotiate curves at a non compensated acceleration 1.8 or 2 m/s².

The main design parameters of tilting systems focusing the Pendolino system, the features of ETR600 last generation of Pendolino series and the analisys of comfort data resulting from on line tests are presented in the paper.

2. Architecture of tilting systems based on “Italian solution”

Tilting trains can be classified into different categories according the features of their tilting system. On every types of tilting trains the tilting systems shall perform three main functions: first, they have to identify accurately and without delay the initial position of curve transitions, then they have to tilt the car body according to the tilting algorithm provided for the system and finally they have to verify that the provided amount of tilt corresponds to the tilt demand.

Different systems can be used to identify the initial position of the curves. With the “Italian solution” the curve transitions are recognized by the signal of the bogie angular velocities measured by gyroscopes located on the first bogie of the train. After the identification of the curve, the compensation of lateral acceleration can be regulated in different ways. On Pendolino trains the type of tilting algorithm has been defined in order to compensate a fixed percentage of total lateral acceleration. This percentage is the same for all curves and it is constant along a curve. In order to achieve that, the tilting system evaluates the bogie lateral acceleration and the angular velocity on x and z direction and produces a tilt request for the first vehicle which is proportional to the lateral acceleration measured on the bogie. This tilt request proportional to the lateral acceleration is then transferred to the subsequent vehicles along the train. Finally, for this architecture of tilting system it is used a very simple loop to verify the effectiveness of the tilting control. For this system the feedback on the tilt request is driven by the comparison between the applied and measured car body angle and the tilt angle requested by the system.

The architecture of this typology of tilting system is presented in figure 1.

The following three aspects are to be pointed about this architecture:

- due to the fact that the tilting system identifies curves by on-board sensors, tilting trains can operate on conventional lines at higher speed than other trains without installing any equipment on the infrastructure;
the identification of the curves on-board results in a time delay on the first car, that can not affect the comfort on passengers only if it remains below a certain threshold level; the use gyroscopes allows to reduce this delay to a minimum;
- due to the fact that the percentage of lateral acceleration compensated for by the system is the same on all curves, the car body acceleration experienced by passengers (and the related level of comfort) is determined only by the value of the compensation coefficient selected for the system; this constant coefficient can be set in order to generate a level of car body acceleration equal or lower than the conventional trains also at increased speed; as a consequence of this constant compensation, passengers can not recognize by the time history of the car body lateral acceleration if they are travelling in a tilting train at the maximum speed or in a conventional train.

3. Design parameters of tilting systems

For tilting trains the car body lateral acceleration $a^*$ is given by the following equation:

$$ a^* = a_{NC} (1 + s_R) - g \sin \theta $$

(1)

where $a_{NC}$ is the non compensated lateral acceleration (at track level), $s_R$ the roll coefficient (or soupless coefficient) and $\theta$ the angle of tilt of the car body commanded by the tilting system. The compensation coefficient $R$ is defined the ratio between the lateral acceleration compensated for by the tilting system and the car body lateral acceleration that a conventional train would undergo on the same curve and at the same speed. It is define by the following equation:

$$ R = \frac{g \sin \theta}{a_{NC} (1 + s_R)} $$

(2)

It has to point out that $R=0$ for a conventional train or when the tilting system is not efficient while $R=1$ when the car body lateral acceleration is completely compensated (no lateral acceleration experienced by passengers in curves). Compensation, that is the value of $R$, can be regulated in different ways. The simplest way to control the lateral acceleration is to compensate for a percentage of the overall lateral acceleration which is the same on every curve and is stable also along the curve negotiation. For this type of systems the value of $R$ is constant. As already said, this is the compensation rule applied for Pendolino trains.

A compensation model with a constant implies that the angle of tilt of the car body (or more correctly the sine of the angle) and the non compensated acceleration are joined by is a simple linear equation:

$$ \sin \theta = R (1 + s_R) \frac{a_{NC}}{g} $$

(3)
Equation (3) gives evidence to the fact that the maximum angle of tilt $\theta_{\text{max}}$ correspond to the maximum value of non compensated acceleration $a_{\text{NC}}(\theta_{\text{max}})$ for which the tilting system maintains a constant compensation coefficient. For higher non compensated acceleration the system is not capable to tilt further the car body and therefore the percentage of acceleration compensated for is not constant any longer, but it declines to proportionately lower values.

