Tilting trains

Technology, benefits and motion sickness

by

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Preface

This is the final report of the research project "*Optimal vehicles for high speed and narrow curves – development of technology for carbody tilting and track friendly running gears"*. The project was initiated by Johan Förstberg at Swedish National Road and Transport Research Institute (VTI) aiming at increasing the competitiveness of trains and in particular tilting trains. A post graduate project was formed together with Swedish Governmental Agency for Innovation Systems (VINNOVA), the Swedish National Rail Administration, (Banverket), Bombardier Transportation (BT), division of rail vehicles at the Royal Institute of Technology (KTH) and Ferroplan Engineering AB.

The project became connected to the research programme "Gröna Tåget" (the Green Train), which slightly changed the aim as the Green Train programme contained development and testing of track friendly running gear for speeds up to 250 km/h.

The present study has been carried out at VTI in cooperation with KTH. The project has been led by a steering committee consisting of Carl Naumburg (VINNOVA), Tohmmy Bustad (Banverket), Evert Andersson (KTH) and Lena Nilsson (VTI). Scientific support has been provided by a reference group consisting of Björn Kufver, Ferroplan, Evert Andersson, KTH and Lena Nilsson, VTI. Support on human factor and medical issues have been provided by Joakim Dahlman and Torbjörn Ledin, both at Department of Clinical and Experimental Medicine at the University of Linköping. Evert Andersson has been the supervisor and Björn Kufver assistant supervisor. The project has reported to the Green Train programme.

The financial support from VINNOVA and Banverket is gratefully acknowledged.

Stockholm, May 2008

Rickard Persson

Abstract

Carbody tilting is today a mature and inexpensive technology allowing higher speeds in curves and thus reduced travel time. The technology is accepted by most train operators, but a limited set of issues still holding back the full potential of tilting trains. The present study identifies and report on these issues in the first of two parts in this thesis. The second part is dedicated to analysis of some of the identified issues. The first part contains Chapters 2 to 5 and the second Chapters 6 to 12 where also the conclusions of the present study are given.

Chapters 2 and 3 are related to the tilting train and the interaction between track and vehicle. Cross-wind stability is identified as critical for high-speed tilting trains. Limitation of the permissible speed in curves at high speed may be needed, reducing the benefit of tilting trains at very high speed. Track shift forces can also be safety critical for tilting vehicles at high speed. An improved track standard must be considered for high speed curving.

Chapters 4 and 5 cover motion sickness knowledge, which may be important for the competitiveness of tilting trains. However, reduced risk of motion sickness may be contradictory to comfort in a traditional sense, one aspect can not be considered without also considering the other. One pure motion is not the likely cause to the motion sickness experienced in motion trains. A combination of motions is much more provocative and much more likely the cause. It is also likely that head rotations contribute as these may be performed at much higher motion amplitudes than performed by the train.

Chapter 6 deals with services suitable for tilting trains. An analysis shows relations between cant deficiency, top speed, tractive performance and running times for a tilting train. About 9% running time may be gained on the Swedish line Stockholm – Gothenburg (457 km) if cant deficiency, top speed and tractive performance are improved compared with existing tilting trains. One interesting conclusion is that a non-tilting very high-speed train (280 km/h) will have longer running times than a tilting train with today's maximum speed and tractive power. This statement is independent of top speed and tractive power of the non-tilting vehicle.

Chapters 7 to 9 describe motion sickness tests made on-track within the EU-funded research project *Fast And Comfortable Trains (FACT)*. An analysis is made showing correlation between vertical acceleration and motion sickness. However, vertical acceleration could not be pointed out as the cause to motion sickness as the correlation between vertical acceleration and several other motions are strong.

Chapter 10 reports on design of track geometry. Guidelines for design of track cant are given optimising the counteracting requirements on comfort in non-tilting trains and risk of motion sickness in tilting trains. The guidelines are finally compared with the applied track cant on the Swedish line Stockholm – Gothenburg. Also transition curves and vertical track geometry are shortly discussed.

Chapters 11 and 12 discusses the analysis, draws conclusions on the findings and gives proposals of further research within the present area.

