KTH Engineering Sciences

Tilting trains

Enhanced benefits and strategies for less motion sickness

Doctoral thesis

by

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Preface

This is the final report of the research project 'Carbody tilt without motion sickness'. This postgraduate project initiated by the Division of Rail Vehicles at the Royal Institute of Technology (KTH) was formed together with the Swedish Governmental Agency for Innovation Systems (VINNOVA), the Swedish Transport Administration (Trafikverket), Bombardier Transportation (BT), The Association of Swedish Train Operators (Branschföreningen Tågoperatörerna) and Ferroplan Engineering AB. Special acknowledgement is made to SJ AB (SJ) for making a train and crew available for the tests. The financial support received from VINNOVA, KTH Railway Group and BT is also gratefully acknowledged.

I am most grateful to my two supervisors, Prof. Mats Berg (KTH) for his sincere dedication and strong support and Dr. Björn Kufver (Ferroplan) for his guidance and constructive comments throughout the work.

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I would also like to thank Jonas Strömblad (SJ), Tommy Sigemo (BT), Einar Persson (BT) and Linnea Nordin (BT) who contributed to the on-track test conducted within the project.

On a personal level, I must thank the woman in my life, Karin, for her understanding. At the same time I apologise to Gustav, our son, for not being around as much as I would have wanted.

Stockholm, April 2011

Rickard Persson

Abstract

Carbody tilting is today a mature and inexpensive technology that allows higher train speeds in horizontal curves, thus shortening travel time. This doctoral thesis considers several subjects important for improving the competitiveness of tilting trains compared to non-tilting ones. A technology review is provided as an introduction to tilting trains and the thesis then focuses on enhancing the benefits and strategies for less motion sickness.

A tilting train may run about 15% faster in curves than a non-tilting one but the corresponding simulated running time benefit on two Swedish lines is about 10%. The main reason for the difference is that speeds are set on other grounds than cant deficiency at straight track, stations, bridges, etc. The possibility to further enhance tilting trains' running speed is studied under identified speed limitations due to vehicle-track interaction such as crosswind requirements at high speed curving. About 9% running time may be gained on the Stockholm–Gothenburg (457 km) mainline in Sweden if cant deficiency, top speed, and tractive performance are improved compared with existing tilting trains. Non-tilting high-speed trains are not an option on this line due to the large number of 1,000 m curves.

Tilting trains run a greater risk of causing motion sickness than non-tilting trains. Roll velocity and vertical acceleration are the two motion components that show the largest increase, but the amplitudes are lower than those used in laboratory tests that caused motion sickness. Scientists have tried to find models that can describe motion sickness based on one or more motion quantities. The vertical acceleration model shows the highest correlation to motion sickness on trains with active tilt. However, vertical acceleration has a strong correlation to several other motions, which precludes vertical acceleration being pointed out as the principal cause of motion sickness in tilting trains.

Further enhanced speeds tend to increase carbody motions even more, which may result in a higher risk of motion sickness. However, means to counteract the increased risk of motion sickness are identified in the present work that can be combined for best effect. Improved tilt control can prevent unnecessary fluctuations in motion sickness related quantities perceived by the passengers. The improved tilt control can also manage the new proposed tilt algorithms for less risk of motion sickness, which constitute one of the main achievements in the present study. Local speed restrictions are another means of avoiding increased peak levels of motion sickness when increasing the overall speed.

The improved tilt control and the proposed tilt algorithms have proven to be effective in on-track tests involving more than 100 test subjects. The new tilt algorithms gave carbody motions closer to non-tilting trains. Rather unexpectedly, however, the test case with the largest decrease in tilt gave a greater risk of motion sickness than the two test cases with less reduction in tilt. It is likely that even better results can be achieved by further optimization of the tilt algorithms; the non-linear relation between motions and motion sickness is of particular interest for further study.

Key words: tilting trains, running time, ride comfort, motion sickness, tilt control

Outline of thesis

The overall goal of the work was to improve the competitiveness of tilting trains compared to non-tilting ones. This can be accomplished either by improving the benefits or by reducing the drawbacks. **Paper A** deals with the first task, while **Papers A**, **B** and **C** deal with the second. **Paper B** investigates the possible contradiction between the two tasks. The introduction to the thesis gives a general overview of the topic followed by five appended papers:

A: **R. Persson.** *Research on the competitiveness of tilting trains*. Proceedings of Railway Engineering – 2007, Engineering Technics Press, ISBN 0-947644-61-10, Edinburgh 2007.

B: **R. Persson.** *Tilting trains – benefits and motion sickness*, Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, Volume 224, Number 6, pp 513-522, ISSN 0954-4097, London 2010.

C: **R. Persson.** *On-track test evaluation*. Proceedings of the 43rd UK Conference on Human Response to Vibration, Leicester 2008.

D: **R. Persson and B. Kufver.** *Strategies for less motion sickness on tilting trains*. Proceedings of Comprail 2010, pp 581-591. WIT Press, ISBN 978-1-84564-468-0, Southampton 2010.

E: **R. Persson, B. Kufver and M. Berg.** *On-track test of strategies for less motion sickness on tilting trains*. Submitted for international publication.

Author’s contribution to papers

Paper A describes running time simulations on the basis of track design geometry. Suggestions concerning the track cant to be installed are given and line capacity briefly discussed in terms of distance between passing possibilities. The simulations and studies were performed and the paper written by Persson. The paper was reviewed by Andersson and Kufver.

Also **Paper B** describes running time simulations on the basis of track design geometry. Running time, however, is here linked to carbody motion and further to the risk of motion sickness. The simulations and studies were performed and the paper written by Persson. The paper was reviewed by Berg and Kufver.

Paper C describes evaluation of on-track motion sickness tests made by the EU-funded research project *Fast And Comfortable Trains* (FACT). Relations between carbody motions and motion sickness are derived. The paper also identifies potential problems with the correlation process. The evaluations were performed and the paper written by Persson. The paper was reviewed by Andersson and Kufver.

Paper D presents tilt algorithms aimed at balancing the conflicting objectives of ride comfort and less motion sickness. Speed profiles designed to avoid local peaks in the risk of motion sickness are also suggested. The tilt algorithms were proposed in collaboration with Kufver. The studies were performed and the paper written by Persson. The paper was reviewed by Berg and Kufver.

Finally, **Paper E** describes evaluation of on-track motion sickness tests where the algorithms proposed in **Paper D** were applied. The test setup and the evaluation process were proposed in collaboration with Berg, Kufver and Andersson. The tests were managed, the evaluations performed and the paper written by Persson. The paper was reviewed by Berg and Kufver.

Besides the papers in this thesis, other publications from this research project are listed below, but they are not formally part of the thesis.

B. Kufver and R. Persson. *On enhanced tilt strategies for tilting trains.* Proceedings of Comprail 2006, pp 839-848. ISBN 978-1-84564-177-9, WIT Press, Southampton 2006.

R. Persson. *Identification of areas where the competitiveness of tilting trains can be further improved.* Proceedings of Railway Engineering – 2007, Engineering Technics Press, ISBN 0-947644-61-10, Edinburgh 2007.

R. Persson. *Tilting trains, a description and analysis of the present situation*. Report. ISBN 978-91-7178-608-1. KTH Rail Vehicles, Stockholm 2007.

R. Persson. *Motion sickness in tilting trains - Description and analysis of the present knowledge*. Report. ISBN 978-91-7178-680-3. KTH Rail Vehicles, Stockholm 2008.

R. Persson. *Tilting trains - Technology, benefits and motion sickness*. Licentiate thesis. ISBN 978-91-7178-972-3, KTH Rail Vehicles, Stockholm 2008.

R. Persson. *Motion sickness in tilting trains*. Proceedings of the 43rd UK Conference on Human Response to Vibration, Leicester 2008.

R. Persson. *Weighting curves to motion sickness***.** Proceedings of the 44th UK Conference on Human Response to Vibration, Loughborough 2009.

R. Persson, R. Goodall and K. Sasaki. *Carbody Tilting – Technologies and Benefits.* Presented at the 21st IAVSD Symposium. Published in Vehicle System Dynamics, Volume 47, No 8, pp 949-981, 2009.

Thesis contribution

The objective of the work was to improve the competitiveness of tilting trains compared to non-tilting ones. The work focused on three main viewpoints: state-of-the-art technology, how the benefits might be increased, and how the drawbacks might be reduced. The thesis is believed to contribute to the international body of knowledge in the following way:

- The starting point of the technology aspect was the brief summary of tilting technology used worldwide and gathered by the International Union of Railways (UIC) [1] and [2]. The present study adds value by making a thorough review, which resulted in the licentiate thesis by the author [3] and a state-of-the-art-study made together with respected international colleagues and presented by the author at the IAVSD conference 2009 [4]. The introduction to the present thesis includes the tilt technology aspect.
- The greater benefit topic is a novel work based on the author's work experience. The main focus is on simulating running times, which are presented in **Papers A** and **B**. The relation of tilting capability, tractive performance and top speed to running time is explored. The link from running time to carbody motion and further to risk of motion sickness is described in **Paper B**.
- The viewpoint of reducing the drawbacks was focused on motion sickness early in the project. The EU-funded research project FACT [5] was the source of the first work within the present study on motion sickness. An evaluation of on-track tests made by FACT is presented in **Paper C**, which also identifies uncertainties in this evaluation process. Algorithms dedicated to selecting a tilt angle for good ride comfort and low risk of motion sickness were outlined together with Kufver in [6] and are further elaborated in **Paper D**. The algorithms are finally applied in an on-track test involving state-of-the-art tilt control evaluated and reported in **Paper E**.

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1 Introduction

A train and its passengers are subjected to lateral forces when the train passes horizontal curves. Carbody roll inwards, however, reduces the lateral acceleration felt by the passengers, allowing the train to negotiate curves at higher speed with maintained ride comfort. Roll may be achieved by track cant and/or carbody tilt. Trains capable of tilting the carbodies inwards in curves are called *tilting trains*. Tilting trains can be divided in two groups: the *naturally tilted trains* and the *actively tilted trains*.

Natural tilt relies on physical laws with a tilt centre located well above the centre of gravity of the carbody. In a curve, under the influence of lateral acceleration, the lower part of the carbody then swings outwards. Natural tilting is known as *passive tilting* in some countries. *Active tilt* may have carbody centre of gravity and rotation centre at about the same height. This form of tilt does not normally have an impact on the safety of the train, since the centre of gravity does not essentially change its (lateral) position. Active tilt relies upon control technology involving sensors and electronics and is executed by an actuator, usually hydraulic or electric. Without actuation there is no significant tilt action. However, natural tilt also often includes control and actuation to ensure satisfactory dynamic performance, in the present work called active tilt support.

The X2 (also known under the name X 2000), Figure 1, is a well known tilting train in Sweden today, but the first considerations and experiments to reduce the lateral force felt by the passengers and thereby allow higher speeds in curves date back to the late 1930s, Deischl [7] and Van Dorn & Beemer [8]. In 1938, Pullman built an experimental pendulum coach for the Atchison, Topeka and Santa Fe Railway which became the first tilting coach in service, Finance [9]. The novel designs were based on natural tilt. The first series of tilting trains were the Japanese class 381, which entered service between Nagoya and Nagano in 1973, and in 1980 Talgo Pendular trains were introduced in Spain, Talgo [10].

Figure 1: SJ class X2 with 6 passenger cars *[Stefan Nilsson]***.**

Active technology was introduced in 1965 when Deutsche Bahn (DB) converted a diesel multiple unit series 624 for tilt, Schäfer [11]. In 1972 a tilting version of series 624, called series 634, was put into service on the Cologne–Saarbrucken line as the first actively tilted train in commercial service. One important development chain for actively tilting trains was the development of the Pendolino trains, which began in 1969 with a prototype tilting railcar, the Y0160. The prototype was followed in 1975 by the Elettrotreni Rapidi (ETR) 401, which became the first Pendolino in commercial service, Finance [9]. Another important development chain began in 1973 when the Swedish State Railways (SJ) and ASEA signed a joint venture agreement concerning the X15, which developed the tilt technology for the later X2 series. Significant tilting train development in the UK was made as part of the Advanced Passenger Train programme reported by Boocock & King [12], and a small number of these trains operated for a few years between London and Glasgow, but they never reached fleet operation and were discontinued before the end of the 1980s. The break-through for actively tilted trains came around 1990 with the introduction of large series commercial trains, like the ETR450 in Italy and the X2 in Sweden. The Series 2000 trains were introduced in Japan at the same time and were the first naturally tilting trains with active tilt support. In 2007 the Shinkansen Series N700 became the first tilting train with a maximum speed above 250 km/h in service.

Carbody tilting is today a mature and inexpensive technology allowing higher speeds in curves and thus reduced travel time. The technology is accepted by many train operators. Today more than 5,000 tilting vehicles, defined as tilting carbodies, have been produced worldwide by different suppliers.