In the hypothesis of a constant compensation coefficient, it can be seen that $R$ depends on just two parameters: the maximum angle of tilt $\theta_{\text{max}}$ and the residual value $a^*(\theta_{\text{max}})$ of carbody lateral acceleration corresponding to $\theta_{\text{max}}$.

In fact, using Equation (1) the maximum non compensated acceleration (at track level) $a_{\text{NCmax}}$ that can be reached in a curve by the tilting train maintaining a constant $R$ can be written as function of $a^*(\theta_{\text{max}})$:

$$a_{\text{NCmax}} = \frac{g \sin \theta + a^*(\theta_{\text{max}})}{1 + s_R} \quad (4)$$

Replacing Equation (4) in Equation (2) the result is:

$$R = \frac{1}{1 + \frac{g \sin \theta_{\text{max}}}{a^*(\theta_{\text{max}})}} \quad (5)$$

which allows to calculate Equation (1) as a function of $R$ (that is of $\theta_{\text{max}}$ and $a^*(\theta_{\text{max}})$):

$$a^* = (1 + s_R) (1 - R) a_{\text{NC}} \quad (6)$$

 Equation (3), (5) and (6) show that, for tilting systems with a constant compensation coefficient, $\theta_{\text{max}}$ and $a^*(\theta_{\text{max}})$ are the two main parameters which are independent variables defining the system design: by means of the selection of their values it is established the algorithm governing the tilt angle.

Table 1 shows the value of $R$ obtained changing $\theta_{\text{max}}$ and $a^*(\theta_{\text{max}})$.

<table>
<thead>
<tr>
<th>Compensation coefficient R</th>
<th>$\theta_{\text{max}}$ [°]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>0.60</td>
<td>0.36</td>
</tr>
<tr>
<td>0.80</td>
<td>0.30</td>
</tr>
<tr>
<td>1.00</td>
<td>0.26</td>
</tr>
<tr>
<td>1.20</td>
<td>0.22</td>
</tr>
</tbody>
</table>

Table 1: Values of $R$ for different $\theta_{\text{max}}$ and $a^*(\theta_{\text{max}})$.

Figure 2 shows the curves of the angle of tilt $\theta$ as a function of non compensated acceleration for tilting systems with the same residual acceleration $a^*(\theta_{\text{max}})$ equal to 0.65 (left figure) and 1 m/s$^2$ (right figure) and with different $R$ (that is with different $\theta_{\text{max}}$). A value of 0.18 is used for $s_R$. In figure 2 it can be observed that:

- for a tilting system with $a^*(\theta_{\text{max}}) = 0.65$ m/s$^2$ and $\theta_{\text{max}} = 8^\circ$ the percentage of carbody lateral acceleration compensated for with respect to a conventional train is 68% and the $a_{\text{NC}}$ corresponding at the maximum angle of tilt is about 1.7 m/s$^2$; these are the design parameters used for the first three series of Pendolino trains;
- for a tilting system with $a^*(\theta_{\text{max}}) = 1.0$ m/s$^2$ and $\theta_{\text{max}} = 8^\circ$ the percentage of carbody lateral acceleration compensated for with respect to a conventional train is 58% and the $a_{\text{NC}}$ corresponding at the maximum angle of tilt is about 2.0 m/s$^2$; these are the design parameters used for the last series of Pendolino ETR600.

For tilting systems with a constant $R$ figure 3 shows the curves of maximum non compensated acceleration $a_{\text{NCmax}}$ that can be reached at $\theta_{\text{max}}$ as a function of $\theta_{\text{max}}$. The height of these curves varies with the residual lateral acceleration $a^*(\theta_{\text{max}})$ tolerated in the carbody at $\theta_{\text{max}}$ (in the figures $a^*(\theta_{\text{max}}) \equiv a^*_{\text{res}}$). In the figure at right $a_{\text{NCmax}}$ is displayed as maximum cant deficiency.
This figure gives evidence to the importance of sufficiently high values for $a^*(\theta_{\text{max}})$: in fact, for the value of $a_{N\text{Cmax}}$, an increase of 0.2 m/s$^2$ with $a^*(\theta_{\text{max}})$ (at the same $\theta_{\text{max}}$) correspond to an increase of about 1° with $\theta_{\text{max}}$ (at the same $a^*(\theta_{\text{max}})$).