Key words: tilting trains, motion sickness, ride comfort, running time, track geometry

Terminology and definitions

Term	Definition
Angle of attack	Relative angle between wheel and rail.
Cant deficiency	The difference between applied cant and a higher equilibrium cant.
Cant excess	The difference between applied cant and a lower equilibrium cant.
Equilibrium cant	The track cant needed to neutralise the horizontal acceleration due to curving.
Horizontal plane	Plane of earth horizon.
Motion sickness	Sickness caused by motion.
Nausea	Sensation of unease and discomfort in the stomach.
Otoliths	Vestibular organs located in the inner ear sensitive to linear acceleration.
Proprioceptive	Information of the body posture from sensors located in muscles and joints etc.
Quasi-static	Condition which is static under a certain period, here typically in a circular curve.
Semicircular canals	Vestibular organs located in the inner ear sensitive to rotational acceleration.
Somatic	Here referring to skin, movement control, organs of sight, organs of equilibrium and part of the nervous system related to these parts of the body.
Sopite	A symptom-complex centred on “drowsiness” and “mood changes”.
Tilt angle (effective)	The angle between the carbody floor plane and the track plane (net value when also deflections in primary and secondary suspensions have been taken into account).
Tilt compensation (effective)	Proportion of track plane acceleration removed by tilt with reference to the carbody floor plane (net value when also deflections in primary and secondary suspensions have been taken into account).
Tilting train	Train with capability to tilt the carbody inward in track curves, thus reducing the lateral acceleration perceived by the passengers.
Track cant	The amount one running rail is raised above the other running rail (in a curve). Track cant is positive when the outer rail is raised above the inner rail.
Velocity storage	Brainstem circuits which extends the frequency response from the vestibular nerve to lower frequencies.
Vestibular organs	Consist of two organs of otoliths sensitive to linear acceleration and three semicircular canals sensitive to rotational acceleration. These organs are located in the inner ear.

Local reference system

Term	Definition
Longitudinal	Parallel to floor plane, in travel direction
Lateral	Parallel to floor plane, right-oriented to travel direction
Vertical	Perpendicular to floor plane
Roll	Rotation around the longitudinal axis of the carbody
Pitch	Rotation around the lateral axis of the carbody
Yaw	Rotation around the vertical axis of the carbody

Symbols and abbreviations

Symbol	Description	Unit
φ_c	Roll angle, carbody relative track plane	deg
φ_t	Roll angle, track	deg
$\dot{\varphi}$	Roll velocity	deg/s
$\dot{\chi}$	Pitch velocity	deg/s
$\dot{\psi}$	Yaw velocity	deg/s
$2b_0$	Distance between the nominal centre points of the two contact patches of a wheelset on track (e.g. about 1500 mm for track gauge 1435 mm)	mm
a_h	Horizontal acceleration	m/s^2
AEIF	European Association for Railway Interoperability	
APT	Advanced Passenger Train	
CEN	European Committee for Standardization	
CNS	Central Nervous System	
CWC	Characteristic Wind Curves	
D	Applied track cant	mm
D_{eq}	Equilibrium cant (the sum of track cant and cant deficiency)	mm
DB	Deutsche Bahn	
ERRI	European Rail Research Institute (former part of UIC, ceased 2004)	
ETR	Elettrotreni rapidi	
FACT	Research programme Fast And Comfortable Trains	
g	Acceleration of Gravity	m/s^2
ICE	Inter City Express	
IR	Illness Rating	-
ISO	International Standards Organization	
k_{MSDV}	Constant in the Motion Sickness Dose Value time dependence	s$^{1.5}$/m [1)]
k_{ND}	Constant in the Net Dose time dependence	s^2/m [1)]
k_O	Constant in Oman's time dependence	s^2/m [1)]
KTH	Royal Institute of Technology (Stockholm, Sweden)	
MISC	Misery Scale	-
MSDV	Motion Sickness Dose Value	-
$MSDV_z$	Motion Sickness Dose Value, vertical direction	-
MSI	Motion Sickness Incidence	-
MSP	Motion Sickness Proportion	-
MSQ	Motion Sickness Questionnaire	
MSS	Motion Sickness Score	-