Tilting trains have lost some of their advantage in terms of running time compared to non-tilting trains because the latter have increased their speed on curves. Increased cant and an acceptance of higher lateral carbody acceleration have contributed to this speed increase. Tilting trains also benefit from these changes, but the relative speed enhancement decreases. The potential for travel time reduction by introducing tilting trains is today about 10–15% according to Persson [13].

Tilting trains are sometimes associated with motion sickness. Evidence of motion sickness on tilting trains has been reported from most countries with tilting trains and is here exemplified with a few reports, from Japan by Suzuki, Shiroto & Tezuka [14] and Ueno, Ogawa, Nakagiri, Arisawa, Mino, Oyama, Kodera, Taniguchi, Kanazawa, Ohta & Aoyama [15], in Sweden by Förstberg [16], in Switzerland by Hughes [17], and in France by Gautier [18]. In Japan, as many as 27% of the passengers experience motion sickness on tilting trains according to Ueno et al. [15]. 6% motion sickness was reported among test subjects in a test made by Förstberg [16] on the X2 train in Sweden and 8–15% motion sickness in a test involving different tilt control strategies, also conducted by Förstberg [19]. Tilting trains generally cause more motion sickness than non-tilting ones. This difference has attracted particular interest and was the starting point for the FACT project [5].

The objective of the work done for this thesis is to improve the competitiveness of tilting trains compared to non-tilting ones. The potential for enhanced benefits by further increasing speed is studied by identifying speed-limiting factors and making comparative running time calculations. However, the higher speeds will also increase the carbody motion amplitudes, which may relate to motion sickness. Higher speed thus seems to be contradictory to less risk of motion sickness, or do options exist? Finding the answer to this question has been a key task in the thesis work. One opening is the difference in time perception between ride comfort and motion sickness, where discomfort is related to momentary perceptions whereas motion sickness is related to aggregate perceptions. Algorithms that take advantage of this difference are proposed and tested by means of on-track tests.

2 Carbody tilting

2.1 *The principle of tilting trains*

The basic principle of tilting trains is to roll the carbody inwards during curve negotiation in order to reduce the lateral acceleration perceived by the passengers, *Figure 2*.

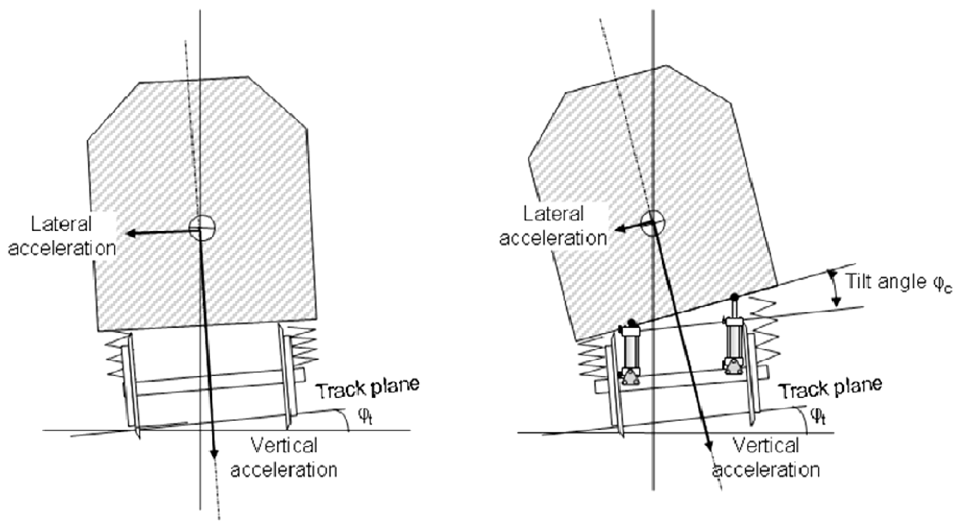


Figure 2: The basic concept of tilting trains. *Despite the higher track plane acceleration for the tilting train (right), the lateral acceleration in the carbody is lower than for the non-tilting train (left), Persson [13].*

When a train is running on a horizontal curve, there will be a horizontal acceleration that is a function of speed *v* and curve radius *R, Equation 1*.

$$a_h = \frac{v^2}{R} \qquad (1)$$

The lateral acceleration in the track plane can be reduced compared to the horizontal acceleration by arranging a track cant *D*. The angle between the horizontal plane and the track plane φ_t is a function of the track cant and the distance between the two nominal contact points of a wheelset $2b_0$, *Equation 2*.

$$\varphi_t = \arcsin(\frac{D}{2b_0}) \qquad (2)$$

The lateral acceleration, as perceived by the passengers, can be further reduced by arranging a carbody tilt angle φ_c relative to the track. The influence on (quasi-static) carbody accelerations from track cant and carbody tilt can mathematically be regarded as a transformation of the coordinate system. The lateral acceleration of the carbody is denoted $\ddot{y}$, *Equation 3*. The vertical acceleration, perpendicular to the carbody floor, is denoted $\ddot{z}$, *Equation 4*.

$$\ddot{y} = \frac{v^2}{R} \cdot \cos(\varphi_t + \varphi_c) - g \cdot \sin(\varphi_t + \varphi_c) \qquad (3)$$

$$\ddot{z} = \frac{v^2}{R} \cdot \sin(\varphi_t + \varphi_c) + g \cdot \cos(\varphi_t + \varphi_c) \qquad (4)$$

where g is the acceleration of gravity.

A reduction of carbody lateral acceleration through increased track cant and carbody tilt is associated with a slightly increased vertical acceleration. Typical values for quasi-static lateral and vertical accelerations are shown in *Table 1*.

Table 1: Typical values for carbody motion quantities in a horizontal curve.

Speed v [km/h]	Radius R [m]	Track tilt angle φ_t [deg]	Carbody tilt angle φ_c [deg] 1)	Lateral acceleration $\ddot{y}$ [m/s^2]	Vertical acceleration $\ddot{z}$ [m/s^2] 2)
104	1000	0	-1	1.0	-0.02
153	1000	5.7	-1	1.0	0.11
200	1000	5.7	6.5 3)	1.0	0.43

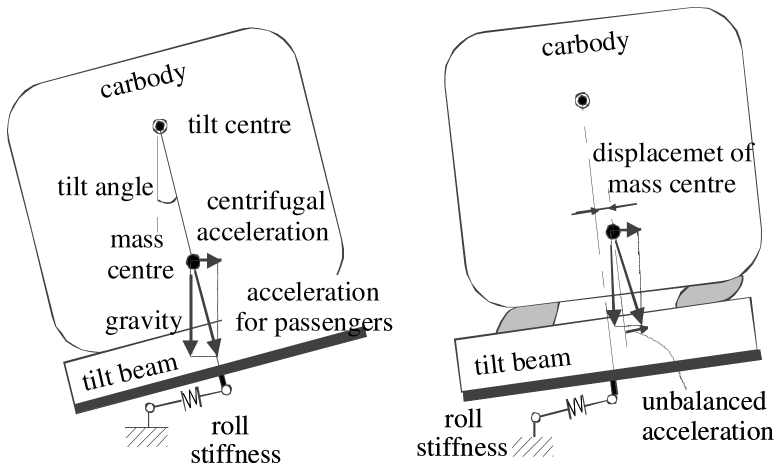
1) *Suspension deflections considered*
2) *The vertical acceleration is here given as offset from g*
3) *This tilt angle corresponds to an actively tilted train.*

The last row in *Table 1* represents what could be considered to be typical values for an actively tilting train, including the key decision on what proportion of the lateral acceleration in the track plane is to be removed in the carbody. This proportion is called the *compensation factor* and in the early days of tilting train development it was often assumed that the compensation should be 100%, but in fact this both increases the required angle of tilt and has implications on ride comfort and motion sickness, as discussed in Chapter 5. Compensation factors of 50-70% are typically used in today's actively tilting trains, whereas naturally tilting trains still retain compensation factors close to 100%.

2.2 *Natural tilting*

2.2.1 Introduction

Natural tilt relies on physical laws with a tilt centre located well above the carbody's centre of gravity. In a curve, under the influence of lateral acceleration, the lower part of the carbody then swings outwards. If there is no roll stiffness associated with the tilt centre then "perfect" tilting action will arise where no lateral acceleration is experienced within the carbody. In practice, however, there will usually be a non-zero roll stiffness which means that there will be some residual lateral acceleration *Figure 3 (left).* Today, natural tilting often includes control and actuation to ensure satisfactory dynamic performance, in the present work called active tilt support. Natural tilting is known as *passive tilting* in some countries. Natural tilt has a negative impact on safety due to the lateral shift of the carbody's centre of gravity.



(a) Without secondary suspension (b) With secondary suspension

Figure 3: The mechanism of natural tilting; *Persson, Goodall & Sasaki [4].*

In this system, the effective carbody centre of gravity including the effect of secondary suspension must be lower than the centre of tilting. The opposite relation between centre of gravity and tilt centre would result in an unstable condition. If flexibility is inserted between the tilting mechanism and the carbody, like the secondary suspension shown in *Figure 3 (right)*, the mass centre of carbody is given a lateral displacement due to the lateral acceleration, giving a resisting torque (displacement times carbody mass times gravity) that tends to reduce the tilt angle. The roll stiffness will further reduce the tilt angle and the tilting centre must thus be set with a certain height margin to the carbody's centre of gravity. Damping of the tilt motion is required to control the otherwise relatively undamped carbody roll motions.

The merits of natural tilting are as follows:

1. The system is simple and reliable.
2. The system has low initial and maintenance costs.
3. The control system is very simple if needed at all.
4. Inverse tilting can not occur.

The demerits of natural tilting are as follows:

1. The carbody's moment of inertia will delay the tilt motion. A low-frequency lateral acceleration, caused by imbalance between track plane acceleration and the compensation by tilting will thus appear in transition curves. This low-frequency lateral acceleration may be both uncomfortable and motion sickness inducing.
2. The high position of the rotation centre gives a lateral movement of the carbody mass centre, which increases the risk of overturning.
3. The lateral movement of carbody lower section reduces the possible carbody width where it is most needed.

2.2.2 Mechanical arrangements

Different mechanical arrangements can be applied to achieve natural tilt. The swing bolster with circular guide, see *Figure 4 (left)*, was invented in Japan and is still the most used tilting arrangement there. High-positioned springs were the first solution and this principle is still used by Talgo in their trains, see *Figure 4 (centre)*. The inclined anti-roll bar links was first proposed by SIG in their NEIKO design [20] and later by Bombardier in their WAKO design described by Schneider [21] and shown in *Figure 4 (right)*.

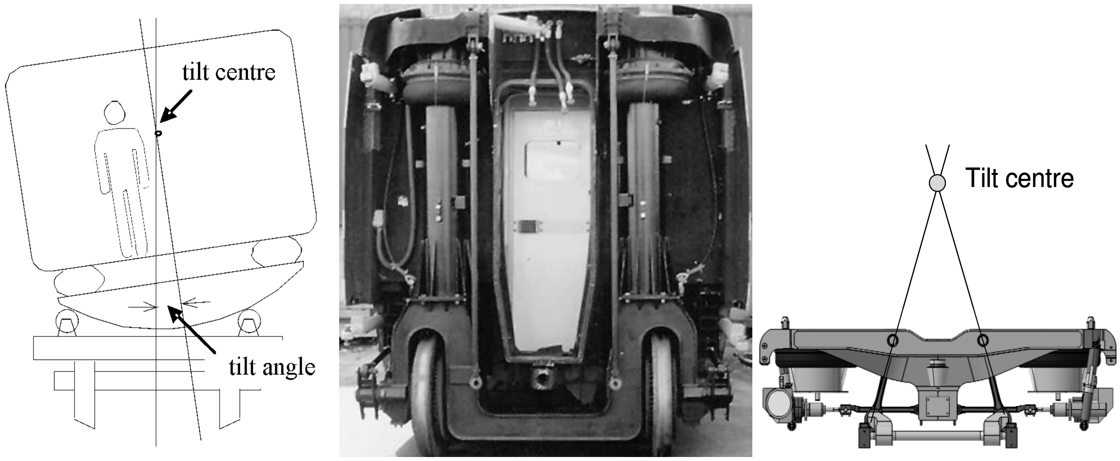


Figure 4: Mechanical arrangements for natural tilt. *From left: swing bolster with circular guide, Persson et al. [4], high-positioned springs, Talgo [10] and inclined anti-roll bar links, Schneider [21].*

Swing bolster with circular arc guide

Swing bolster with circular arc guide is a common solution in Japanese tilting trains. In this system, the bogie has a swing bolster (also called a tilting bolster), which allows motion along a circular path. The carbody is suspended on the tilting bolster; the carbody can thus tilt around the centre of the circular path of the tilting bolster. The carbody's centre of gravity is 600-900 mm lower than the tilt centre. Thus, the tilting centre is at the height of a sitting passenger's head. There are two types of tilting mechanism. One consists of a tilting bolster, which has a circular arc shape on the bottom surface and support rollers, *Figure 4 (left)*. The other type uses bearing guides, which are part of the circular arc guide rail. Both solutions allow the carbody to tilt 5 to 6 degrees.