Figure 2: Angle of tilt as a function of $a_{\text{NC}}$ for different $\theta_{\text{max}}$ and $a^*(\theta_{\text{max}})$

About the item of $a^*(\theta_{\text{max}})$ it has to be pointed out that on the Italian railway infrastructure and also on many other European networks as well as on most cases of European regulations (including EN 14363 and UIC 518) the mandatory or recommended permissible value of cant deficiency for conventional trains is 150 mm corresponding to a maximum value of non compensated acceleration of about 1 m/s$^2$. This value of lateral acceleration (or at least this value multiplied with the roll coefficient) shall be considered a reference limit also for tilting trains in order to avoid a car body lateral acceleration exceeding the value of conventional trains (and generating a reduced comfort).

According to the model of a tilting train with a constant $R$, this means to fix an upper limit for $a^*(\theta_{\text{max}})$ equal to 1 m/s$^2$ which is reached at the maximum angle of tilt. If a constant $R$ is required
within all the range of non compensated acceleration, this means also that the limit of 1 m/s² for
car body lateral acceleration is reached only when the train is negotiating curves with the
maximum non compensated acceleration (as a result of Equation (6)).

For tilting systems with a constant R the left side of Figure 4 shows the curves of the car body
lateral acceleration a* as a function of the non compensated acceleration for systems with
different \( \theta_{\text{max}} \) and with the same residual acceleration \( a^* (\theta_{\text{max}}) \) equal to 1 m/s². It can be noticed
that the value of a* undergoes a variation of gradient at the value of a NC corresponding to
\( \theta_{\text{max}} \). As the design parameter \( a^* (\theta_{\text{max}}) \) is fixed at 1 m/s², for all curves this value of a NC corresponds
to 1 m/s². On the right side of the figure, the curves for the first three series and for the last one
of Pendolino tilting trains are shown. For these two tilting systems \( \theta_{\text{max}} \) is the same (equal to 8°),
but \( a^* (\theta_{\text{max}}) \) changes from 0.65 to 1 m/s², so it is different also the value of a NC corresponding to
a variation of slope in the curves of car body lateral acceleration.

![Figure 4: Car body lateral acceleration as a function of aNC for different \( \theta_{\text{max}} \) and a* (\( \theta_{\text{max}} \))](image)

All the previous analysis deals with the steady condition of the tilting system when the train is
negotiating the full curve and does not take into the tilt rate (that is the car body roll rate), which
is the main parameter for the behaviour of the tilting system in the curve transition curve. The
mean and maximum values of the tilt rate are linked both to \( \theta_{\text{max}} \) and to \( a^* (\theta_{\text{max}}) \) and they affects
from one side the readiness of the system to reach the required angle – that means that tilt rate
has not to be low – on the other side the passenger comfort, that means that the tilt rate has not
to be too high.

4. Tilting trains as design parameter for new railway lines

This section presents the analysis of the effects of the tilting system design parameters on track
maximum speed and curve radius in order to show that the benefits of multipurpose tilting trains
such Pendolino trains are not only connected to the increase in operational speed with respect
to conventional trains and, as a consequence, only to the increased capacity of the
infrastructure. In fact, in the design phase of new railway lines an operation model with tilting
train is an essential option to investigate in order to reduce the curve radius of the line without
decreasing the speed. This reduction of the curve radius at the same maximum speed of the
line gives the possibility to achieve a lower cost of the infrastructure e.g. reducing number and
length of tunnel or viaducts that are necessary on the new line.

