Tracks for tilting trains - A study within the Fast And Comfortable Trains (FACT) project

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Abstract
The tilt mechanism reduces the lateral acceleration perceived by the passengers. Therefore, tilting trains, if provided with a suitable running gear, may run at higher cant deficiencies than non-tilting trains. However, the nominal track geometry still defines a ceiling for permissible train speed, but at a higher level.

The research project Fast And Comfortable Trains (FACT), organised by the European Commission and the UIC, had the overall objective to identify procedures to enhance the performance of tilting trains, without compromising passenger comfort and the safety of the track / vehicle system.

FACT Work Package 1 had the objectives to provide methodology for upgrading infrastructure to achieve the optimal performance for using tilting trains, with special attention to mixed traffic conditions, and to identify economical design of track and/or coach for a given performance and a given comfort level.

In the final research report produced within FACT WP1, Tracks for tilting trains, a general overview of considerations for the track is given, and a state-of-the-art overview of research on track/vehicle interaction, with a focus on the track geometry, is presented.

The major track aspects of tilting trains are related to the horizontal alignment and applied cant, since the relation between low-frequency variables, such as low-frequency roll velocity, low-frequency lateral jerk etc. depends to a high degree on the horizontal alignment. Alignment design is a balancing act between conflicting objectives, such as large curve radii and long transition curves. Furthermore, the Tracks for tilting trains report covers the shape of the transition curves (linear versus S-shaped curvature functions), the lengths of track elements between transition curves, and vehicle dynamics at curve entries without transition curves.

Important conclusions, among others, are:
- The optimum transition curves are longer for tilting trains than for non-tilting trains.
- The specific advantage of tilt is more pronounced on curves with low cant (for example on freight lines) However, short transition curves reduce the advantage of tilting trains.
- Horizontal curves without transition curves eliminate the advantage of tilting trains.
- Tilting trains may run at high cant deficiencies also at speeds above 250 km/h.
- Passengers in tilting trains may be exposed to high vertical acceleration when trains are running on horizontal curves.

The FACT WP1 also analysed proposed limits for various track variables in a draft European standard for alignment parameters (CEN – prEN 13803-1, dated 2004) and recommended that this proposal should be changed in order to avoid situations with unacceptable values for the rate of change of cant deficiency.

Background
Tilting trains are provided with a mechanism that tilts the vehicle body in addition to the effect of applied cant. The tilt mechanism reduces the lateral acceleration perceived by the passengers. Therefore, tilting trains, if provided with a suitable running gear, may run at higher cant deficiencies than non-tilting trains, i.e. run at higher speed. Nowadays, it is a mature technology that many railways have taken into revenue service.

The research project Fast And Comfortable Trains (FACT) was organised in cooperation with the European Commission and the UIC and had the overall objective to identify procedures to enhance
the performance of tilting trains, without compromising passenger comfort and the safety of the system.

The work was organised in several work packages:
- WP1 Infrastructure improvement
- WP2 Passenger comfort improvement
- WP3 Modelling tools
- WP4 Exploitation of the results
- WP5 Management

Partners in the FACT project were UIC/ERRI, Alstom, Bombardier, CD, DB, ISVR, JBV, SNCF, Talgo and VTI. Ferroplan was subcontracted to VTI (Swedish National Road and Transport Research Institute) to work within Work Package 1.

FACT Work Package 1 had the objectives to provide methodology for upgrading infrastructure to achieve the optimal performance for using tilting trains, with special attention to mixed traffic conditions, and to identify economical design of track and/or coach for a given performance and a given comfort level.

**Consideration regarding permissible speed**

The permissible speed in this research paper relates to track alignment and cant. There are other aspects regarding permissible speed that should be taken into consideration when setting the enhanced permissible speed for tilting trains, such as catenary, signalling, platform safety aspects, safety aspects regarding level crossings, etc. These are aspects should be considered for all types of trains, i.e. they are not tilt specific.

**Nominal motions on horizontal curves**

Consider a vehicle, travelling on a circular curve with the horizontal radius $R$ (m) and applied cant $D$ (mm), at zero gradient and at a constant speed of $V$ (m/s). In a coordinate system with two axes in the horizontal plane and the third axis perpendicular to the horizontal plane, perceived motions can be described as follows.

- Horizontal acceleration $a_h = -\frac{V^2}{R}$  
- Vertical acceleration $a_v = g$
- Yaw velocity $\psi_h = \frac{V}{R}$
- Pitch velocity $\chi_y = 0$

The sign in Equation (1) indicates that a lateral force is felt to the left when the vehicle runs on a right-hand curve. The magnitude and sign in Equation (2) indicate the magnitude and direction of the gravitational force.