Roll dampers are installed between the bogie frame and the tilting bolster to limit overshooting caused by the moment of inertia of the carbody. The characteristics of the roll damper are decided by the trade-off between motion overshoot and tilting delay in transition curves. Active tilt support is a means to improve the control of the motion. The function of this tilt support is similar to the control of actively tilted trains but with much lower force requirements.

High-positioned air spring

This arrangement is today only used by Talgo. A pair of air springs, that also serve as secondary suspension, are installed on high pillars on the running gear. The centrifugal acceleration will force the carbody to tilt around the centre of the air springs. An electro-pneumatic valve connects the two air springs to control the roll stiffness. The Talgo train is based on articulated running gear technology with a set of air springs at one end of the car. At the other end the carbody is connected to the next carbody by a bell crank mechanism that allows relative roll motion; the vertical links of the mechanism are visible in *Figure 4 (centre)*.

Its simple structure is a merit through its realization of natural tilting without any complex device or mechanism. On the other hand, the system is difficult to apply without passenger space intrusion on trains with conventional bogies.

Inclined anti-roll bar links

Similar to the high-positioned air springs solution, the mechanism with inclined anti-roll bar links uses the air springs as flexible roll elements. However, the springs can here be installed below the carbody since the motion is guided by the inclined anti-roll bar links whose intersection gives the centre of rotation. The tilting capability is less than other natural tilting arrangements and should be considered as compensating for suspension flexibility rather than providing tilt. The principle is a simple one but other suspension elements must be added to ensure proper lateral ride comfort. NEIKO applies additional conventional spring elements whereas WAKO makes use of active lateral suspension that also controls the tilt motion.

2.3 *Active tilting*

2.3.1 Introduction

Active tilt includes some form of mechanism by which the tilting of the carbody is created, and relies upon control technology involving sensors and electronics and is executed by an actuator, usually hydraulic or electric. Without the actuation there is no significant tilt action. This form of tilt does not normally have an impact on the safety of the train, since the centre of gravity does not essentially change its (lateral) position. Of course the overturning moment is still increased as a consequence of the higher curving forces, but it is not exacerbated by the lateral centre of gravity shift mentioned in the previous section and safety margins with active tilt only become unacceptable in high crosswinds. The issue of overturning is further discussed in Section 3.2.

As concluded in Chapter 1, active tilting has become the predominant tilting technology, at least for European railways. These systems require the following elements: a suitable mechanical arrangement to provide tilt, powered actuators to operate the system, and sensors and controllers to provide effective operation. Whereas the focus in Japan is upon natural tilting trains, most major European manufacturers offer trains based upon mature and effective active tilt.

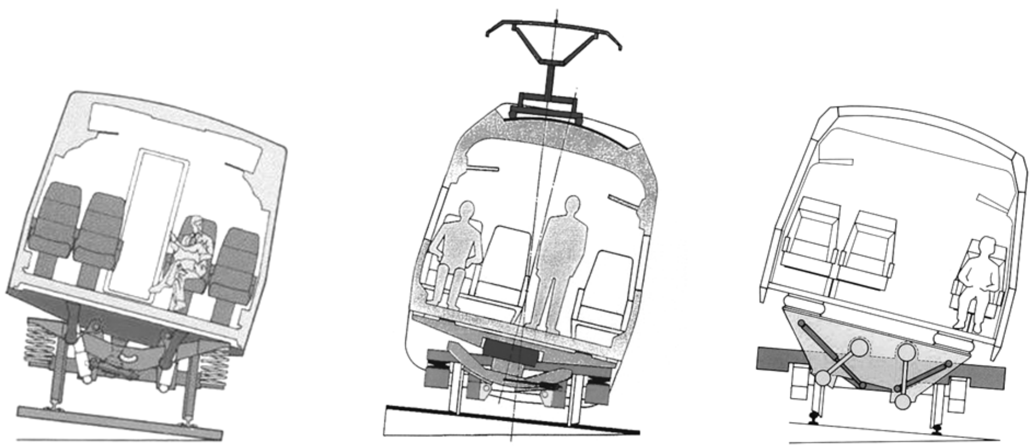


Figure 5: Modern active tilting trains: *ETR610, Alstom Pendolino, Bombardier X2, Persson et al. [4].*

The early Pendolino trains designed by Fiat in Italy have evolved progressively: they still retain the original tilt-above-secondary swing link scheme but the newest ETR610 trains have a much more compact mechanical arrangement – *Figure 5 (left).* The Alstom Pendolino trains for the UK take some of their technological heritage from Fiat but have introduced tilt-below-secondary using a circular roller beam for the bolster instead of the swing links *Figure 5 (centre*), Hauser [22]. The electro-mechanical actuators used are derived from developments in Switzerland by SIG prior to its acquisition by Fiat and subsequent merger with Alstom. The Swedish X2 train (*Figure 5 right*) has operated successfully in Sweden and elsewhere, with tilt-below-secondary using swing links and servo-hydraulic actuators. This is a similar mechanical scheme to that used by Bombardier for the Super Voyager trains in the UK.

2.3.2 Mechanical arrangements

The requirement for active tilt is to provide rotation somewhere around the carbody's centre of gravity, which both prevents lateral shift of the centre of gravity and the consequent reduction in safety (mentioned in Section 2.2), and also minimizes the impact on the vehicle cross-section to meet loading gauge requirements. Excluding the arrangements embodied in natural tilting, there are three mechanical arrangements that can provide an active tilting system. These are tilt across, tilt above and tilt below the secondary suspension.

The first approach, which can be called tilt *across* the secondary suspension, is to achieve tilt directly by applying active control to the secondary roll suspension. One method which has been tried in both Europe and Japan is to apply differential control to the air springs, but if valves are used to inflate and deflate the air springs this causes a dramatic increase in air consumption from the compressor, significantly higher than required for the braking system, for example, and has generally not found favour. However, one Japanese development has achieved it by transferring air between the springs using a hydraulically-actuated pneumatic cylinder; Higaki, Fugimori, Horike, Yasui, Koyanagi, Okamoto & Terada [23]. The alternative method of direct control of the roll suspension is by means of an active anti-roll bar (stabiliser), and this is applied in Bombardier's regional Talent trains, Dusing, Lu & Jakob [24]. This uses the traditional arrangement consisting of a transversely mounted torsion bar on the bogie with vertical links to the vehicle body, except that the links are replaced by hydraulic actuators and thereby apply tilt via the torsion bar.

Tilt across the secondary suspension is very much a minority solution, because most implementations use a tilting bolster to provide the tilt action. An important distinction is where this bolster is fitted relative to the secondary suspension, which leads to the second and third mechanical schemes. With the tilting bolster *above* the secondary suspension, the increased curving forces need to be countered by the secondary lateral suspension. This arrangement is used in the Italian Pendolino trains, see *Figure 5 (left)*. However, since a stiffer lateral suspension is not consistent with providing superior ride quality at the higher operating speed of a tilting train, in practice either greater lateral suspension movement or some form of active centring method is needed to avoid reaching the limits of travel. When the tilting bolster is *below* the secondary suspension, the base upon which the secondary suspension (usually air springs) is installed is now tilted. This avoids the increased curving forces on the lateral suspension, examples shown in *Figure 5 (centre and right)*. This is probably the most common of all schemes, the necessary rotation being achieved either using a pair of inclined swing links or a circular roller beam, in both cases designed to provide tilt about a "virtual" centre a little above the floor of the carbody.

2.4 *Actuation systems*

This section mainly refers to actively tilted systems, but also to the active tilt support sometimes applied to natural tilted systems.

2.4.1 Actuator technology

Some of the first actively tilting trains relied on active technology based on pneumatic systems where suspension elements were also the active elements, resulting in excessive compressed air consumption as mentioned above. An important technological step forward came with rollers and pendulums, which carry the carbody load and allow movement. The movement may then be controlled by an actuator that does not have to carry the carbody load, resulting in much lower energy consumption.

Servo-hydraulic actuator systems became the natural choice for the mechanically-oriented railway engineers. Such hydraulic systems have a hydraulic power supply comprising an electric motor that drives a pump that delivers a fixed pressure and electro-hydraulic valves to regulate the flow that supplies hydraulic cylinders fitted across the tilting arrangement.

The electro-mechanical actuators showed advantages and become an alternative in the 1990s. High-efficiency power amplifiers feed electric motors that drive screws fitted with high-efficiency ball or roller nuts to convert rotary motion to linear. *Figure 6* shows a typical electro-mechanical tilt actuator. They are less compact than hydraulic actuators at the point of application, but overall they provide significant integration benefits as they require less space.

***Figure 6: Electro-mechanical tilt actuator**, ESW [25].*

A hybrid technology is electro-hydraulic actuation, in which an electric motor driving a fixed-displacement pump is used with a sealed hydraulic circuit connected to normal hydraulic cylinders. Control is via the power amplifiers that feed the motors and there is no need for a separate hydraulic power supply. The solution is pointed out as the future activation system in Japan, which has until now tended to use pneumatic actuators; Enomoto, Kamoshita, Kamiyama, Sasaki, Hamada & Kazato [26].

2.4.2 Control and sensing

A good tilt system is one which reacts quickly so that the applied tilt follows as closely as possible the progressive rise in cant deficiency through curve transitions, but at the same time reacts as little as possible on straight track so as not to degrade the lateral ride quality; Goodall, Zolotas & Evans [27]. Control and sensing strategies have progressively developed to meet this requirement, from rather simple early methods to more sophisticated approaches that characterise today’s techniques.

Early ideas involved putting an accelerometer on the vehicle body to measure the lateral acceleration and provide a classical application of negative feedback in which the accelerometer signal is used to apply tilt in a direction that will bring it towards zero, see top view in *Figure 7*. However, the control loop embracing the secondary suspension was problematic; if the control loop bandwidth was set sufficiently low as not to interfere with the suspension it became too slow on curve transitions. This dynamic interaction can be avoided by putting the accelerometer on the tilting bolster, see *Figure 7 (centre)*. An even better solution was to move the accelerometer to the non-tilting part (bogie) of the vehicle to measure how much tilt was needed to reduce the carbody lateral acceleration to zero, and was then multiplied by a factor less than 100%, see *Figure 7 (bottom)*. Most active tilting trains today use a tilt compensation factor in the 50-70% range.

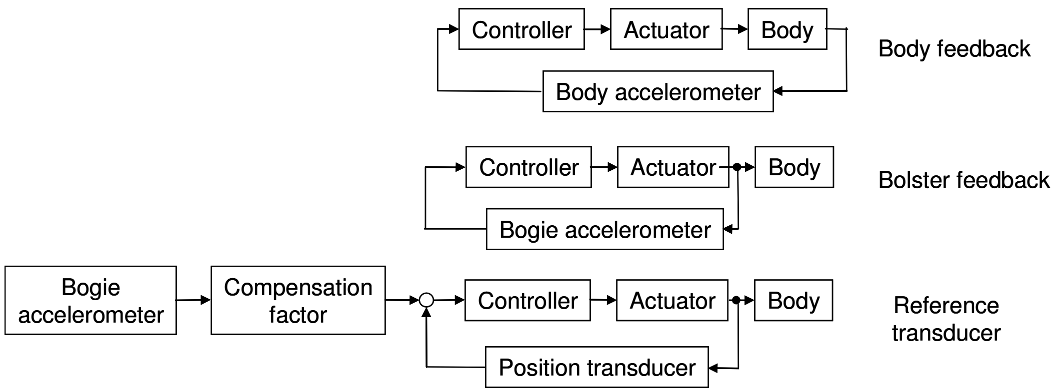


***Figure 7: Block diagram of tilting system layouts**, Persson [13]*

Because the accelerometer on the bogie not only measures the (quasi-static) curving acceleration but also lateral accelerations due to track irregularities (significantly larger when measured on the bogie), it is necessary to add a low-pass filter to reduce the effects of track irregularity. Unfortunately, sufficient filtering introduces a delay, resulting in a low-frequency lateral acceleration oscillation perceived by the passengers. Alstom's Tiltronix® system, shown in *Figure 8,* illustrates the sophisticated nature of modern tilt controllers that use lateral accelerometers and roll and yaw gyros to reduce delay and suppress the influence of track irregularity, Hauser [28].