If a\( \text{NC} \) is explicited in Equation (6) the result is:
\[ a^* = (1 + s_R) \left( 1 - R \right) \left( \frac{V^2}{r} - g \frac{h}{s} \right) \quad (7) \]

where \( V \) is train velocity in the curve, \( r \) the curve radius, \( h \) the curve cant and \( s \) the track gauge. Deriving \( V \) from Equation (7) the result is:

\[ V = \sqrt{r \left[ \frac{a^*}{(1 + s_R) \left( 1 - R \right)} + g \frac{h}{s} \right]} \quad (8) \]

Deriving \( r \) from Equation (7) the result is:

\[ r = \frac{V^2}{a^* + g \frac{h}{s}} \quad (9) \]

Equations (8) and (9) has been used to verify the impact of different tilting systems with a constant \( R \) and identified by their design parameters \( \theta_{\text{max}} \) and \( a^* (\theta_{\text{max}}) \), on the amount of increase of curve maximum speed that can be achieved on different curve radius and on the amount of decrease of the minimum curve radius of a new line maintaining the same maximum line speed.

The left side of figure 5 shows the graphs of the maximum speed that can be reached in a curve with a cant of 160 mm as a function of the curve radius for tilting systems with a car body residual acceleration \( a^* (\theta_{\text{max}}) = 1 \text{ m/s}^2 \) and with different maximum angles of tilt \( \theta_{\text{max}} \). It can be seen, as an example, that the maximum speed in curve with a radius of 1600 m is 200 km/h for a conventional train and it increases to about 230 km for a system with \( \theta_{\text{max}} = 4^\circ \) and up to about 250 km/h for a system with \( \theta_{\text{max}} = 8^\circ \).

The left side of figure 5 shows the graphs of the maximum speed that can be reached in a curve with a cant of 160 mm as a function of the curve radius for tilting systems with a car body residual acceleration \( a^* (\theta_{\text{max}}) = 1 \text{ m/s}^2 \) and with different maximum angles of tilt \( \theta_{\text{max}} \). It can be seen, as an example, that the maximum speed in curve with a radius of 1600 m is 200 km/h for a conventional train and it increases to about 230 km for a system with \( \theta_{\text{max}} = 4^\circ \) and up to about 250 km/h for a system with \( \theta_{\text{max}} = 8^\circ \).

The right side of figure 5 shows the graphs of the maximum curve radius that a tilting train negotiates at a fixed speed as a function of \( \theta_{\text{max}} \) and for different values of \( a^* (\theta_{\text{max}}) \). The figure
gives evidence to the efficiency resulting from the use tilting train for the reduction of curve radius, especially on high speed lines. As an example, a speed of 300 km/h is possible when negotiating a curve with a radius of about 3600 m for conventional trains; for tilting trains with a residual car body acceleration $a^*(\theta_{\text{max}}) = 1$ m/s$^2$ and $\theta_{\text{max}} = 4^\circ$ the radius decreases to 2800 m, while a tilting train with $a^*(\theta_{\text{max}}) = 1$ m/s$^2$ and $\theta_{\text{max}} = 8^\circ$ requires a radius of about 2300 m for 300 km/h.

