RESEARCH ON THE SPECIFIC ASPECTS OF TILTING

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Abstract

During the last 10 years, tilt technology has progressed from unproven technology to a commercial success. However, not all the technical challenges have yet been solved and a number of the potential benefits of tilting trains remain to be exploited. This presentation is aimed at providing an update on recent Swedish research.

The research has been conducted with full-scale train tests and tests with a vehicle simulator capable of generating different combinations of lateral and roll motions. These experiments with students as test subjects were focused on ride comfort and motion sickness as functions of the motion environment. The tests were also aimed at finding a better tilt control strategy for a tilting train. Other experiments were conducted through computer simulations of vehicle reactions. Tilting and non-tilting trains were simulated on different track geometries, in order to define the best alignment and cant with respect to passenger comfort and wheel/rail forces.

The results from the test subjects show that provocation of motion sickness is highly dependent on the net motion dose of roll motions (time integrated roll acceleration with leakage).

On the track side, results show that the amount of cant that minimises discomfort is dependent not only on vehicle speed and curve radius, but also on vehicle characteristics (such as tilt compensation ratio) and the lengths of the transition curves. The transition lengths that minimise discomfort are dependent on the variables mentioned above and on the angle between the connecting straight lines (when boundaries in available terrain corridors are taken into account).

If cant is not optimised for the tilting trains, an alternative solution is to use a variable tilt compensation ratio (which may be individual for each curve). In order to enable the train to predict optimal tilt on the next curve, track geometry data should be stored in onboard computers. Future research will be focused on these aspects.
Introduction

During the last 10 years, tilt technology has progressed from unproven technology to a commercial success. However, not all the technical challenges have yet been solved and a number of the potential benefits of tilting trains remain to be exploited. This paper is aimed at providing an update on Swedish experience.

Background

The idea of reducing travel times by using tilting trains, rather than major re-alignments of existing lines, was discussed as early as 1938 in Germany. Experimental trains with passive or active tilt were built in France in 1957 and in Germany in 1965, followed by Italy, Japan, Great Britain, Sweden, Spain, Canada, Switzerland and Norway. Certain countries, such as France, Germany and Great Britain, halted development at an early stage, while Japan, Sweden and Italy continued with tilt development and became the first to put this type of train into revenue traffic. This paper summarises the specific aspects of tilting with special attention to recent research.

There are a number of high-speed issues which are not tilt-specific, such as braking distances, signalling distances, catenaries for high train speeds, passenger safety on platforms which certain trains pass at high speeds, pressure waves in tunnels, etc. All these issues must be taken into account when raising train speeds, but the technology is the same for tilting as for non-tilting trains.

Wheel/rail forces

The specific aspects of tilting are related to high-speed curving, i.e. running through curves with high cant deficiencies. There are two preconditions for this operation. First, the forces on the track must be reasonably low. Second, the track must have the capability to carry the load. When these preconditions are fulfilled, the body tilt system must be optimised and modifications of the track should be considered in order to provide the best possible passenger comfort.

High wheel/rail forces and excessive wheel wear were problems at early stages in tilt development. It has been found that radial steering bogies, enabling the wheelsets to significantly reduce the angle of attack, reduce both the guiding forces and the wear rate of the wheels. The radial steering capability may be achieved by controlled steering or by self-steering bogies (also called soft bogies), the latter requiring a careful design of the primary suspension. In the case of the Swedish X2000 tilting trainset, vehicle as well as track side measurements have confirmed the self-steering performance of the soft bogies, which at the same time are stiff enough to permit stable operation on tangent track at speeds up to 250 km/h and above.
When curving at high cant deficiencies, there is always an extra vertical load on the outer rail while the inner rail is relieved. Hence, vertical wheel/rail forces must be taken into account. The three most basic vehicle solutions for achieving low vertical peak-loads are:

1. Low nominal axle loads;
2. Low unsprung masses, which reduces the dynamic peak loads, and;
3. Low heights of the mass centres of the vehicles.