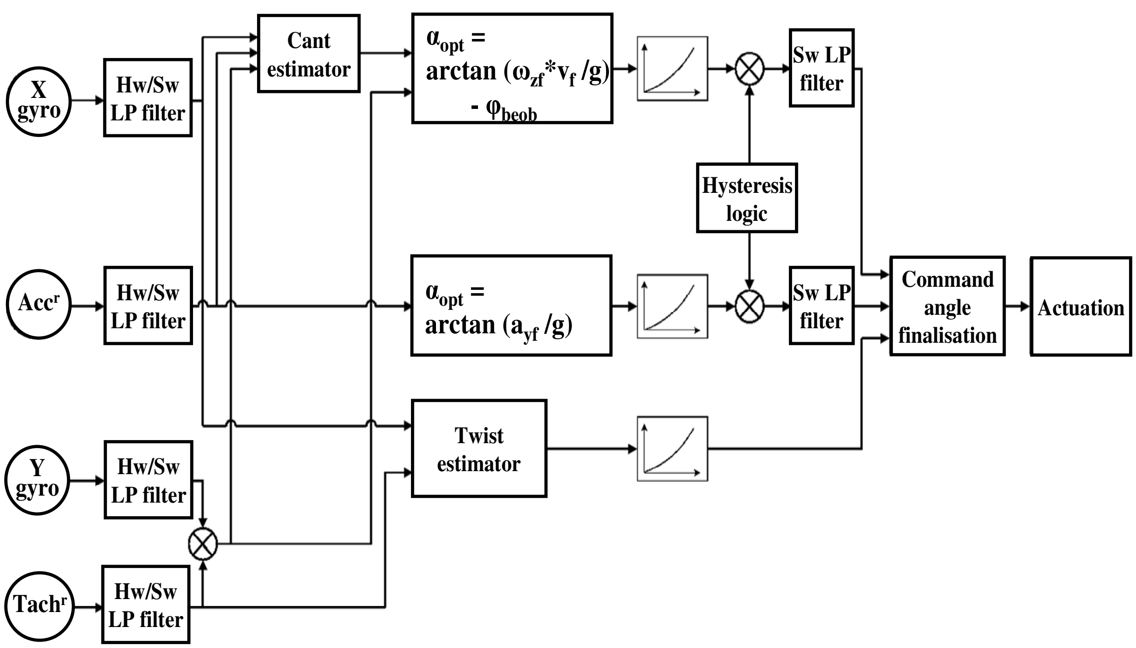


***Figure 8: Modern active tilting controller**, Hauser [28].*

An obvious development is to feed the tilt controllers with signals from a database which defines the track design geometry, instead of from quantities measured while running. *Figure 9* shows how this solution is applied to control natural tilt. An onboard computer stores data and the location of the curves. A train position detection system that uses the wayside transducers in an ATS (Automatic Train Stop) system shows the absolute location of the train and dead reckoning is used to obtain the running distance from the last absolute location. The control system is able to start the tilting motion before entering the curves by means of preview control using the onboard database. This reduces the tilting delay significantly and thereby also the low-frequency lateral acceleration that may otherwise cause motion sickness in sensitive passengers. The solution can be made independent of the ATS-system by means of GPS (Global Positioning System) as described in **Paper E**. Curve matching is another possible solution suggested by Sasaki [29], where the track design geometry is estimated from the train's measured data and compared with the database to find the position of the train. Such functionality is part of Alstom's Tiltronix® system, Hauser [28].

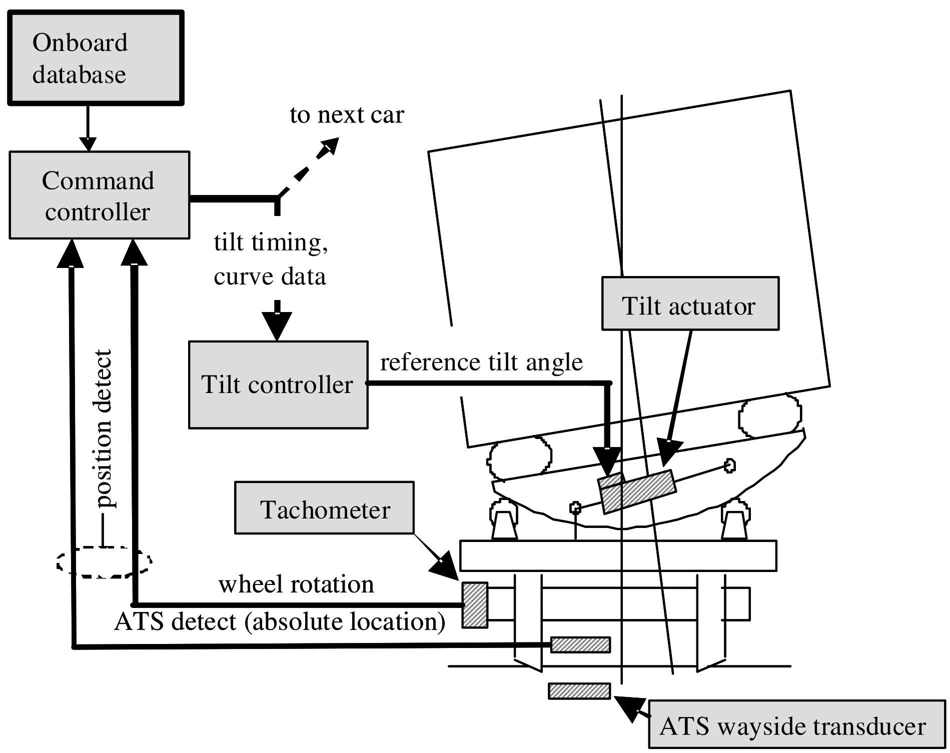


***Figure 9: Structure of controlled natural tilting**, Sasaki [29].*

3 Vehicle–track interaction

The vehicle-track interaction is well documented in textbooks such as those by Iwnicki [30] and Andersson, Berg & Stichel [31], which deal with most aspects of the subject. The purpose of this chapter is limited to identifying speed limitations due to vehicle-track interaction.

3.1 *Track forces*

Identifying track forces is a natural part of the homologation (certification) process for railway vehicles. Standards, for example CEN [32], define requirements regarding track shift forces, derailment ratio, lateral wheel forces and vertical wheel forces. The track forces are often measured with measuring wheelsets to show compliance with the requirements. The standards normally consider three quantities in the on-track tests to be safety critical: the risk of shifting the track laterally, the risk of derailment due to wheel flange climbing, and running instability. These three quantities are here considered from the viewpoint of being limiting for enhanced speed of tilting trains.

3.1.1 Track shift forces

Track shift force is the sum of lateral wheel-rail forces on a wheelset and relates to the risk of shifting the track laterally when a train passes. The criterion is also known as the Prud'homme criterion after the originator, Prud'homme [33]. The track shift force can be divided into two parts: a quasi-static part and a dynamic part. The quasi-static part is dependent on cant deficiency, which is higher for a tilting train than for a non-tilting one. The dynamic part is dependent on speed, which (for the same curve radius) is also higher for a tilting train than for a non-tilting one, assuming that no improvements are made to the running gear and suspension. According to Andersson & Halling [34], important factors for keeping the track shift forces below the specified limits are:

1. Low static loads (impact on quasi-static part)
2. Low unsprung mass (impact on dynamic part)
3. Suspension characteristics (impact on dynamic part and the radial steering ability, which influences the quasi-static force distribution between the two axles in a bogie).

The subject has been studied by, among others, Kufver [35] and Lindahl [36] by means of simulation of the vehicle-track interaction for high-speed tilting vehicles. They found that track shift forces can be safety-critical for tilting vehicles at high speeds. At 360 km/h Lindahl set the maximum allowed cant deficiency to 275 mm from the track-shift point of view when assuming track irregularities of today's 200 km/h track in Sweden. However, the aim of the present study is to enhance speed on existing lines with a target speed of about 250 km/h. A slight improvement of the track irregularity level might be needed, but it is not the track shift forces that set the limits for enhanced speed in the first step.

3.1.2 Derailment ratio

The ratio between lateral and vertical track forces on a wheel is often used as the derailment criterion, also known as the flange climbing criterion. The lateral force on the flange is here balanced by the vertical force at the same wheel. The risk of derailment is higher at low speeds than at high speeds since tracks for low speeds may have tighter curve radii and larger track irregularities. A tilting train runs under such conditions at the same speed as non-tilting ones and it is not under these conditions the speed should be increased further.

3.1.3 Running instability

Running instability can be evaluated from either track shift forces or bogie lateral accelerations. The input quantity is in both cases band-pass filtered around the assumed bogie instability frequency and compared to a limit value. Instability is mainly a straight-track problem that generally increases with speed, but can occur at high-speed curving as well. The risk is to some extent mitigated by better track, less worn rails and larger minimum track gauge, at higher speed. The requirements regarding running stability and track shift forces also counteract each other, since the suspension characteristics advantageous for track shift forces may be disadvantageous for running stability. This counteraction is particularly evident in high-speed tilting trains. However, tests within the Swedish research programme Gröna Tåget (Green Train) have proven that it is possible to develop a bogie with good curving performance to meet the track forces requirements and with sufficient stability margin for at least 250 km/h; Andersson, Orvnäs & Persson [37].

3.2 *Crosswind stability*

Crosswind stability is an area where much research is in progress. Different calculation methods have been suggested and applied by different researchers. Flange climbing is not considered to be safety-critical for crosswind, since an increased lateral force is accompanied by an increased vertical force on the potentially climbing wheel. Crosswind stability is rather an issue due to the risk of overturning the vehicle about the outer rail in curves. Studies of crosswind stability use simulations, where a certain load margin should remain on the wind-side (inner) wheels.

The Association Européenne pour l'Interopérabilité Ferroviaire (AEIF) has included guidance on crosswind stability in a standard for interoperability, [38]. This standard does not explicitly deal with tilting vehicles at enhanced speed. A comparative technique based on Characteristic Wind Curves (CWC) is described. These curves show the maximum crosswind speed as a function of vehicle speed, *Figure 10*, where the wheel unloading criterion should be fulfilled. The selected reference vehicles are: the Inter-City-Express (ICE) -3, the Train à Grande Vitesse (TGV) Duplex and the ETR500, all non-tilting high-speed vehicles. Any other vehicle used on interoperable lines must have better or equal CWCs than these reference vehicles.

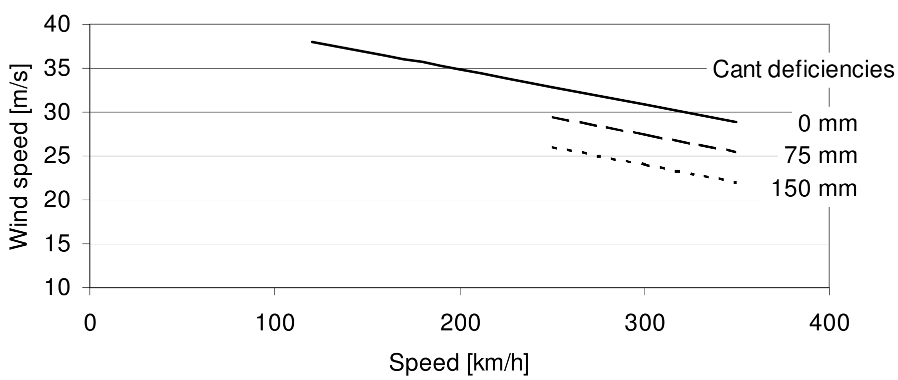


Figure 10: Characteristic wind curves as functions of speed*, for different cant deficiencies at standard track gauge, in the flat ground case, Persson [13].*

AEIF [39], states that the infrastructure manager must, for each interoperable line, ensure that the conditions on the line are not more severe than the reference vehicles can handle. Suggested measures in infrastructure and operations to ensure safety are:

1. Locally reduced train speed, possibly temporary during periods of risk of storms
2. Installing equipment to protect the actual track section from crosswinds
3. Taking other necessary steps to prevent vehicles overturning.

Extending the requirements shown in *Figure 10* to the high cant deficiencies used by tilting trains would result in lower critical wind speeds and/or lower permissible cant deficiencies at high speed. A better approach would be to take advantage of the possibilities to improve the vehicle to resist crosswinds better than today's reference vehicles. Diedrichs, Ekequist, Stichel & Tengstrand [40] showed the relations between different properties of vehicle and crosswind stability. The vehicle properties studied with respect to crosswind stability were:

1. Train height
2. Train width
3. Carbody vertical centre of gravity
4. Mass of leading bogie
5. Nose shape, cross-section shape and other properties that affect the aerodynamic coefficients of the vehicle
6. Train speed
7. Air density (dependent on air pressure and temperature).

The property with the strongest relation to crosswind stability was the train height.

The interesting question now arises: can modifications of the vehicle design totally mitigate the risk of overturning in the vehicle speed and cant deficiency ranges of the present study?