In the canted track plane (assuming standard gauge 1435mm), the motions can be described as follows.

- Lateral acceleration $a_L = a_h \cos(\phi) + a_v \sin(\phi)$
- Vertical acceleration $a_V = -a_h \sin(\phi) + a_v \cos(\phi)$
- Yaw velocity $\psi_H = \psi_h \cos(\phi) + \chi_y \sin(\phi)$
- Pitch velocity $\chi_Y = -\psi_h \sin(\phi) + \chi_y \cos(\phi)$
- Cant angle $\phi = \arcsin(D/1500mm)$

A non-tilting vehicle, running with cant deficiency, sways slightly outwards on a curve, compared to the track plane, resulting in a slightly smaller roll angle than the cant angle. The roll angle depends on the roll coefficient of the vehicle.

A tilting vehicle travels on the same curve at a higher speed, and with a roll angle for the floor which is larger than the cant angle. The roll angle depends on the roll coefficient of the vehicle and the compensation ratio in the tilt system.

Figure 1 shows that vertical acceleration, yaw velocity and pitch velocity are higher for a tilting vehicle running at enhanced speed than for a non-tilting vehicle running at normal speed. The same applies
to the product of yaw and pitch velocities. (This product has been calculated since simultaneous rotations in two directions may cause nausea.) Lateral acceleration may be higher or lower, depending on the magnitude of the tilt compensation ratio.

![Graph showing motion quantities for a tilting vehicle running at 20% enhanced speed as functions of the total roll angle (cant plus tilt). The quantities are relative to the motions of a non-tilting vehicle (roll coefficient 0.2) running on a circular curve with 150 mm cant and 150 mm cant deficiency [18].](image)

When running on transition curves, the roll velocity is higher for a tilting vehicle running at enhanced speed than for a non-tilting vehicle running at normal speed. This is due to the higher change of roll angle and the shorter duration on the transition. As for lateral acceleration, lateral jerk may be higher or lower, depending on the magnitude of the tilt compensation ratio.

It should be noted that a larger roll angle (higher compensation ratio of the tilt system) reduces perceived lateral acceleration, yaw velocity and lateral jerk, but increases roll velocity, vertical acceleration, pitch velocity and the product of yaw and pitch velocities. The fact that roll velocity, vertical acceleration, yaw velocity and pitch velocity are higher for a tilting train running at enhanced speed is inevitable.

Tilt motions may be synchronized with the track alignment with the help of accelerometers (measuring lateral accelerations), gyros (measuring rate of change of cant or yaw velocity) and/or positioning systems (transponders in the track, GPS). However, even if the tilt motion can be perfectly synchronized with the track alignment, the actual amount of tilt must be carefully balanced in order to avoid excess motions with respect to roll velocity, vertical acceleration, etc.

**Comfort criteria**

The most useful way to quantify instantaneous comfort disturbances due to alignment has been found to be the $P_{CT}$ functions derived by former British Rail Research and incorporated in the recent CEN standards ENV 12299 [1] and prEN 12299 [2]. It was found that the comfort disturbances appeared in entry transitions and in reverse transitions. Transition curves where lateral acceleration decreased, i.e. run-off transitions, did not lead to any significant comfort disturbances, unless they also included large track irregularities.

By statistical analysis, it was found that the percentage of disturbed passengers can be expressed as follows:
Standing passengers \(P_{CT} = \max(25.54 \dot{y} + 20.69 \ddot{y} - 11.1, 0) + 0.185 \dot{\vartheta}^{2.283} \quad (10)\)

Seated passengers \(P_{CT} = \max(8.97 \dot{y} + 9.68 \ddot{y} - 5.9, 0) + 0.120 \dot{\vartheta}^{1.626} \quad (11)\)

where, over the transition curve, \(\dot{y}\) = maximum absolute value of lateral acceleration of vehicle body (expressed in m/s\(^2\)), \(\ddot{y}\) = maximum absolute value of lateral jerk of vehicle body (expressed in m/s\(^3\)), \(\dot{\vartheta}\) = maximum absolute value of roll velocity of vehicle body (expressed in degrees per second).