Recently, wheel loads and radial steering performance have been measured in extensive tests in Norway. For example, it was found that track shift forces were lower than the criterion of Prud'homme, even at cant deficiencies of 300 mm and on small curve radii. In conjunction with these tests, track stability was measured with a Swedish track laboratory coach, and it was found that the investigated track could carry lateral loads exceeding the criterion of Prud'homme. The deflections of the fasteners have also been measured, and it was found that they were less than the fatigue criterion specified by the supplier (Pandrol).

Hence, both extensive full-scale tests and ten years of revenue traffic in Sweden have proven that the pre-conditions for high-speed curving are fulfilled. The basic principle of tilting, which does not influence the wheel/rail forces and wheel wear, is to roll the vehicle body inwards on curves. The tilt motion reduces the lateral acceleration and jerk perceived by passengers, but exposes them to more severe roll motions (roll velocities and roll accelerations).

**Passenger comfort**

Since the reduction of lateral motions must be paid for with increments in roll motions, the tilt motions should be optimised with care. Also, it should not be forgotten that ride comfort depends to a high degree on alignment and cant.

Two aspects of passenger comfort are taken into account. First, there may be instantaneous discomfort when entering curves. Previously, this aspect of comfort has been taken into account with separate limits for lateral acceleration and lateral jerk. However, certain track modifications result in higher acceleration and lower jerk, or vice versa. Hence, a quantity termed $P_{CT}$, derived by British Rail Research (now AEA Technology), has been used to quantify the combined effect of simultaneous lateral acceleration, lateral jerk and roll velocity. It should also be mentioned that at the World Congress on Railway Research WCRR-99, Japanese researchers published extended formulas which also include the effect of roll acceleration on comfort.

The second aspect of passenger comfort is the risk of motion sickness among sensitive passengers. It is believed that this risk is dependent on the accumulated effect of several curves. Research to find a dosage, that takes different types of motions (lateral, vertical, roll, etc.) into account is being conducted at the VTI with full-scale tests on tilting trains in Sweden and Norway and with simulator studies involving a large number of test subjects, see Figures 1-2.
Figure 1. Schematic drawing of the simulator seen from the rear. Horizontal and roll motions are generated by the outer moving system, while the shakers generate vertical vibrations.

Figure 2. Interior view of the cabin with a subject. A curtain normally separates the two subjects in the cabin.
The dosage takes leakage into account, which is necessary where a tilting train runs partly on curvaceous and partly on relatively straight lines, see example in Figure 3.

**Figure 3. Example of evaluation according to net dose model from NSB comfort tests during 1999 between Kongsberg and Nakksjoe. Leakage of dose is clearly seen during stops and certain less curved sections.**

The results from these tests indicate that the combination of lateral and roll motions is more provocative of motion sickness than lateral motions alone. While a reduced amount of tilt may reduce the risk of motion sickness among sensitive passengers, such a measure increases the instantaneous discomfort ($P_{CT}$). A problem that arises is to balance the two types of comfort disturbance against each other.

The optimisation of the tilt algorithm includes not only the compensation ratio (the percentage of the lateral acceleration reduced by the tilting), but also the tilt motion, whereas limitations on tilt velocity and/or tilt acceleration may be considered, as well as time delays in the tilt system.

**Track geometry**

Tilting trains were originally designed to run faster than conventional non-tilting trains on "existing tracks". However, it was found at an early stage that permissible train speed and/or passenger comfort could be improved with minor adjustments of the horizontal alignment and cant. Areas which have been carefully investigated are:

1. What is the optimal cant on different curves, when tilt compensation ratio has been fixed?
(2) What is the best combination of curve radius and lengths of transition curves where a terrain corridor is defined by obstacles, such as existing catenary masts, bridges, platforms etc., and:

(3) What is the most suitable mathematical form for transition curves and superelevation ramps?