Lindahl [36] has simulated crosswind stability for tilting vehicles at very high speed. He found a relation between wind speed and possible cant deficiency for the vehicles. As an example, at a speed of 350 km/h the vehicle could sustain a constant crosswind of 23 m/s at 250 mm of cant deficiency. Lindahl used a fictitious but realizable vehicle with good crosswind properties. A study closer to the scope of the present work was made by Andersson, Häggström, Sima & Stichel [41]. They studied the risk of overturning on Botniabanan, a costal line in northern Sweden built for a maximum speed of 250 km/h for tilting trains. Andersson et al. arrives at the same crosswind and cant deficiency as Lindahl, but at a lower speed. Andersson et al. used properties of today's tilting trains in their study. The significant speed difference shows the potential in vehicle improvement.

The study by Andersson et al. gave one combination of vehicle speed and cant deficiency, but there is a need for a relation giving a permissible cant deficiency as a function of vehicle speed. This relation can be derived from Lindahl [36] and *Figure 10* to approximately 1 mm lower permissible cant deficiency for 1 km/h of increased speed. This relation was used in some of the running time calculations in the next chapter.

4 Analysis of services suitable for tilting trains

This chapter gives selected viewpoints on the suitability of tilting trains. Running time is the most important aspect but there are others. Running time benefits based on allowed speeds in curves often exaggerate the benefit of tilting trains. Some more realistic running time gains are given by operators and research organisations like KRRI for two Korean mainlines [42], which indicate running time benefits of 16% and 18%. However, even these benefits are unfair as they compare today's services with a new tilting train. Simulated running time benefits on equal basis for two rather different Swedish mainlines can be found in Section 4.2.

4.1 *Running speed benefits*

Running speed benefits can be derived from the relations between enhanced permissible speed for tilting trains and the permissible speed for non-tilting trains. These requirements can be found in national track standards, but the levels vary. A study of the running speed benefits was made by Kufver for the FACT project [43]. The conclusions are summarized by Persson et al. in [4] and shown in *Table 2*.

***Table 2: Running speed benefits calculated for today's national track standards**, [4]*

Track segment	Guiding property	Relation between permissible speed for active tilting and non-tilting trains	
		Sweden	All networks 1)
Circular curves	Cant + Cant deficiency	115%	111-122%
Cant transitions	Rate of change of cant	118%	85-131% 2)
Transition curves (with coinciding cant transitions)	Sum of rate of change of cant and rate of change of cant deficiency	113%	97-116% 2, 3)

1) Countries considered are the Czech Republic, France, Germany, Italy, Norway, Spain, Sweden, the UK and Japan.
2) Japan is the only country with more restrictive limits for tilting trains than for non-tilting ones.
3) France and Germany have no limit on the rate of change of cant deficiency.

4.2 *Running time benefits*

Running time is a better measure of the benefit of tilting trains than running speed. A good estimation of the running time benefits with tilting trains can be obtained with running time simulations. The running time benefit is then derived by simulation on a selected railway line indicating a realistic running time benefit compared with non-tilting trains. The assumptions for calculations can be kept simple, for example enhanced speed compared to non-tilting trains is allowed on the same track sections as today and that the speed on these sections is set from only a cant deficiency perspective. Limitations on cant excess for low speed trains and limitations on cant deficiency due to crosswind are considered here. Despite the simple assumptions concerning speed, the author's investigation became very extensive due to the many input variables, which included the train's maximum speed, train power, starting acceleration, braking deceleration, permissible cant deficiency and stopping pattern on two full lines, Stockholm–Gothenburg and Gothenburg–Kalmar. An Excel-based simulation program developed by Bombardier UK was used. The program calculated the running time step by step based on route data and vehicle characteristics. Most of this work can be found in Persson [13], but also to some extent in **Papers A** and **B**.

The two studied lines were selected to show the potential for tilting trains on lines with different conditions. The Stockholm–Gothenburg line has a variety of horizontal curves ranging from 352 m radius and up. The numerous curves with about 1,000 m radii are often speed setting, but there are fairly straight sections where the top speed of the trains can be exploited. The Gothenburg–Kalmar line has many more tight curves ranging from 206 m radius and up. The speed profile becomes more fluctuating than for Stockholm–Gothenburg as there is no dominating curve radius and the top speed of the train can seldom be used.

Comparing two solutions of *today*, a non-tilting train with a maximum cant deficiency of 150 mm and a tilting train with 245 mm maximum cant deficiency, gives a 15% running speed benefit for the tilting train. The corresponding simulated running time benefit on both lines was 9% in favour for tilting trains. The time benefit is an average of all combinations of top speed, power and acceleration/braking performance.

A comparison between two *future* solutions, a non-tilting train with a maximum cant deficiency of 168 mm and a tilting train with a 275 mm maximum cant deficiency, gives a 16% running speed benefit for the tilting train. The corresponding simulated running time benefit is 10% on both studied lines.

As expected, the simulated running time benefits were less than the running speed benefits. There are several reasons for this the main one being that speeds are set on other grounds than only cant deficiency at straight track, stations, bridges, etc. It may be worth noting that a non-tilting train with a maximum cant deficiency of 168 mm and a top speed of 275 km/h will have a longer running time than a tilting train with a maximum cant deficiency of 275 mm and only 200 km/h top speed on the Stockholm–Gothenburg line. Non-tilting high-speed trains are therefore not an alternative on this type of line when travel time counts.

4.3 *Further viewpoints on suitability of tilting trains*

Distance between stops

The results of the two studied lines above show the advantage of tilting trains; both lines are examples of services with long or intermediate distances between stops. For short distances between stops, improved tractive power is a better choice than tilt. More tractive power gets the train up to speed faster while tilting capability increases the line speed on curved lines. A break-even distance of 6-20 km was found by Persson [13] but this differs considerably depending on the conditions.

Line capacity

Introducing tilting trains or enhancing the speed of existing tilting trains will increase the relative average speed compared to other trains on the line. This will reduce line capacity on double-track lines. The reduced line capacity can to some extent be restored by building more passing possibilities to allow faster trains to overtake slower ones. Building new dedicated high-speed lines adds capacity to the network and may be a choice when reduced travel time and capacity is requested, although at a higher cost than tilting trains on existing lines.

Upgraded track or tilting trains?

Tilting trains can in some cases be an alternative to upgrading the lines to larger curve radii. This solution was suggested by Eicher [44] for the Swiss services between Lausanne and Zurich to achieve a regular-interval timetable with train crossings at the passenger exchange points. The cost of an infrastructure upgrade is assumed to be higher than the additional cost of tilt, including the higher cost of acquisition and lifetime support for tilting trains.

5 Human response

5.1 *Ride comfort*

The comfort of passengers in railway vehicles is influenced by a number of different factors such as temperature, noise, vibration, etc. The passenger comfort considered here is the part influenced by dynamic behaviour of the vehicle, excluding motion sickness which is discussed in Section 5.2. A state-of-the-art report on passenger ride comfort was made by Griffin [45], which covered most aspects of the subject. The focus here is on the difference between tilting and non-tilting trains running on the same track on which the tilting train runs both faster and at a higher track plane acceleration (cant deficiency).

5.1.1 Average ride comfort in one direction

The present techniques to evaluate average ride comfort imply measurement (or simulation) of carbody accelerations and apply frequency weighting of the measured signals. Weighting curves valid for the three directions can be found in the International Standards Organization (ISO) document [46], the lateral weighting curve being shown in *Figure 11*. The European Committee for Standardization (CEN) [47] provides further guidelines applicable to rail vehicles. The process starts by taking the average rms values of accelerations during 5-second periods. The population of several periods is then subjected to statistical evaluation. The requirements could be set as a certain percentage of the population should meet the limiting value. Weighted accelerations up to 0.3 m/s^2 rms are considered comfortable.

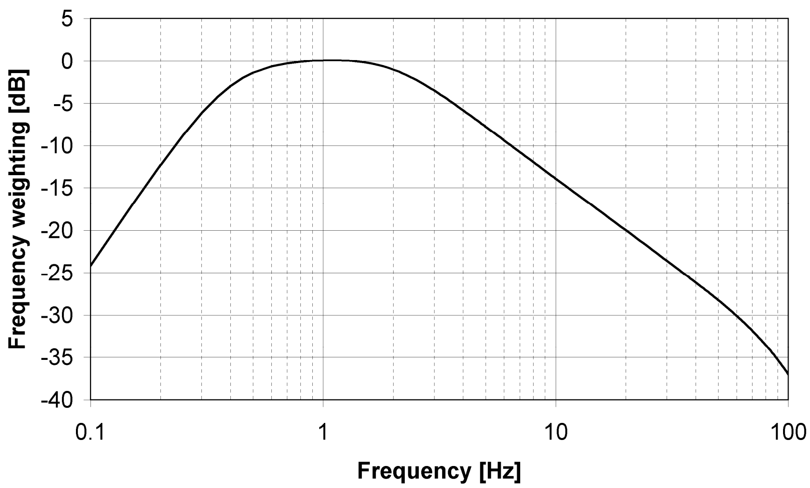


***Figure 11: Weighting function W_d, for lateral acceleration to ride comfort**, ISO [46].*
The weighting function shown includes the band limiting filter.

The accelerations related to the vibrations and motions of the vehicle generally increase with increased speed. Ride comfort evaluation based on weighted accelerations will therefore commonly deteriorate with increased speed. And, since tilting trains run faster than non-tilting ones on the same track, ride comfort may be degraded. Further, lower ride comfort does not fit well with passengers' expectations of a faster train and must thus be counteracted by reduced vibration transfer from track to passenger, i.e. improved vehicle suspension.

5.1.2 Combination of different directions

ISO [46] recommends use of a total value of weighted rms acceleration for comfort and describes how this could be determined from vibrations in orthogonal coordinates by use of a quadratic mean. ERRI has further elaborated this method for railway applications against a comfort index, which is described in CEN [47]. The evaluation is based on populations calculated in one direction from which one value corresponding to a certain percentile of the population is taken. The selected values are then combined into one by calculating the quadratic mean. The use of just one value from each direction gives the method some questionable features, as described by Kufver, Persson and Wingren [48]. The conclusion regarding the role of vehicle suspension is the same as previously described.

5.1.3 Comfort on curve transitions

The higher track plane acceleration for tilting trains compared to non-tilting ones is well compensated by the tilt when it comes to lateral acceleration perceived by the passenger. The tilt normally also compensates for the shorter time in curve transitions when evaluating lateral jerk perceived by the passenger. However, the reductions in lateral quantities are achieved by rolling the carbody inwards in the curve, thus increasing the roll motions in curve transitions, which may cause discomfort. Criteria for comfort in transition curves seek to combine the influence of lateral and roll motions into one criterion. One such criterion is the P_{CT} Comfort index given by CEN [47], which calculates the percentage of passengers dissatisfied on the basis of *Equation 5.* The TC_T Comfort index by Suzuki, Shiroto, Tanka, Tezuka & Takai [49] is another criterion for transition curves that calculates the discomfort on a 1 to 4 scale, where 1 is not uncomfortable and 4 is extremely uncomfortable, by means of *Equation 6*. Both equations are here given with coefficients applicable to seated passengers, but there are also coefficients validated for standing passengers. The P_{CT} and the TC_T criteria have several similarities and will in practical use lead to similar results.

$$P_{CT} = \max\left\langle (8.97 \cdot |\ddot{y}_{1s}|_{\max} + 9.68 \cdot |\dddot{y}_{1s}|_{\max} - 5.9);0 \right\rangle + 0.12 \cdot (|\dot{\varphi}_{1s}|_{\max})^{1.626} \qquad (5)$$

$$TC_T = 0.4 \cdot \ddot{y} + 0.4 \cdot \dddot{y} + 0.02 \cdot \dot{\varphi} + 0.04 \cdot \ddot{\varphi} + 0.8 \qquad (6)$$

where $\ddot{y}$ = Lateral acceleration in carbody [m/s^2], $\dddot{y}$ = Lateral jerk in carbody [m/s^3], $\dot{\varphi}$ = Roll velocity in carbody [degrees/s] and $\ddot{\varphi}$ = Roll acceleration in carbody [degrees/s^2].

5.2 *Motion sickness*

Motion sickness is a normal response to real, perceived, or even anticipated movement. The response is believed to be generated by conflicting signals between human sensors due to low-frequency movements. It is typically experienced by passengers in automobiles, on trains, on ships, on airplanes and more. The phenomenon is far less common among drivers indicating that foreknowledge of movement allows a human being to understand the nature of the movements to be experienced. One of the first reports on motion sickness dates back to the 5th century BC when, according to Reason & Brand [50], Hippocrates is said to have declared that sailing on the sea disorders the body. Motion sickness has a long connection with psychology, exemplified by early laboratory tests conducted by Purkinje at the beginning of the 19th century with the purpose of treating mentally ill people by inducing nausea. Motion sickness is documented in textbooks such as those by Reason & Brand [50] and Griffin [51], which deal with most aspects of the subject. The purpose of this section as well as the literature study by Persson [52] is to summarize information that can contribute to explain the motion sickness experienced on tilting trains.