Even though motion sickness is a rare phenomenon in railway traffic, it has been reported from Great Britain, Italy and Japan that tilting trains sometimes cause motion sickness [25]. Motion sickness is probably not correlated to a single curve but is rather a cumulative effect from several curves. According to ORE, JNR believed the problems to be associated with short transition curves. Problems with motion sickness in tilting trains have also been reported with regard to Cisalpino Pendolinos in Switzerland [14], the French experimental tilting TGV [8], X2000 in Sweden [11] and others.

The cause of motion sickness is not fully understood [21]. Japan has introduced limits of 5 degrees/s for roll velocity and 15 degrees/s\(^2\) for roll acceleration. These limits have been slightly changed to 0.1 rad/s for roll velocity and 0.3 rad/s\(^2\) for roll acceleration, and since then the problems with motion sickness have decreased, but are not totally eliminated [24].

Studies in Norway and Sweden have shown that the degree of nausea seems to be best correlated with a net dose (accumulated dose with a certain leakage) of roll motions [11]. In Sweden, there is also a discussion whether yaw and pitch motions (or combinations of roll, yaw and pitch) may contribute to nausea. The final results from FACT WP2 showed good correlation with a net dose of vertical acceleration (low-pass filtered or band-passed filtered) and lateral acceleration multiplied by roll velocity [9, 10, 12].

**Track superstructure**

The original thought behind the tilting train technology is that these trains should be capable of running faster than conventional trains on existing tracks. This applies also to the track superstructure. Generally, tilting trains do not require special arrangements on the track superstructure, even though it is recommended to use high-quality components in a good maintenance condition.

Procedures for approval of tilting trains running at enhanced permissible speeds are defined in UIC 518 [29] and UIC 518-1 [30]. CEN standards EN 14363 [3] and prEN 15686 [4] are also under development. By adopting the UIC or CEN rules with respect to lateral and vertical forces, as well as the ratio between lateral and vertical forces, safety criteria regarding enhanced permissible speeds on curves will be fulfilled. (On the vehicle side, typical arrangements for reducing the forces on the track are low nominal axle loads, low unsprung masses, low heights of the mass centres of the vehicles, radial steering bogies.)

**Radius and cant**

Generally, the permissible speed \(V\) depends on curve radius \(R\) as follows:

\[ V = k(R/l_{im}+D_{im})^{0.5} \quad (12) \]

where \(l_{im}\) = limit for cant deficiency (mm), \(D_{im}\) = limit for applied cant (mm), standard gauge, \(k\) = conversion factor for units.

On a circular curve with a given cant \(D\), the relationship between the enhanced permissible speed for tilting trains \(V_T\) and the permissible speed for conventional non-tilting trains \(V_C\) may be expressed as follows:

\[ V_T/V_C = ((D+l_T)/(D+l_C))^{0.5} \quad (13) \]

where \(l_T\) = limit for cant deficiency for tilting trains, \(l_C\) = limit for cant deficiency for conventional non-tilting trains.

Figure 2 shows this relationship as a function of applied cant, and with the assumptions \(l_T = 300\) mm and \(l_C = 100\) mm, as well as \(l_T = 250\) mm and \(l_C = 150\) mm.
Enhanced permissible speed for tilting trains

$\gamma_T = 300\text{mm} \& \gamma_C = 100\text{mm}, \text{ and } \gamma_T = 250\text{mm} \& \gamma_C = 150\text{mm}$

Even though permissible speeds do increase with high cant, the specific advantage of tilting trains compared to non-tilting trains is potentially greater for curves with low cant, such as on freight lines or other lines where slow trains have been prioritised when choosing the cant.

**Cant transitions**

Railway companies apply two types of limits on cant transitions (superelevation ramps):

The first type of limit is the cant gradient (the change of applied cant per metre along the track). This limit is a derailment criterion and is aimed at limiting wheel unloading for torsion stiff wagons. When the cant has been chosen, the minimum length of a cant transition is not dependent on permissible train speed.

The second type of limit is the rate of change of cant (the change in applied cant per second). This limit is a comfort criterion and is aimed at limiting the roll velocity of a vehicle. When cant has been chosen, the minimum length of a cant transition depends on permissible train speed.

After full-scale tests with tilting trains, certain railway companies have chosen an increased limit for the rate of change of cant for tilting trains. However, the tilt system does not compensate for high rates of change of cant. On the contrary, it increases the roll velocity as perceived by the passenger. These facts indicate that the limit for rate of change of cant for conventional trains may be too restrictive.

It is noted that high roll velocities are not only correlated to instantaneous comfort disturbances. There are several indications that motion sickness is correlated to the cumulative exposure (doses) to roll motions.