These research questions have been investigated with computer simulations of the dynamic vehicle reactions, and by aggregating the combined effect of different motions according to experience from comfort research. The simulations were conducted using comprehensive multi-body computer codes with 42 degrees of freedom for each vehicle and additional degrees of freedom for the track, see Figure 4. Simulations have been conducted both with and without track irregularities.

Figure 4. Vehicle models in the GENSYS simulation program. Each of the seven bodies can translate in three directions and rotate in three directions.

The results show, for example, that the optimal cant on a circular curve depends on the lengths of the adjacent transition curves. This is due to the effects of the lateral jerk and the roll velocity. It may also be noted that design cant should be lower than the equilibrium cant also on curves that all trains pass at the same speed. In Figure 5, discomfort when cant is low is due to high lateral acceleration and lateral jerk, while discomfort when cant is high is due to high roll velocities.
If cant is not optimised for the tilting trains, another solution is to have a variable tilt compensation ratio (that may be individual for each curve). In order to enable the train to predict optimal tilt on the next curve, track geometry data should be stored in onboard computers. Future research will be focused on these aspects.

Long transition curves are favourable for all kinds of trains, but lengthening of a transition curve forces the adjacent circular curve inwards. Hence, in limited terrain corridors, the lengths of transition curves compete with curve radii, since also increasing a radius forces the track inwards. The objective for the alignment engineer should be to find optimal combinations of curve radii and transition lengths. In this context, it has been found that for tilting trains it is preferable to have longer transition curves than for non-tilting trains, even though radii must be slightly reduced, see example in Figure 6.
Figure 6. Passenger discomfort $P_{CT}$ as a function of transition lengths in a predefined terrain corridor. Longer transition curves are associated with smaller curve radius. Data from Kufver (2000).

S-shaped superelevation ramps and the corresponding type of transition curves have not been found superior to linear ramps and the clothoid type of transition curves. This is due to higher values of lateral jerk and roll velocity in the middle of the transition (compared to linear ramps and clothoid type of transition curve).

The two last observations are important when designing new railways. It is advisable to take the specific aspects of tilting into consideration from the very beginning, since the possibilities of arranging optimal transition lengths are greater before a railway is built. Despite this knowledge, also recent railway projects have focused on a desire for large curve radii, which is less important if tilt operation is considered. With another approach, the infrastructure cost could have been reduced and at the same time passenger comfort improved.

It must be emphasised that the tilt in itself compensates for low cant (with respect to comfort). Tilting trains have an especially great potential advantage on lines where cant is chosen for slow freight trains. Unfortunately, such railways rarely have suitable transition lengths for making full use of this advantage. Well-planned alignment design is a precondition for making full use of the advantages of tilting trains.

Concluding remarks

Vehicle development has resulted in technical solutions that enable trains to run through curves with high cant deficiencies. The track shift forces are less than the criterion of
Prud'homme and the vertical wheel/rail forces are reasonably low. The engineering effort may be focused on the aspect of passenger comfort.

The tilt reduces the perceived lateral motions, but increases the roll motions. For a majority of the passengers, the combined effect on ride comfort is positive, but the effect may be enhanced by adjustments of the track geometry. Both when maintaining and renewing existing lines and when designing new ones, the specific aspects of tilting trains should be taken into consideration.

Acknowledgements:

This paper is based on research projects conducted at the VTI, Linköping, in cooperation with Professor Evert Andersson at the Royal Institute of Technology (KTH) Stockholm.

Sponsors of the projects are Bombardier Transportation (Adtranz Sweden), the Swedish National Rail Administration (Banverket), the Norwegian National Rail Administration (Jernbaneverket), the Norwegian State Railways (NSB), TrainTech, the Swedish Agency for Innovation Systems (VINNOVA), and the Swedish National Road and Transport Research Institute (VTI).

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