5. Features of ETR600 Pendolino tilting train

The new fleet of twelve Pendolino ETR600 represents the fourth generation of high speed tilting trains, following the steps of ETR401 (late 70’s), ETR450 (80’s) and ETR460/470/480 (90’s). ETR600 is a fixed composition EMU with an overall length of 187,4 meters that consists of four motor cars (distributed traction) and three trailer vehicles (two cars carrying the main transformers) for a total of seven vehicles. The tare weight of ETR600 is 432 t and the maximum weight per axle is limited to 17t/axle with exceptional load. This results have been achieved using a total aluminium bodysheild and optimizing the design of the car frame. The train is compliant to the TSI standard and for this reason it is equipped on the front nose with a crash absorption structure that can dissipate up to 6 MJ, while the carbody structure of the flat end is specifically designed for an energy absorption of 1,7 MJ. The train is equipped with 4 pantographs and the power can be supplied at 3 kV dc, 1,5 kV dc and 25 kV ac 50 Hz catenary voltages, while the signalling equipments is compliant to ERTMS Level 2 and include STM for the italian SCMT signalling system. This allows ETR600 to be used in operations on all Italian conventional and high speed lines. Due to the fact that the maximum train speed is 250 km/h and the maximum non compensated acceleration is 2.0 m/s$^2$, as the previous series, this tilting train is an example of multipurpose train designed for operations on conventional lines and on high speed network. The four motor cars are equipped each with an integrated traction/auxiliary converter based on the last generation of water cooled 6,5 kV IGBT technology that allows also regenerative and rheostatic braking. Each traction converter supplies – through two dedicated inverters – two asynchronous forced ventilation motors that are installed on the carbody underframe and power is transmitted to the gearbox through a cardan shaft. The eight traction motors offer together a total traction power of 5500 kW at rims that allowed the train - during the homologation test runs under 3 kV dc catenary - to reach easily and safely a speed of 282 km/h. The use of redundancies and the optimisation of command-control chain in terms of load insertion allows the train to reach and maintain easily the maximum speed also with 75% of the traction power, and to supply all the auxiliary loads also with 50% of the converters in service. The New Pendolino, with its bodysheild width of 2830 mm and its wide passenger windows and doors has been developed thinking to the maximisation of internal available space. The possibility to increase the internal space is given also from the adoption of tilting pantographs (the pantographs are tilted in the opposite direction respect to the carbody) instead of traditional systems where the pantos are fixed on a “portal” that is directly referred to the bogeis. A total of 432 seats is available in the train, 100 of which are first class, together with a bar-bistrot with a wide stand up area, a small office for the train staff, nine toilets and all the facilities for 2 people on wheel chair.

6. Features of ETR600 Pendolino tilting system

As already said, ETR 600 tilting system is defined by a constant compensation coefficient $R=0,58$ given by $\theta_{\text{max}}=8^\circ$ and $a^*(\theta_{\text{max}})=1$ m/s$^2$. As a consequence, the tilting algorithm requires an angle of tilt proportional to the non compensated acceleration up to 2 m/s$^2$, that is the maximum $a_{\text{NC}}$ in operations. At this value of $a_{\text{NC}}$ the maximum angle of tilt is achieved and the residual carbody lateral acceleration is equal to 1 m/s$^2$. The architecture of the ETR600 tilting system corresponds to figure 1. The sensor used to identify the curve transitions are located only on the two bogies at the two ends of the train
within a redundant sensor box, identified as SUT (Sensor Unit Tilting). As shown in the figure, these sensors are an accelerometer for lateral direction and two gyroscopes for \( \omega_x \) and \( \omega_z \). In order to minimise the time delay of the system on the first two vehicle of the train the value of \( a_{NC} \) used by tilting algorithm is corrected using the gyroscope signals, while for the other vehicles the system uses the value of \( a_{NC} \) comes from the lateral accelerometer only.

With respect to the previous series of Pendolino trains on ETR600 the residual acceleration \( a^*(\theta_{max}) \) has been modified from 0.65 to 1 m/s\(^2\) and the tilt rate decreased to a maximum instant value of 5°/s. The following two main advantages comes from this change:

- at high value of \( a_{NC} \) the car body acceleration remains linear without any abrupt change and without exceeding the values for conventional trains;
- as the angle of tilt required for a definite \( a_{NC} \) is lower, also the tilt rate experienced by passengers in curve transitions is lower, therefore the comfort level is improved.

The tilting system of ETR600 is is hierarchically structured into three levels: train level, vehicle level and subsystem level.

At train level the structure consists of train tilting control units installed on each vehicle. The units installed on end vehicles are called TTP (Train Tilting Processor), those installed in intermediate vehicles are called VTP (Vehicle Tilting Processor). The TTP on the vehicle with the occupied driver cab operates as master unit while the rear TTP operate as VTP.

All the units of a train are connected through a redundant CAN communication line and through a hardware loop TSL (Train Security Loop) acting on driver desk warnings (lamps, buzzer). The TTP is connected through a local vehicle bus to the redundant sensor boxes SUT installed on leading bogie and it is also connected to the TCMS (Train Control and Monitoring System) through a redundant MVB communication line. TTP master is the interface of tilting system towards the train control system.