**Length of transition curves**

Transition curves are curved segments of the track where horizontal curvature changes gradually along the track. Hence, vehicles are exposed to a rate of change of cant deficiency (change of cant
deficiency per second) and possibly also to a rate of change of cant (if there is a coincidental cant transition). When a vehicle runs at the enhanced speed on a transition curve, both these rates become higher, compared to curving at normal speeds.

When a vehicle is exposed to a rate of change of cant deficiency, passengers are exposed to lateral jerk. The lateral jerk in the vehicle body is reduced when the vehicle is tilting, but the roll velocity is increased. Hence, a tilting vehicle running at enhanced permissible speed may have higher, the same or lower lateral jerk compared with a conventional vehicle, but will always have higher roll velocity.

On transition curves, several limits apply: The rate of change of cant deficiency, the cant deficiency, and, if combined with a cant transition, the applied cant, the cant gradient and the rate of change of cant. Several combinations of binding criteria exist. If a transition curve is long, the limits for applied cant and cant deficiency will dictate the enhanced permissible speed, which will be the same as for an adjacent circular curve. If a transition curve is short, the rate of change of cant and/or the rate of change of cant deficiency will dictate the enhanced permissible speed to a lower value than for the adjacent alignment elements.

Inserting a transition curve between a tangent track with fixed position and a circular curve requires an inward shift of the circle, which increases with the transition length squared. The original tangent track and the circular curve must be shortened.

These consequences limit the possibilities of arranging long transition curves, both when building new lines and upgrading existing ones. It may be necessary to reduce the horizontal radius in order to compensate for large values of inward shift and/or shortenings of adjacent elements. Hence, the recommendations for large curve radii and long transition curves are normally in conflict.

The optimal combinations of radius and transition lengths in limited terrain corridors have been investigated in [17] with GENSYS simulations of vehicle dynamics on tracks with and without track irregularities. Figure 3 shows $P_{CT}$ values plotted as a function of transition lengths for four hypothetical terrain corridors (defined by the angle between the adjacent straight tracks and by the position of the binding obstacle along the track).

![Figure 3. $P_{CT}$ for standing passengers in a tilting coach (SJ UA2) passing curves with a change in direction of $\Delta \psi = 0.1$ and 0.5 rad and with a binding obstacle at the midpoint and the endpoint of the curve respectively, at 250 km/h [18].](image)

Conclusions, among others, are that optimal lengths of the transition curves depend on the limit for applied cant, the roll coefficient of the vehicle and a body tilt system, if used. Tilting trains favour longer transition curves than non-tilting trains. A higher limit for cant, a lower roll coefficient and a
higher degree of compensation in the body tilt system (if used) favour longer transition curves. The transition lengths that minimise $P_{CT}$ are almost independent of the track irregularities.

**Types of transition curves**

The most common type of transition curve is the clothoid, where horizontal curvature varies linearly as a function of chainage. A corresponding type of cant transition is the linear ramp, where cant varies linearly with chainage. The linear ramp has discontinuities in cant gradient (kinks) at the ends. Hence, there is a discussion whether or not these vertical kinks can be arranged and whether or not the vehicle dynamics on these locations are unfavourable. There exist alternative types of cant transitions with continuous cant gradient (S-shaped ramps) and corresponding types of transition curves.

Several studies regarding S-shaped ramps from Sweden [17], USA [15], Japan [13, 23] and China [22] were compared in the FACT project. The conclusion was that when vehicle response is evaluated according to international standards from UIC [29, 30] and CEN [1, 2, 3, 4] there seem to be no substantial advantages to be gained from using S-shaped cant transitions and corresponding types of transition curves.

**Lengths between transition curves**

At a tangent point between two alignment elements, there is a discontinuity in the mathematical definition of the track. This is especially pronounced where a cant transition with a constant cant gradient starts and ends. These discontinuities in the track generate additional vehicle vibrations. Hence, certain railway companies define a minimum length for circular curves and straight tracks between transition curves and cant transitions. Such a length is aimed at ensuring that vibrations induced at one tangent point are damped before the next tangent point is reached.

Kufver [16] simulated dynamic vehicle response on short circular curves, short straights between two curves in the same direction and short straights between two curves in the opposite directions. All curves were provided with the clothoid type of transition curves and linear cant transitions.