5.2.1 Signs and symptoms

Motion sickness can generally be explained as feeling dizzy or nauseated, but there are plenty of signs and symptoms that can be related to motions sickness. Several of these are common to stress. Collecting them into groups improves understanding, but the split is not obvious. *Table 4* shows one possible grouping that indicates what type of signs and symptoms that may be expected in cases of motion sickness. The "objective group" is interesting since these signs and symptoms can be used as objective measures of the degree of motion sickness.

Table 4: Examples of signs and symptoms of motion sickness found in the literature

Gastro-related	Somatic	Objective	Emotional
Stomach awareness	Dizziness	Skin humidity	Anxious
Nausea	Exhausted	Pulse rate	Nervous
Inhibition of gastric motility	Increased salivation	Blood pressure	Scared
Sick	Yawing	Body temperature	Tense
Queasy	Drowsiness	Respiration rate	Apathy
Retching	Hot / Warm		
Vomiting	Cold sweating		
	Increased salivation		
	Headache (especially frontal)		

5.2.2 Motion sickness questionnaires

Questionnaires with a selection of signs and symptoms and different scales play an important role in judging the degree of motion sickness. These questionnaires can be divided in one-dimensional and multi-dimensional. Graybiel, Wood, Miller & Cramer [53] developed the Pensacola Diagnostic Index (PDI) which is an example of a multi-dimensional symptom list. Graybiel et al. use nausea, skin pallor, cold sweating, increased salivation and drowsiness and call them the *big five* symptoms. They scale and add the symptoms to a total sickness score. The score is finally transferred to a severity expression ranging from severe sickness to slight malaise.

The one-dimensional questionnaires are scales, also called nausea rating scales, used in particular in field tests since they condense information from large quantities of data in a convenient way. Lawther & Griffin [54] developed the *illness rating* (IR) scale; the IR scale is derived from the PDI but transferred to a one-dimensional well-being scale. The original IR scale had four levels, but Turner [55] modified the scale to have 5 levels for improved resolution, *Table 5*. Förstberg [19] chose to extend the scale further to 7 levels, which is also used in **Papers C** and **E**.

Table 5: Modified illness rating, Turner [55]

Label	Scale
I feel alright	0
I do not feel quite well	1
I feel rather unwell	2
I feel bad	3
I feel very bad	4

5.2.3 Evidence of motion sickness

Some examples are given here to show the breadth of the motion sickness problem.

Air

Turner, Griffin & Holland [56] claim that air sickness remains a problem today for passengers on small aircraft only. 8.4% of the passengers reported motion sickness during short-haul flights on small aircraft.

Space

Motion sickness in space has been well known since the first space flights, Lackner & DiZio [57]. They report that 70% of the astronauts on the first space missions suffered motion sickness and that incidence is lower for experienced astronauts. Despite training programs for adaptation or habituation, motion sickness in space remains a problem.

Sea

As mentioned in the introduction to motion sickness, this response at sea has a long history. More recent research is conducted by Lawther & Griffin [58] reporting from an extensive passenger survey on ferries crossing the English Channel; 7% experienced motion sickness among 20,000 passengers.

Road

Passengers are much more prone to motion sickness than drivers. Turner & Griffin [59] report that 13% felt nausea in a questionnaire study of 3,256 coach travellers. Poor forward visibility was associated with increased sickness.

Simulators

Motion sickness in simulators has been acknowledged as a problem since the 1950s when helicopter pilots became sick during training in flight simulators, Casali & Frank [60]. Motion sickness is also reported for conditions involving visual stimuli only, such as Cinerama and simulators without motions. Delorme & Marin-Lamellet [61] give one example of the latter, reporting that only 50% of the test subjects could fulfil a drive in a car simulator without a motion platform.

Rail

As mentioned in Chapter 1, tilting trains are claimed to cause more motion sickness than non-tilting ones. However, fair comparisons are seldom possible as conditions like train type, track section or speed differ. There are several pieces of evidence of motion sickness for both tilting and non-tilting trains in service. Kaplan [62] reported that 0.13% of the passengers suffered motion sickness among 370,000 passengers on the non-tilting trains on the Baltimore and Ohio Railroad. Quite a contrast comes from Suzuki, Shiroto & Tezuka [14], who reported that 18% of the passengers experience motion sickness on non-tilting trains. The data comes from a large passenger survey made on 14 different types of train on the conventional narrowgauge Japanese network. The span of the reported sickness shows the difficulties involved in giving a general level of motion sickness. Some of the difference is due to the reporting method, where Kaplan merely counted complaints while Suzuki et al. asked passengers. The 18% reported for non-tilting trains in Japan could possibly be compared to the 27% reported by Ueno et al. [15] on the naturally tilted Japanese train class 381. Evidence of motion sickness in tilting trains has also been reported in Europe by Förstberg [16], Hughes [17] and Gautier [18], as mentioned in Chapter 1. The extent of motion sickness in Europe seems to be less than in Japan since even provocative on-track tests with active tilting trains show motion sickness levels of about 10%, Förstberg [19].

5.2.4 Hypotheses of motion sickness

The sensory conflict is the most common explanation to motion sickness. The different sensitive capabilities of the human motion information sources give a sensory conflict. This conflict can be exemplified by a passenger sitting on a moving train, looking inside and feeling the movements but unable to see them. The theory has been developed over the years by for example Claremont [63], Reason & Brand [50] and Benson [64], and can today explain most motion sickness situations.

One model of the conflict theory is given by Bles, Bos & Kruit [65], *Figure 12*. The model consists of two paths, the top path representing the actual information from the sensors processed by the Central Nervous System (CNS) and the lower path the internal model, which estimates the effect of a given motion command (active motions). The estimated and the actual information are compared, and a conflict signal is generated if they differ. In the model habituation is represented by the conflict feedback, which leads to an update of the internal model. Passive motions (without motion command) are in the model represented by external influence; these can by themselves create conflict because the external influence does not have any direct influence on the internal model. Under influence of external motions active motions may result in conflict.

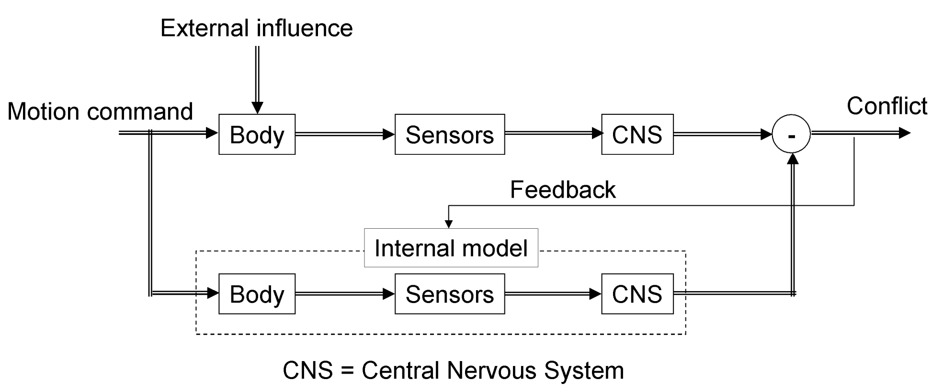


***Figure 12: Model of the conflict theory**, modified from Bles et al. [65].*

The conflict can also be described by the difference between the sensed direction and the expected direction of *vertical*. The conflict is described by Bles, Bos, de Graaf, Groen & Wertheim [66] as follows:

> "Situations which provoke motion sickness are characterized by a condition in which the sensed vertical as determined on the basis of integrated information from the eyes, the vestibular system and the non-vestibular proprioceptors is at variance with the subjective vertical as expected from the previous experience."

Most researchers have today accepted the sensory conflict theory, but there are also competing theories. The over-stimulation theory is one and is based on over-stimulation of sensors rather than conflict between different human sensors. Supporters of the theory give examples where no conflict is involved such as low-flying fighter aircraft where the only input comes from the pilot's vision. Riccio & Stoffregen [67] proposed another competing theory on the basis of ecological evolution. They claim that no sensory conflict exists and suggest that motion sickness is caused by postural instability associated with environmental situations that destabilize the postural control system. Supporters of the theory give examples where conflicts are involved without causing motion sickness.

5.2.5 Frequency dependence of motion sickness

O'Hanlon & McCauley [68] derived a relationship of motion sickness incidence (vomiting) to motion frequency and amplitude. This relationship became the basis for a frequency weighting function between vertical acceleration and motion sickness, which became accepted by ISO and denoted W_f [46], see *Figure 13 (top)*. This weighting function is primarily applicable to standing or seated passengers exposed to motions on ships. The function has been used in railway environment, but has also been challenged in this application by Persson [69]. Weighting curves were in that study calculated between measured vertical acceleration and non-zero motion sickness experienced at on-track tests, showing an increased sensitivity at lower frequencies, see *Figure 13 (top)*.

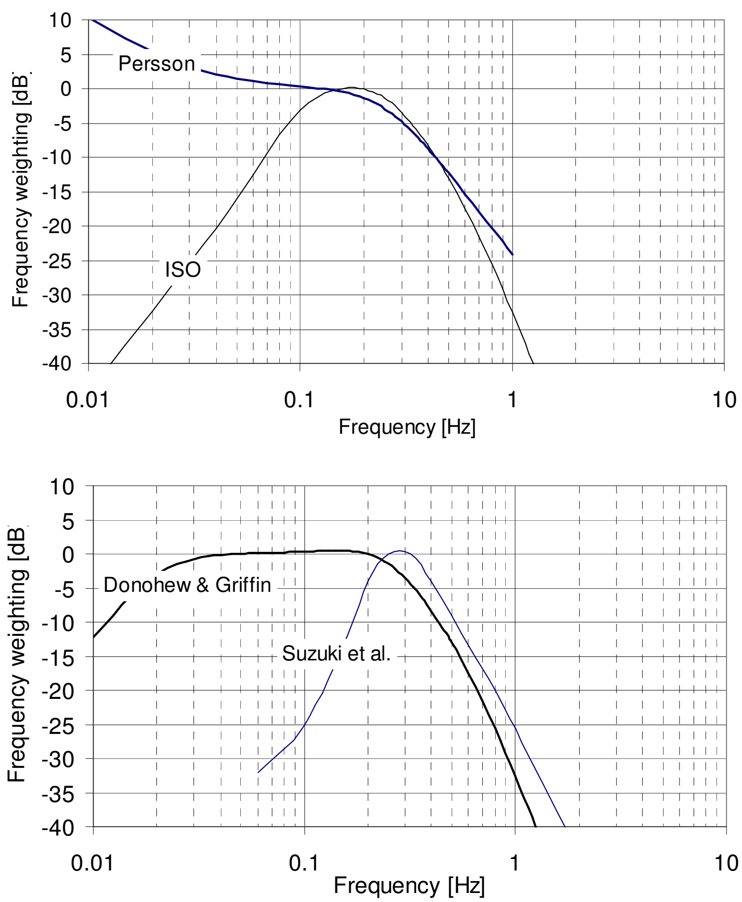


Figure 13: Weighting functions for acceleration to motion sickness.
Vertical acceleration (top), ISO [46], Persson [69].
Lateral acceleration (bottom), Suzuki et al. [49], Donohew & Griffin [70].

Donohew & Griffin [70] proposed a weighting function for the lateral direction. The result was based on laboratory tests with pure lateral motions. Suzuki et al. [49] have investigated the relation between motions and motion sickness in natural tilting trains under various conditions on Japanese commercial lines. Suzuki et al. derived a relation between the percentage of people who felt absolutely dreadful and weighted lateral acceleration. The result of their investigation is shown in *Figure 13 (bottom)*, which also shows the weighting curve proposed by Donohew & Griffin for the same direction.

The weighting curves found for on-track tests differ noticeably from those found in laboratories. The cause to this difference could possibly be due to the presence of several motions at the same time that disturb the evaluation for on-track tests.

5.2.6 Time dependence of motion sickness

There is a complex time dependence involved with motion sickness that is different for fall ill and recovery. ISO [46] has taken a simplified approach in the *Motion Sickness Dose Value* (MSDV) time dependence that indicates the *vomiting* frequency as a percentage, *Equation 7*.

$$MSDV_z(t) = k_{MSDV} \cdot \sqrt{\int_0^T a_{wf}^2(t) \cdot dt} \qquad (7)$$

where $a_{wf}(t)$ is the frequency-weighted vertical acceleration [m/s^2] and $k_{MSDV} = 1/3$ [s$^{1.5}$/m] for a mixed population of male and female adults. The motion sickness dose value will always give a value that increases with time. Suzuki et al. [49] used *Equation 7* for the lateral direction and denoted the result $MSDV_y(t)$.