NASA	National Aeronautics and Space Administration (US)	
ND	Net Dose	
NSB	Norwegian State Railways	
ORE	Office for Research and Experiments (precursor to ERRI)	
P_{CT}	Percentage of dissatisfied passengers on curve transitions	-
P_{DE}	Percentage of dissatisfied passengers on discrete events	-
PDI	Pensacola Diagnostic Index	-
PSD	Power Spectral Density	
Q	Vertical wheel-rail force	N
Q_l	Vertical wheel-rail force on the left wheel of a wheel group	N
Q_r	Vertical wheel-rail force on the right wheel of a wheel group	N
ΔQ	Average (dynamic) vertical wheel force reduction on the two unloaded wheels of a bogie	N
Q_0	Static vertical wheel force	N
R	Horizontal curve radius	m
RCF	Rolling Contact Fatigue	
r.m.s.	root mean square	
SJ	Swedish State Railways	
SMSI	Symptoms of Motion Sickness Incidence	-
SNCF	La Société Nationale des Chemins de Fer Français	
TGV	Train á Grande Vitesse	
TGV-Duplex	Two level TGV train	
TNO	Human Factor Research Institute (Soesterberg, the Netherlands)	
TSI	Technical Specification for Interoperability	
UIC	International Union of Railways	
v	Speed	km/h [2)]
VI	Vector intercept	-
VTI	Swedish National Road and Transport Research Institute (Linköping, Sweden)	
W_f	Frequency function for weighting accelerations in relation to motion sickness, developed for vertical direction	-
W_g	Frequency function for weighting accelerations in relation to motion sickness, developed for lateral direction	-
X2000	Swedish tilting train	
$\ddot{x}$	Longitudinal acceleration in carbody	m/s^2
$\ddot{y}$	Lateral acceleration in carbody	m/s^2
$\dddot{y}$	Lateral jerk in carbody	m/s^3
$\ddot{z}$	Vertical acceleration in carbody	m/s^2

1) With transversal acceleration as input

2) Except otherwise stated

Table of contents

1 Introduction

1.1 *Background to the present study*

Growing competition from other modes of transportation has forced railway companies throughout the world to search for increased performance. Travel time is the most obvious performance indicator that may be improved by introducing high-speed trains. Trains with capability to tilt the carbodies inwards in track curves constitute a less costly alternative than building new tracks with large curve radii. The tilt inwards reduces the centrifugal force felt by the passengers, allowing the train to pass curves at enhanced speed with maintained ride comfort. Trains capable to tilt the bodies inwards are often called *tilting trains*. Carbody tilting is today a mature and relatively inexpensive technology.

International Union of Railways (UIC) [1998, 2005] has reported on tilting train technology where tilting trains and known tilting technology are described briefly. The present report covers tilting trains and known tilting technology as well as an analysis of the present situation.

The technology is accepted by most train operators, but motion sickness is an issue still holding back the full potential of tilting trains. The difference between non-tilting and tilting rolling stock has received particular interest as the tilting trains usually cause more motion sickness than non-tilting ones. This was the starting point for the EU-funded research project *Fast and Comfortable Trains* (FACT). The FACT-project contained three parts: part 1 was related to track layout, part 2 to the onset of motion sickness and part 3 to how to calculate motion sickness by simulations.

FACT involved on-track tests where the evaluation showed good correlation between vertical carbody acceleration and motion sickness. However, vertical acceleration was not claimed to be the prime cause of motion sickness.

The correlation between a certain motion component and its impact on the onset of motion sickness is important for reducing motion sickness. In particular the limited set of variables which can be influenced and controlled in the tilting train itself, or by modifications of the track design geometry.

Motion sickness is also experienced in other modes of transportation. Motion sickness at sea is the most known, but the knowledge derived at sea can not be applied on trains as the motions differ. The levels of vertical acceleration at sea are proven to cause motion sickness during laboratory tests, but no single motion can explain the onset of motion sickness in (tilting) trains.

1.2 *Objective and method of the present study*

The objective of the present study is to identify areas where the competitiveness of tilting trains can be improved and to conduct further research on identified areas.

The research is divided in two stages with different aims and activities. The aims and activities in the second stage are depending on the results of the first stage.

Stage 1

- To make an overview of the present situation regarding technology, knowledge and development trends of tilting trains.
- To identify areas where research can improve the competitiveness of tilting trains.

Stage 2

- On services suitable for tilting trains – The aim is to analyse what parameters have impact on the running times for tilting trains.
- On motion sickness - The aim is to gather available knowledge on motion sickness by performing a literature study covering motion sickness with particular focus on tilting trains. Reports from other modes of transportation as well as laboratory tests give valuable input and are therefore included.
- On motion sickness - A second aim has been to analyse the motion sickness during on-track tests performed within the FACT-project in more detail than it was possible within the FACT-project itself.
- On suitable track geometry – The aim is to analyse what track parameters have impact on comfort and motion sickness.

1.3 *Publication list*

In the present study, research reports have been published as follows:

Persson R: (2007a.) Tilting trains, a description and analysis of the present situation. ISBN 978-91-7178-608-1. KTH Stockholm.