At vehicle level the structure consists of the tilting control unit (VTP or TTP) which operates as Vehicle Master in respect to different slave control units, not all installed in each vehicle, that physically control the actuation systems. These slave control units represent the subsystem level, and include the hydraulic control unit for the car body rotation, the pneumatic control unit for the active lateral suspension and also the hydraulic control unit for the pantograph counter-rotation.

The VTP is connected to each control unit via a redundant CAN communication line and through dedicated hardware safety loops (one for each subsystem). These hardware loops allow in case of failures to disable the relevant subsystem actuation by direct opening of dedicated emergency valves which in turn discharge the pressure from the actuation cylinders (both hydraulic and pneumatic). All the hardware loops are connected to a dedicated electronic card (Safety Card or SC) installed in the TTP / VTP electronic rack, and the loops can be opened both by the corresponding actuation control unit or by the TTP / VTP itself that acts as a supervisor for normal operating conditions of each subsystem. The intervention of one instance is generally sufficient to open the local loop, thus actuating the corresponding emergency valve, and to open also the TSL, thus actuating the appropriate warning elements on the driver’s desk. The only exception being the PSL (Pantograph Safety Loop), whose local opening doesn’t reflect on the TSL but induce hardwired commands from the SC to the fast lowering pneumatic valve of the pantograph and to the emergency valve to discharge hydraulic pressure from the pantograph counter-tilting actuation cylinders. In order to correctly act as a supervisor, the SC include also a dedicated accelerometer to measure directly the lateral acceleration being present on passenger level.

The design of the tilting system is such that no single local failure can lead to unavailability of the system. This result has been achieved through a reasoned and balanced use of redundancies and the optimization of the control SW.

7. Safety analysis and FTA of ETR600 Pendolino tilting system

A complete safety analysis has been performed for the tilting system of ETR600, starting with a description of all the possible scenarios for potential accidents, then with the identification of the hazards and with a consequent preliminary risk analysis to identify all the subsystems and equipments of the train that are potentially dangerous when in fault condition. The scope of this
The analysis has been done according to the norm EN 50126, by means of the identification of a frequency of occurrence of hazardous events and of a hazard severity level, using the definitions and descriptions listed on Table 2 and 3.

<table>
<thead>
<tr>
<th>Category</th>
<th>Definition</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Frequent</td>
<td>Likely to occur frequently. Hazard will be continuously experienced</td>
</tr>
<tr>
<td>B</td>
<td>Probable</td>
<td>Will occur several times. Hazard can be expected to occur often</td>
</tr>
<tr>
<td>C</td>
<td>Occasional</td>
<td>Likely to occur several time. Hazard can be expected to occur several times</td>
</tr>
<tr>
<td>D</td>
<td>Remote</td>
<td>Likely to occur sometime in system life-cycle. Hazard can reasonably be expected to occur</td>
</tr>
<tr>
<td>E</td>
<td>Improbable</td>
<td>Unlikely to occur but possible. Can be assumed that hazard may exceptionally occur</td>
</tr>
<tr>
<td>F</td>
<td>Incredible</td>
<td>Extremely unlikely to occur. Can be assumed that hazard may not occur</td>
</tr>
</tbody>
</table>

Table 2: Frequency of occurrence of hazardous events

<table>
<thead>
<tr>
<th>Severity level</th>
<th>Definition</th>
<th>Consequences to persons</th>
<th>Consequences to service</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>Catastrophic</td>
<td>Fatalities and/or multiple severe injuries</td>
<td>Severe damage to the train</td>
</tr>
<tr>
<td>3</td>
<td>Critical</td>
<td>Single fatality and/or severe injury</td>
<td>Loss of a major system</td>
</tr>
<tr>
<td>2</td>
<td>Marginal</td>
<td>Minor injury</td>
<td>Severe system(s) damage</td>
</tr>
<tr>
<td>1</td>
<td>Insignificant</td>
<td>Possible minor injury</td>
<td>Minor system damage</td>
</tr>
</tbody>
</table>

Table 3: Hazard severity level

The evaluation of the risk is then performed combining the frequencies of occurrence of a hazardous event with the severity of its consequences using a "frequency-consequence" matrix and assigning a priority to each risk classification (see Table 4 and 5).