Kufver & Förstberg [71] derived the Net-Dose time dependence *ND(t),* which describes motion sickness both at fall ill and recovery. The intention of the Net-Dose value is to describe the degree of motion sickness as a function of time. The dependence is a first order low-pass filter on the absolute value of the input variable, which may mathematically be described as *Equation 8.*

$$ND(t) = k_{ND} \cdot \int_0^T \left|a_{wf}(t)\right| \cdot e^{k \cdot (t-T)} \cdot dt \qquad (8)$$

where $a_{wf}(t)$ is the frequency-weighted vertical acceleration [m/s^2], k_{ND} =constant [s/m] and k =constant [1/s].

The time constant is often evaluated at recovery as the time to recover 63% of the motion sickness present when the motion input stopped. Evaluation during the recovery stage avoids the interference from the fall ill threshold. The time constant can also be obtained by correlating motion with motion sickness in on-track tests. 10 minutes is an often used time constant. The Net-Dose function may also be used with other signal input than vertical acceleration; examples are lateral acceleration and roll velocity. The Net-Dose time dependence is used in **Papers C**, **D** and **E**.

Habituation is another kind of time dependence of motion sickness. The ability to adapt to motions has been observed at sea for a long time. Habituation is made to one specific environment while other motions may still cause motion sickness. Most researchers have reported time constants for habituation in the range of a few days. Habituation has been observed in motion sickness on-track tests where the test subjects became less motion-sick on the second day of exposure.

5.2.7 Motion sickness in laboratories

Motion sickness as a result of provocative experiments in laboratories is one very important key to finding the cause of motion sickness because the sensations induced in laboratories may be simplified compared with real-world environments. Motion sickness tests in a laboratory environment have a long history and the number of tests performed is huge. Purkinje [72] gives one of the first reports on the subject from a test where he used constant yaw velocity combined with roll or pitch movements to provoke motion sickness. The purpose of this test was to treat mentally ill people by inducing nausea. The focus here is to give examples that could contribute to explain the motion sickness experienced on trains rather than give a state-of-the-art review overall. Some of the tests referred to were conducted quite some time ago; this is because the focus has lately been on more specific cases that are not so relevant here.

Longitudinal motions

Golding, Müller & Gresty [73] summarize laboratory tests performed with pure longitudinal motions. The test subjects were seated in an upright position oscillating back and forth at frequencies between 0.1 Hz and 1.0 Hz. Golding et al. used seats with high backrests and instructed the subjects to keep their head against the headrest to provide some support for their upper body and head. The amplitudes were altered from 0.19 to 3.98 m/s^2. The researchers found a sensitivity peak at 0.2 Hz, indicating that a similar weighting function to the one applied in the vertical direction may also be useful in the longitudinal direction.

Lateral motions

Donohew & Griffin [70] proposed a different weighting function for the lateral direction than that used for the vertical direction. The result was based on laboratory tests with purely lateral motions. The test subjects were seated in an upright position, oscillating from side to side at frequencies between 0.0315 Hz and 0.8 Hz. The backrest was low and gave little support for the test subject’s upper body and no support for their head The weighting function for lateral direction has the greatest sensitivity, between 0.02 Hz and 0.25 Hz, see *Figure 13 (bottom)*.

Vertical motions

O’Hanlon & McCauley [68] made comprehensive tests for the vertical direction with seated subjects. They used aircraft seats and instructed the subjects to keep their head against the headrest to provide some support for their upper body and head. 50% of the test subjects reported motion sickness at a frequency of 0.1 Hz and an amplitude of 0.30 m/s^2 rms and 25% of the test subjects reported motion sickness at a frequency of 0.1 Hz and an amplitude of 0.16 m/s^2 rms, in both cases after two hours of exposure. O’Hanlon & McCauley derived a relationship of Motion Sickness Incidence (vomiting) to motion frequency and amplitude. This relationship became the basis for the well-established weighting function W_f, ISO [46], see *Figure 13 (top)*.

Roll motions

Howarth [74] reported on laboratory tests with pure roll at frequencies ranging from 0.025 Hz to 0.40 Hz, at an amplitude of 8 degrees. The backrest was low and little support for the test subject’s upper body and no support for their head. Howarth found no difference in the sickness produced by the different frequencies but all differed from the static reference case. Howarth concluded that pure roll motion may provoke some motion sickness but differs from translation motions by its dependence on displacement instead of acceleration.

Pitch motions

McCauley, Royal, Wylie, O'Hanlon & Mackie [75] have shown in laboratory tests that pure pitch at 0.345 Hz give 9% of the test subjects motion sickness at an amplitude of 7 degrees. They used aircraft seats and instructed the subjects to keep their head against the headrest to provide some support for their upper body and head. The pure pitch case was a reference case when McCauley et al. combined pitch with vertical acceleration. They concluded that pure pitch motion is not the primary cause of motion sickness at sea.

Yaw motions

There are ample examples of tests that use constant yaw velocity (typically rotation around an Earth-vertical axle) combined with at least one other motion. Among others, Eyeson-Annan, Peterken, Brown & Atchison [76] used the pure yaw motion as reference case not provoking motion sickness.

Combined motions

The tests Purkinje [72] made were tests with combined motions using constant yaw velocity and roll or pitch movements to provoke motion sickness. This combination has over the years proven to be very nausea-inducing. McCauley et al. [75] combined pitch or roll with vertical motions. They compared the result from the combined tests with pure reference cases and came to the conclusion that vertical motion alone can provoke sickness and that combination with pitch or roll does not significantly increase the incidence of sickness. Wertheim, Wientjes, Bles & Bos [77] more or less repeated the tests conducted by McCauley et al. some 20 years earlier but came to the conclusion that pitch or roll *does* increase the incidence of sickness when added to vertical motions. Dahlman [78] combined vertical acceleration with roll motions in a test that focused on sea sickness. He found that the case with combined motions gave significantly more motion sickness than cases with pure vertical acceleration or pure roll motion.

Förstberg [19] combined horizontal acceleration with roll in a test with tilting trains in focus. The horizontal acceleration was more or less compensated by the roll motion. Förstberg used 0.167 Hz oscillations with shapes and amplitudes simulating trains passing curves. He came to the conclusion that roll motions alone do not provoke motion sickness, but roll motions *do* increase the incidence of sickness when combined with lateral motions. Lobb & Griffin [79] conducted similar tests to investigate the effect of partial compensation. The tests only included the cases no compensation, half compensation and full compensation. The results were very clearly in favour of half compensation. It should be noted that half compensation here relates to the horizontal acceleration, which translated to a railway case with track cant corresponds to a far lower compensation factor than 50%.

Tests with combined motions have generally shown that these are more motion sickness provoking than the corresponding reference tests made with pure motions. However, there are exceptions to this conclusion.

5.2.8 Measured motion quantities in on-track tests

Figure 14 shows a Power Spectral Density (PSD) diagram for carbody roll acceleration, which is one of the motion components with a large difference between tilting and non-tilting trains. The measured motion quantities are reported by Förstberg [19] and taken from a tilting car at a maximum cant deficiency of 245 mm on the Swedish line between Katrineholm and Norrköping. This 47 km long track section contains numerous 1,000 m horizontal curves, which limit the trains' speed. A one-way run at a maximum cant deficiency of 245 mm took about 20 minutes. There were no intermediate stops. The train in condition A compensates

63% of the cant deficiency, giving a maximum quasi-static lateral carbody acceleration of 0.6 m/s^2. The non-tilting cases were run with the same train, but with the tilt inactive at a lower speed than the tilting cases. For roll acceleration, the main difference is found below 1.0 Hz where the tilting train shows larger amplitudes than the non-tilting one. Measurements made on the Norwegian line between Kristiansand and Vegårdshei reported by Persson [52] show similar differences between tilting and non-tilting trains despite this line containing numerous 300 m horizontal curves. The vertical acceleration shows differences similar to the roll acceleration. The main difference for lateral acceleration is found below 0.05 Hz where the non-tilting train shows larger magnitudes than the tilting one. The three remaining motion components show no significant differences.

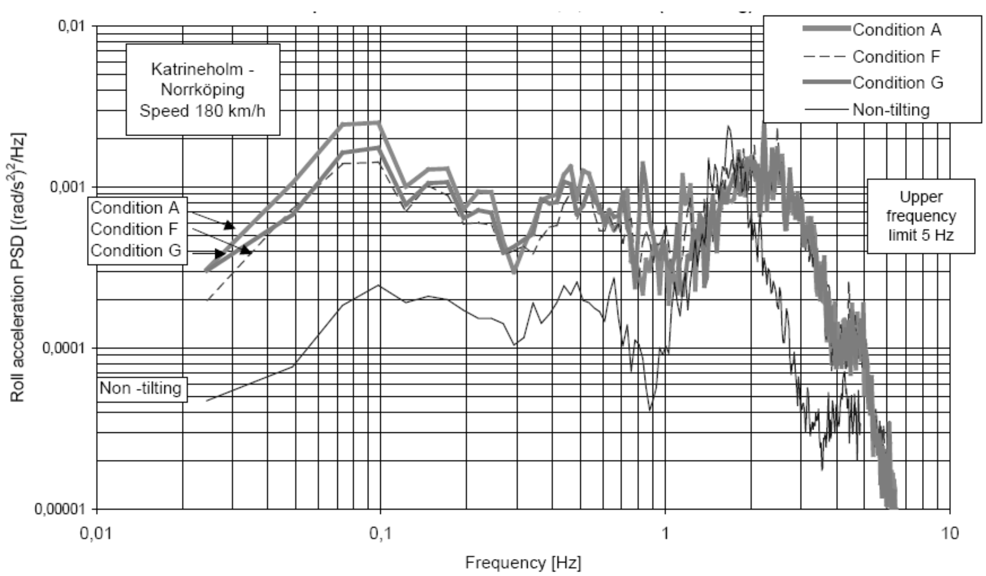


Figure 14: Carbody roll acceleration for tilting (condition A, F and G) and non-tilting trains. *The non-tilting case was also made with a tilting train but at a lower speed and without compensating the lateral acceleration, Förstberg [19].*

5.2.9 Measured motion quantities vs. experienced motion sickness

One interesting question is whether motion quantities specifically measured in tilting trains have caused motion sickness in the laboratory. Comparisons are made for the three motion components that have shown the largest differences between tilting and non-tilting trains and can be found in **Paper B**. The conclusion is that no laboratory tests that used one pure motion, which has resulted in signs of motion sickness, have been performed at such low-level motions as measured on the tilting train.

Combined motions, which in Section 5.2.7 were found to increase the risk of motion sickness, may possibly account for the difference. The degree of self-controlled motions as a result of subject activity could be another difference because test subjects in laboratories are often asked to rest, whereas test subjects in on-track tests are often asked to read.

6 Reducing the risk of motion sickness on tilting trains

Reducing the risk of motion sickness on tilting trains has been a subject since they were introduced and is also one of the goals of the present work. The difference in risk of causing motion sickness relative to non-tilting trains has attracted particular interest, and reducing the risk of motion sickness to the same level as non-tilting trains would be a good improvement. The task is here assumed to be equal to reducing the motion difference between the two train types. The actions in scope can be divided into four groups: tilt control, speed restrictions, reduced tilt and track design geometry. Actions from the four groups can and should be combined for best effect. However, there are other means to influence the risk of motion sickness than changing the motions; this option is exemplified in the last section of this chapter.

Tilt control

The tilt control has developed successively over time as mentioned in Section 2.4 and some of this development was forced by the risk of motion sickness. Omitting the secondary suspension from the control loop is one such example, where the improved tilt control avoids low-frequency dynamic interaction due to suspension flexibility.

Avoiding influence from track irregularities is another means of improving tilt control that mainly relates to ride comfort, but also has a relation to motion sickness. Förstberg [19] studied limitations of tilt velocity and tilt acceleration to reduce unnecessary tilt motions caused by track irregularities in an on-track test. The limit on tilt velocity was determined by the requirement to tilt the carbody without delay in the network's most demanding transition curve. The intention of limiting tilt acceleration was to give a smooth tilt motion with reduced track irregularity influence. In the test the two limitations were combined with reduced tilt, showing less risk of motion sickness than in the reference case. However, the effect of the limitations on motion sickness could not be separated from the effect of reduced tilt due to the test setup. There are also practical implications with limiting the tilt motion such as delayed tilt action and poor control stability.