Persson R: (2008). Motion sickness in tilting trains, Description and analysis of the present knowledge. ISBN 978-91-7178-680-3. KTH Stockholm.

Contributions to conferences have been made as follows:

Persson R: (2007b). Identification of areas where the competitiveness of tilting trains can be further improved. Proceedings: Railway Engineering - 2007, 20-21 June 2007, London, Engineering Technics Press, ISBN 0-947644-61-10, Edinburgh.

Persson R. (2007c). Research on the competitiveness of tilting trains. Proceedings: Railway Engineering - 2007, 20-21 June 2007, London, Engineering Technics Press, ISBN 0-947644-61-10, Edinburgh.

1.4 *Thesis contributions*

This thesis is believed to make original contributions as follows:

1. This thesis gives a state of the art report on tilting trains, including the interaction between track and vehicle. Cross-wind stability is identified as critical for high-speed tilting trains and limitation of permissible cant deficiency may be needed, reducing the benefit of tilting trains at very high speed.
2. This thesis gives a state of the art report on motion sickness in tilting trains. A possible contradiction between reduced risk of motion sickness and ride (instantaneous) comfort is identified.
3. This thesis reports on analysis of motion sickness tests performed on tilting trains. In particular, the results support recent research by showing correlation between vertical acceleration and motion sickness.
4. This thesis discusses the track geometry. In particular, guidelines for design of track cant, optimising the counteracting requirements on comfort in non-tilting trains and risk of motion sickness in tilting trains.
5. This thesis shows relations between cant deficiency, maximum speed, tractive performance and running times for a tilting train.

Part 1: Literature study

2 Tilting trains

2.1 *The tilt concept*

A train and its passengers are subjected to centrifugal forces when the train passes horizontal curves. Carbody roll inwards reduces the centrifugal force felt by the passengers allowing the train to pass curves at enhanced speed with maintained ride comfort. Roll may be achieved by track cant, or when the track cant is insufficient, carbody tilt. Trains capable of tilting the bodies inwards in curves are often called *tilting trains*. Tilting trains can be divided in two groups: the *passively tilted trains*, called naturally tilted trains in Japan, and the *actively tilted trains* (active tilt is called forced tilt in certain publications).

The passive 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 centrifugal force, the lower part of the carbody then swings outwards. It should be noted that passive tilt has a negative impact on safety due to the lateral shift of the centre of gravity of the carbody.

The active tilt relies on active technology, controlled by sensors and electronics and executed by an actuator, usually hydraulic or electric. Tilt as such has normally not an impact on safety of actively tilted train, as the centre of gravity does not essentially change its (lateral) position.

The basic concept of tilting trains is the roll of the carbodies inwards the curve in order to reduce the lateral force perceived by the passenger, Figure 2-1.

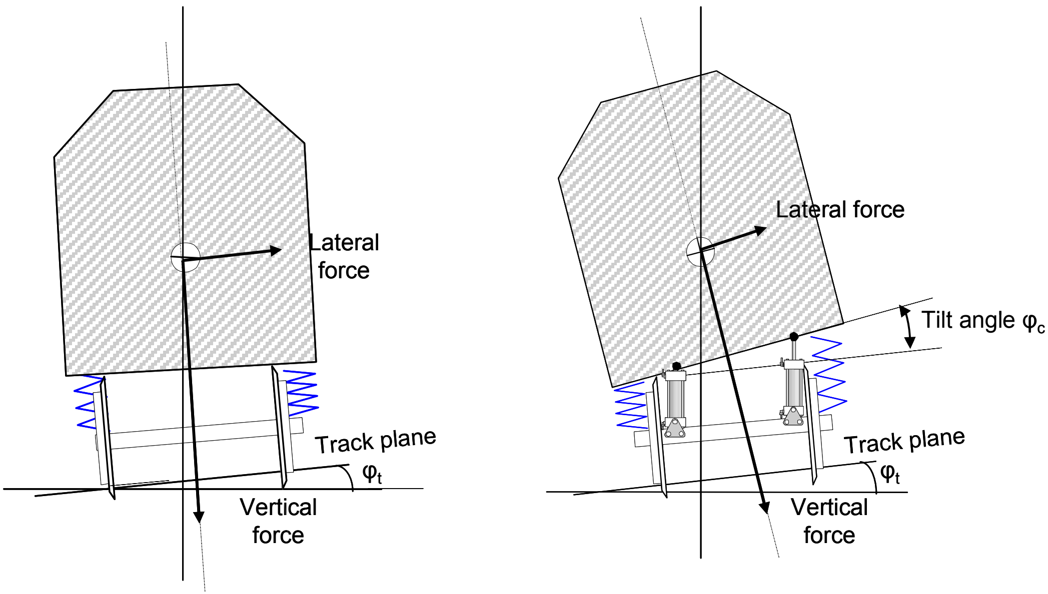

***Figure 2-1:* The basic concept of tilting trains.** *Despite the higher track plane acceleration for the tilting train (right), the lateral force in the carbody is lower than for the non-tilting train (left).*