![Figure 4. Normalised evaluation variables in the wheel/rail interface on a short circular curve. SJ X2 power car at 250 km/h [18].](image)

The maximum and minimum vertical wheel/rail forces (Q), maximum guiding forces (Y), maximum track shift forces (SY), and maximum wheel climbing ratios ($Y/Q$) vary very little as a function of the lengths of elements with constant curvature. For short straight track, the variation of each variable is less than 4% when the length of the straight track is varied between 0 and 100 m. These small variations are far less than variations caused by track irregularities and stiffness variations. For short circular curves, the variations are slightly greater. The greatest variation was found for the X2 power car at a speed of 250 km/h, see Figure 4.

For each variable, except Min Q, low values are preferable. The striking conclusion is that very short lengths of the circular curve are not disadvantageous.
Passenger comfort (evaluated according to CEN [1, 2] was found not to be a problem on transition curves after short circular curves and short tangent tracks between curves in the opposite directions. Passenger comfort may be slightly worse on transition curves after a short straight placed between curves in the same direction. However, unnecessarily hard requirements for lengths of circular curves and tangent tracks may lead to unnecessarily short transition curves which are believed to be a greater problem for tilting trains.

Abrupt changes in curvature

Where the horizontal curvature changes instantaneously, permissible speeds are determined either by a limit for an abrupt change in cant deficiency or a fictitious rate of change of cant deficiency, based on the assumption of virtual transitions. In short, the concept of virtual transition states that where transition curves are omitted, the bogie distance of the vehicle may be used as a fictitious transition length for the calculation of the rate of change of cant deficiency.

Simulations of vehicle dynamics [19] have shown that the concept of virtual transitions overestimates the lateral jerk and that the principle with a fixed limit for the abrupt change of cant deficiency is more consistent with the resulting lateral jerk.

In any case, where transition curves are omitted, the tilt system will not have sufficient time for arranging a suitable tilt angle. Hence, speed restrictions due to abrupt changes in curvature should be the same for tilting and non-tilting trains.

Switches and crossings

Traditional types of turnouts are not provided with transition curves in the diverging track. When a tilting vehicle runs through the diverging route of such a turnout, no enhancement of permissible speed will be achieved.

Where switches and crossings are placed on a curved through track, many railway companies apply a more restrictive limit for the permissible cant deficiency on the through track, both for tilting and non-tilting vehicles. Enhancements in permissible speed tend to be low.

Vertical curves

The tilt system cannot compensate for high level of vertical acceleration on a vertical curve. Hence, there is no reason to have different limits for vertical acceleration for tilting and non-tilting trains. However, it should be noted that the perceived vertical acceleration is higher when running on horizontal curves with large roll angle. Hence, combinations of concave vertical curves and horizontal curves with small radii should be avoided for lines for tilting trains.

Track standards

In the FACT project, track standards from certain railways were collected and analysed. An extract of the results is presented in Table 1.

With respect to $P_{CT}$, it was found that many tilting trains offer better comfort than conventional trains on the same line ($P_{CT}$ values are lower). This means that there may be a potential for slightly lower compensation ratio, which would increase $P_{CT}$ but at the same time reduce the roll motions. This may be an advantage for passengers with a tendency to motion sickness. (Also vertical acceleration will be slightly reduced if the compensation ratio is lowered.)

Certain countries and a working draft CEN standard [6] (as well as UIC leaflet 705-1 [31]) have no limits for the rate of change of cant deficiency. This may lead to very high values for this comfort related track variable. A numerical example is given for the case when the limits in [6] are used: For a curve with the radius $R=2000$ m, transition lengths $20$ m, and applied cant $D=20$ mm, the enhanced permissible speed is $230$ km/h. For this speed, the cant deficiency is $I=292$ mm, the rate of change of cant is $dD/dt=64$ mm/s and the rate of change of cant deficiency is $dI/dt=933$ mm/s. Such a high rate of change of cant deficiency introduces several problems. To compensate for the rate of change of cant deficiency in the track plane, the roll velocity would be very high indeed (at 50% compensation
ratio, the roll velocity would be about 20 degrees per second). However, it is very unlikely that the tilt system would respond quickly enough. Slow response (low tilt velocity and tilt action not in phase with the transition curve) would lead to very high lateral jerk and high lateral acceleration. There may even be safety problems for standing and walking passengers. Also, with a bogie distance of 18-19 metres, it will be impossible to arrange a suitable tilt for both ends of the vehicle. Hence, FACT recommended CEN to propose a limit for rate of change of cant deficiency.

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<td>180</td>
<td>95</td>
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Table 1. Certain track limits for plain track - exceptional values. Values in brackets are derived by FACT [18].