The track data based tilt control described in Section 2.4.2 was developed to reduce the low-frequency lateral acceleration that may otherwise cause motion sickness in sensitive passengers. These low-frequency accelerations are due to tilt action delay and tend to have a dominant frequency where sensitivity to motion sickness is high. Another advantage of track data based tilt control is the absence of track irregularity influence without the drawbacks mentioned above with regard to limiting tilt velocity and tilt acceleration. This control system is now part of most natural tilting systems in Japan. Novel tilt control systems involving track databases obtain the absolute train position from the safety system. The state-of-the-art solutions are made independent by using global positioning systems or by curvature matching, as suggested by Sasaki [29] and Hauser [28].

Speed restrictions

Reduced speed is of course contradictory to the main purpose of tilting trains, which is to reduce running time. However, the speed restrictions needed to reduce the risk of motion sickness can often be made quite locally with little influence on the total running time. The idea of local speed restrictions is far from new; as operators often find certain track sections to be more motion sickness provoking than others, even a minor reduction in speed is found to give a significant reduction of the risk of motion sickness. One such example comes from Sweden where the class X2 trains run 5 km/h slower than allowed on a particularly curved track section between Partille and Alingsås when the timetable so permits. Local speed restrictions are discussed in **Paper D**.

Reduced tilt

Making the motions of tilting trains more non-tilting like is the same as tilting a little less and letting the passengers feel a little more lateral acceleration on curves. The first solution was to introduce a tilt compensation factor less than 100%, as stated earlier in Section 2.4. However, a *fixed* compensation factor must be set high enough to avoid discomfort in the most demanding curves. Reducing tilt by means of a lower compensation factor has been the subject of several on-track tests such as those conducted by Förstberg [19]. The results are generally positive measured as less risk of motion sickness, but negative measured as ride comfort.

Compensation factors *non-linear* in respect of the ratio between tilt and track plane acceleration are applied in most tilting trains to avoid track irregularity influence on straight track. However, the non-linearity can also be used to reduce the tilt at low track plane accelerations, which will make the tilting train more non-tilting like at these track plane accelerations. The drawback of such solutions is the increased maximum roll velocity in curve transitions. It is unclear whether these solutions have a reducing effect on the risk of motion sickness.

Compensation factors *variable* over distance allow just as much tilt as necessary to be applied to avoid discomfort in each curve. The solution was outlined by the author together with Kufver in [6] and further elaborated in **Paper D**. The algorithms were finally applied in on-track tests, which were evaluated and reported in **Paper E**. The variable compensation reduced the tilt on average but, rather unexpectedly, the lowest risk of motion sickness was not recorded for the test case with the largest reduction of tilt. This is an indication of a non-linear relation similar to non-linear relations observed in laboratory tests made by Lobb & Griffin [79].

Track design geometry

The track design geometry has a great impact on the carbody motions in the frequency range of motion sickness. Modifying the amount of cant to reduce carbody vertical and roll motions under conditions of comfort in transition curves was studied in [3] with the result given as a guideline. The amount of cant became less important for tilting trains with variable compensation factors as these may consider the installed cant as well. However, there are two other cases when track design geometry can not be compensated by advanced tilt control. The first is to avoid adding vertical accelerations from carbody tilt to those from vertical track design geometry. In practice this mean that horizontal curves should not coincide with concave vertical curves. The second case is to extend curve transitions as a way of reducing the carbody's roll velocity.

Other options than changing the carbody motions

This topic is outside the scope of the present work, but it may be worth noting that there are other options to reduce the risk of motion sickness than those related to carbody motions. A brief glance through the literature gives the following examples that can be applied on tilting trains:

- ✓ Avoid self-generated motions (don't read and rest your head against the seat back)
- ✓ Lower the ambient temperature
- ✓ Increase ventilation
- ✓ Eat a light meal before travelling and avoid alcohol
- ✓ Drink plenty of water.

7 Present work

In addition to this introductory part, the present thesis comprises five papers, A–E. These are summarized below.

7.1 *Summary of Paper A*

Research on the competitiveness of tilting trains. This work is based on running time simulations for a comprehensive set of input variables, including stopping pattern, permissible cant deficiency, top speed, tractive power and starting acceleration. The potential for further running time reduction is exemplified on the Swedish mainline Stockholm-Gothenburg. 15 minutes running time (9%) may be gained if cant deficiency, top speed and tractive performance are improved compared with existing tilting trains. Non-tilting high-speed trains were not an option for running time reduction on this line due to the numerous curves. A thorough study of the track design geometry was made to obtain proper input to the running time study, which as a spin-off gave suggestions regarding the track cant to be installed. The paper also includes a brief study of the need for passing possibilities at increased speed differentiation on double-track lines. The paper was presented by Rickard Persson at the Railway Engineering Conference in London in 2007.

7.2 *Summary of Paper B*

Tilting trains – benefits and motion sickness. The paper relates benefits in terms on running time reductions to influence on carbody motions with correlation to the risk of motion sickness. The running time simulations were performed for a limited set of input variables with conclusions similar to those in **Paper A**. However, further increasing the speed of tilting trains will influence carbody motions. Increasing the amplitudes of motion components with relation to motion sickness should be avoided. Motion sickness experience gained in the laboratory and on-track is summarized and compared to identify what motion components to avoid. The conclusion was that no principal cause could be appointed since the motion amplitudes on tilting trains are lower than those used in laboratory tests that caused motion sickness. It was assumed that carbody roll acceleration and carbody vertical acceleration, which were the motion components with the largest increase for the tilting train compared to the non-tilting one, contribute to the increased risk of motion sickness. The impact of increased speed on these two motion components is quantified in the paper and mitigation proposals are given.

7.3 *Summary of Paper C*

On-track test evaluation. The paper reports on an evaluation of on-track motion sickness tests made within the FACT project at the Nordic field tests in 2004 with the task of identifying the principal sources of motion sickness. The method chosen for this analysis was to use linear regression between combinations of the collected motion data during the run. The evaluation tried six combinations of motions as hypotheses concerning the cause of motion sickness set by respected colleagues. The data was also thoroughly examined for new combinations of motions that can be used as hypotheses in future evaluations. The best correlation between a motion component and motion sickness was found for vertical acceleration. However, disturbing correlation between different motion components made it difficult to point to the principal cause of motion sickness. The paper was presented by Rickard Persson at the Conference on Human Response to Vibration in Leicester in 2008.

7.4 *Summary of Paper D*

Strategies for less motion sickness on tilting trains. The paper assumes that the increased risk of motion sickness on tilting trains has a relation to the motion difference between tilting trains and non-tilting ones. Reductions of the motion difference between tilting (running at enhanced speed) and non-tilting trains (running at normal speed) can be achieved by tilting less. Reducing tilt has until now been equal to increasing the discomfort related to quasi-static lateral acceleration. However, there is a difference in time perception between discomfort and motion sickness, which opens up for new solutions. The paper takes advantage of this difference and presents new tilt algorithms aimed at balancing the conflicting objectives of ride comfort and less risk of motion sickness. An enhanced approach is taken, where the degree of tilt depends on the local track design geometry and the train speed. Reduced speed is another way to reduce the risk of motion sickness and the speed restriction can be made locally to avoid local peaks in the risk of motion sickness. The result of the new algorithms and the local speed restrictions are derived from simulations and set in relation to today's conditions on the Swedish Stockholm–Gothenburg mainline. The paper was presented by Rickard Persson at the 12th International Conference on Computer System Design and Operation in Railways and other Transit Systems (Comprail) in Beijing in 2010.

7.5 *Summary of Paper E*

On-track test of strategies for less motion sickness on tilting trains. The tilt algorithms presented in **Paper D** are here used in practice in an on-track test involving more than 100 test subjects. This test is believed to be the first test ever where each curve was given its own optimized tilt angle in order to reduce the risk of motion sickness on tilting trains. The evaluation shows that the rms values on carbody roll acceleration and carbody vertical acceleration that in **Paper B** and **C** were identified to have a relation to motion sickness can be influenced without changing the requirements with respect to carbody lateral acceleration and lateral jerk. Relaxing the requirements will lead to further reduction of carbody roll acceleration and carbody vertical acceleration. The evaluation also shows that reduced quantities related to motion sickness lead to a reduction in experienced motion sickness. However, this relation seems to be valid in a certain range as the test case with the largest decrease in tilt gave a greater risk of motion sickness than the two test cases with less reduction in tilt. This non-linear relation has also been observed by other researchers in laboratory tests.

8 Conclusions and future work

This thesis has dealt with subjects important for improving the competitiveness of tilting trains compared to non-tilting ones. A state-of-the-art survey is provided and used to identify important research areas where work should be conducted. This work has contributed to the body of knowledge of tilting trains and this chapter presents the overall conclusions.

Carbody tilting

Tilting trains can be divided into two groups, depending on whether active force is needed to create tilt or not, called actively tilted trains and naturally tilting trains. However, many of today's naturally tilting trains do have an active system to improve control of the tilt motion. As early as the late 1980s control systems utilizing wayside information was introduced in naturally tilting trains in Japan. This development was forced by requirements concerning ride comfort and low risk of motion sickness.

Knowing the train position is the key to perfect tilt control. In the on-track test that concluded the present work the design took advantage of global positioning systems to obtain the absolute position and dead reckoning to find the relative position with reference to the last absolute position given. Train position and track data information constitutes a good basis for an advanced tilt control, which is a good match to some of the means to reduce the risk for motion sickness suggested below.

Vehicle–track interaction

Increased top speed and permissible cant deficiency of tilting trains tend to reduce safety margins. Potential limitations arise from lateral track shift forces and crosswind stability. Proper vehicle design can restore the safety margins to some extent, but the permissible cant deficiency should be a function of speed for high-speed tilting trains due to crosswind requirements. Such function was proposed and used as an assumption in the analysis of suitable tilting train applications in the present study.

Analysis of services suitable for tilting trains

It seems to be difficult to replace tilting trains on long-distance hauls on curved lines when travel time counts. The tilting trains often cut the running time by about 10% compared to non-tilting trains. The possibility to further increase tilting trains' running speed is here studied under identified speed limitations due to vehicle-track interaction such as crosswind requirements at high speed curving. About 9% running time may be gained on the Stockholm–Gothenburg (457 km) main line in Sweden if cant deficiency, top speed and tractive performance are improved compared with existing tilting trains. Non-tilting high-speed trains are not an option on this line due to the large number of 1,000 m curves. Improving the performance of the tilting trains will in the present network increase the speed relative to other trains on the network. On double-track lines this will be negative for the line capacity and building a new line becomes an alternative when the present line is close to its maximum capacity. For services with short distances between stops, improved tractive performance may be a better choice than tilt.

Human response

The influence on average ride comfort from increased speed and cant deficiency compared to today's trains can be compensated by improved vehicle suspension. The influence on curve related quantities, such as lateral acceleration and lateral jerk, can be compensated by tilt but possibly at the expense of increased vertical and roll motions.

On-track tests have been used to correlate carbody motions to experienced motion sickness. The methodology how to perform the evaluation has been studied, difficulties identified and the frequency weighting curve for vertical acceleration to motion sickness challenged for on-track test evaluation. The cause of motion sickness experienced on tilting trains is still not fully understood. The explanation could have come by comparing motion quantities measured in tilting trains with motions that have caused motion sickness in laboratories. However, the comparison made in the present study, could not appoint any principal cause since the motion amplitudes on tilting trains are lower than those used in laboratory tests that caused motion sickness. Can the combination of motions existing on tilting trains or self-controlled motions as result of subject activity possibly be involved?

Reducing the risk of motion sickness

Some means to reduce the risk of motion sickness have been identified during the course of the present work and these can be combined for best effect. Improved tilt control can prevent unnecessary fluctuations in motion sickness related quantities perceived by the passenger. Modern track data based control systems are a good help to achieve this. Local speed restrictions have been successfully used for many years to reduce the risk of motion sickness on motion sickness provoking track sections. New tilt algorithms for less risk of motion sickness aimed at reducing the difference in motion between non-tilting and tilting trains have been proposed, tested and reported in the present thesis. These algorithms consider the possible contradiction between ride comfort and motion sickness. However, discomfort is related to momentary perceptions whereas motion sickness is related to aggregate perceptions. Tilt algorithms have been proposed that allow the rms value of carbody lateral acceleration and lateral jerk to increase while limiting the maximum values of the same quantities. This requires each curve to be given its own optimized tilt angle, which was made possible by the new tilt algorithms and a modern track data based control system. Good track design geometry can also reduce the risk of motion sickness by avoiding coinciding horizontal curves and concave vertical curves, that otherwise give vertical acceleration peaks, and extending the length of curve transitions to reduce roll velocity.

Future work

The attempt to find the sources, and their relative contributions, of motion sickness in the present work was not so successful and it is unlikely that any simple answer exists. It is probably more worthwhile to work on tilt control, which is evolving strongly. The improved tilt control as such will be further developed by the train suppliers; this will be beneficial for both ride comfort and reduction of the risk of motion sickness. It is likely that independent research organisations, such as universities, can contribute to further optimization of the tilt algorithms.

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