<table>
<thead>
<tr>
<th>Risk Classification</th>
<th>Risk category</th>
<th>Actions to be applied</th>
</tr>
</thead>
<tbody>
<tr>
<td>4A, 4B, 4C, 3A, 3B, 2A</td>
<td>Intolerable</td>
<td>Shall be eliminated</td>
</tr>
<tr>
<td>4D, 3C, 3D, 2B, 2C, 1A</td>
<td>Undesirable</td>
<td>Shall be accepted when risk reduction is impracticable and with Safety Authority agreement</td>
</tr>
<tr>
<td>4E, 3E, 2D, 1B, 1C</td>
<td>Tolerable</td>
<td>Acceptable with adequate control and with Railway Authority agreement</td>
</tr>
<tr>
<td>4F, 3F, 2E, 2F, 1D, 1E, 1F</td>
<td>Negligible</td>
<td>Risk is acceptable</td>
</tr>
</tbody>
</table>

Table 4: "Frequency-Consequence” matrix

The results of this safety analysis has put in evidence a few hazards strictly related to the tilting system, the more relevant being the one related to carbody counter-rotation.

The risk scenario in this case is given by the train counter-tilting (tilting is activated in the opposite direction than requested by the real track conditions) due to the failure of TTP / hydraulic control unit and the failure of the hydraulic servovalve. The effect of such event could
be the collision / impact against the infrastructure, with potentially catastrophic consequences. For this reason, the target for risk classification in this case has been set at 4E / 4F level, that has been achieved discharging the hydraulic system by means of a dedicated fast discharge valve (in order to bring the car body to 0° position) and by means of the implementation of Safety Relevant software for TTP, VTP and hydraulic control units. The FTA (Fault Tree Analysis) for the event “Carbody counter-tilting” is shown in figure 6.

7. Results of ride comfort measurements for ETR600 Pendolino

Finally some results about ride comfort measurements carried out on 2007 for the approval of Pendolino new generation ETR600 are presented in this section. Measurements of dynamic parameters were carried out both on high speed lines at maximum speed 250 km/h and on conventional lines with small radius curves at cant deficiency 300 mm (αNC=2 m/s²). The analysis of ride comfort is focused on the index for curve transitions P_CT, which indicate the percentage of the passengers that are dissatisfied with the comfort. Even if the magnitude of dissatisfaction depends on the expectations of the passenger, for a particular type of service a higher P_CT always indicates a poorer passenger comfort. According to norm ENV12299 this index is a function of the maximum values along the curve transition of lateral acceleration, lateral jerk and roll velocity. Even if this index is not mandatory for the dynamic approval of the train, it provides a good information about the level of ride comfort on tilting trains.

Measurements were carried out on vehicle 7, leading and motor vehicle of the test train, and vehicle 3, intermediate and trailer one both with design mass and also under normal payload condition. As an example, for the normal payload conditions figures 7 and 8 show the values of P_CT on entry transition of curves respectively for a line with majority of curve radius between 400 m and 600 m and for a line with majority of curve radius between 600 m and 900 m. In each figure the top diagram display values of non compensated acceleration in the curves of the line and the diagrams below the values of PCT index for leading vehicle and an intermediate one.
Figure 7: Ride comfort measurements - PCT on curves between 400 m and 600 m

Figure 8: Ride comfort measurements - PCT on curves between 400 m and 600 m
As it can be seen in the figures, measurements show that even with non compensated acceleration up to 2.25 m/s² the values of P\textsubscript{CT} index are below 35%.

8. Conclusion

Design parameters of tilting systems have been investigated to focus which of them have to be defined in tilting train specifications and it has been described the process for the optimization of the tilting algorithm from the first series to the new generation of Italian Pendolino trains. Features and data about of the new ETR600 Pendolino tilting train and its tilting system are presented in the paper, focusing on safety and FTA analysis of the tilting system. Finally, some ride comfort measurements carried out for the approval of this new tilting trains have been shown to verify the results achieved with this new train design.

References