Short transition curves tend to reduce the advantages of tilting trains. Even though this is reflected in most track standards (reducing the enhanced permissible speed), short transition curves are believed to contribute to tendencies to motion sickness.

Conclusions, exploitation of the results and future research

Modern track components are generally capable of carrying the load caused by high cant deficiencies. However, certain countries apply more conservative rules for permissible cant deficiency at switches and crossings and at "stiff" track points, such as ballast free track on bridges, transitions between ballasted and ballast free track, expansion joints, level crossings etc.

The major track aspects for tilting trains are related to the horizontal alignment and cant. Tilting trains are capable of compensating for low cant (high cant deficiency). However, the horizontal alignment will still create a ceiling for the enhanced permissible speed (even though it is higher than the permissible speed for non-tilting trains). The relation between low-frequency variables, such as roll velocity, low-frequency lateral jerk, etc. depends to a very high degree on the horizontal alignment. I.e., a measure on the tilting train to reduce roll velocity inevitably leads to increased lateral jerk.

The alignment design is a balancing act between conflicting objectives. Both lengthening of the transition curves and increasing the radius lead to an inward shift of a curve between two straight tracks. Hence, lengthening of the transition curves may require a reduction of the radius of the circular portion of the curve. The optimum transition lengths for tilting trains are longer than those for non-tilting trains.

Long transition curves are favourable both with respect to local comfort ($P_{CT}$) and with respect to doses of roll motions (related to nausea). Tracks with short transition curves reduce the interoperability of high-speed tilting trains. Horizontal curves without transition curves eliminate the advantage of tilting trains. Good design practice is to arrange long transition curves, at least when this can be done with no or very low marginal costs. The most cost-effective opportunity is when a new line or a major re-configuration is designed. Tilt aspects may be taken into account also for lines where tilt service is not in the short-term plans. They may also be taken into account when designing high-speed lines, in order to enable even faster service with tilting trains in the future. It should be noted that the Japanese railways are introducing tilting Shinkansen of series N700. These trains will run at $V=270 \text{ km/h}$ and $V=300 \text{ km/h}$ where the non-tilting series 700 runs at $V=250 \text{ km/h}$ and $V=285 \text{ km/h}$, respectively. We may see more very high-speed tilting trains as vehicle technology develops.
Combinations of high cant deficiency and high speed have also received increased interest in recent Swedish development projects as few existing tilting trains explore this combination. The tilting train X2000 has been tested at 245 mm cant deficiency up to a speed of 275 km/h, and a non-tilting Regina train has been tested at 230 mm cant deficiency and 240 km/h, as well as 200 mm cant deficiency at 260 km/h, without exceeding the permissible wheel/rail forces according to [3, 4] and [29, 30].

Results from the FACT project are exploited in the development of EN standards. The prestandard ENV 12299 (Ride comfort for passengers) [1] from 1999 is being developed to a standard (pr)EN 12299 [2], and includes clarifications of the procedures for evaluating passenger comfort with the $P_{CT}$ index.

The prestandard ENV 13803-1 (Alignment parameters) from 2002 [5] does not include rules for tracks for tilting trains. It is currently developed into a standard (pr)EN 13803-1 [7], which includes rules for both conventional and tilting trains. The working draft standard (prEN 13803-1, dated 2004 [6]) was changed in several important respects. Among the changes for both types of trains are relaxed requirements for lengths between transition curves. For tilting trains, a limit for rate of change of cant deficiency is introduced. This limit has no correspondence in the older UIC leaflet for tilting trains [31].

After the FACT project, certain studies regarding the performance of tilting trains have continued in Sweden. Kufver and Persson [20] have presented an algorithm for balancing the conflicts between the desire for low $P_{CT}$ (high tilt compensation) and low risk of nausea (low tilt compensation).

Persson [26] has shown that high cant deficiency, high speed and high tractive performance are three key factors to improve running times on the Swedish Stockholm - Gothenburg line (where tilting trains are currently running up to 200 km/h). He also indentified motion sickness as one area where research could improve the competitiveness of tilting trains.

Persson [27] has presented guidelines for applied cant that optimises the counteracting requirements for comfort in non-tilting trains and low risk of motion sickness in tilting trains. The guidelines were compared with the applied cant on the Swedish Stockholm - Gothenburg line, indicating a potential for improvements. Motion sickness in tilting trains was also the subject for a literature study [28] where Persson showed that no laboratory tests resulting in motion sickness have been performed at motion levels equal to levels measured in tilting trains. Furthermore, combinations of motions are a more likely cause of motion sickness as they are more provocative than single motions.

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References