When a vehicle is running on a horizontal curve, there will be a horizontal acceleration which is a function of speed *v* [here m/s] and curve radius *R,* Equation 2-1.

$$a_h = \frac{v^2}{R} \qquad [2\text{-}1]$$

The lateral acceleration in the track plane can be reduced compared with 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 contact points of a wheelset $2b_0$, Equation 2-2.

$$\varphi_t = \arcsin(\frac{D}{2b_0}) \qquad [2\text{-}2]$$

The lateral acceleration, as perceived by the passenger, can be further reduced by arranging a carbody tilt angle φ_c in relation to the track. The lateral acceleration in the carbody is normally denoted $\ddot{y}$, Equation 2-3. The vertical acceleration, perpendicular to the vehicle floor, is normally denoted as $\ddot{z}$, Equation 2-4. Note: *v* in [m/s] in Equation 2-3 and 2-4.

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

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

A reduction of lateral acceleration by increased track cant or carbody tilt is correlated with a slightly increased vertical acceleration. Typical values for lateral and vertical accelerations are shown in Table 2-1.

Table 2-1: Typical values for motion quantities on a horizontal curve.

Speed v [km/h]	Radius R [m]	Track cant D [mm]	Carbody tilt angle φ_c [deg]	Lateral acceleration $\ddot{y}$ [m/s²]	Vertical acceleration $\ddot{z}$ [m/s²] 1)
113	1000	0	0	0.98 3)	0
113	1000	150	0	0	0.05
160	1000	150	0	0.98 3)	0.15
166	1000	150	6.5 2)	0	0.23
201	1000	150	6.5 2)	0.98	0.44

1) The vertical acceleration is here given as offset from *g*
2) This tilt angle corresponds to an actively tilted train
3) The real value is 15 to 30 % higher due an outward sway of the carbody due to flexibility in primary and secondary suspensions

2.2 *Tilting trains of the world*

The first considerations and experiments on reducing the centrifugal force felt by the passenger and thereby allowing higher speeds in curves date from the late 1930s, [Deischl, 1937] and [Van Dorn & Beemer, 1938]. In 1938, Pullman built for the Atchison, Topeka and Santa Fe Railway an experimental pendulum coach, but the lack of damping produced a motion sickness inducing rolling motion, [Wikipedia, 2006]. The novel designs where based on passive technology. In 1956, Pullman-Standard built two train sets, called Train-X, which became the first tilting trains in commercial service. The trains were withdrawn from service after a short period due to poor running behaviour. The first large series of tilting trains were the Japanese class 381, which started to run between Nagoya and Nagano in 1973. In 1980, the first tilting Talgo train was put into service between Madrid and Zaragoza in Spain. All these trains had passive (or natural) tilt.

Active technology was introduced 1957 when La Société Nationale des Chemins de Fer Français (SNCF) built a vehicle that could tilt up to 18 deg. Deutsche Bahn (DB) converted 1965 a diesel multiple unit series 624 for tilt. In 1972 a tilting version of series 624 called series 634 were put into service on the line Cologne – Saarbrucken 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 started 1969 with a prototype tilting railcar, the Y0160. The prototype was 1975 followed by Elettrotreni rapidi (ETR) 401, which became the first Pendolino in commercial service, Figure 2-2.

Figure 2-2: The Italian ETR401, *photo by Paolo Zanin.*

Another important development chain started in 1973 when the Swedish State Railways (SJ) and ASEA signed a joint venture with the X15, which developed the tilt technology to the later X2000.

British Rail gained a lot of experience with their prototype tilting train, the Advanced Passenger Train (APT). One example is the comfort indexes P_{CT} and P_{DE}, which were developed from tests with APT, [Harborough, 1986]. The trains featured several new developments, with the drawback of poor reliability. The project was finally abandoned, and some patents were sold to FIAT which applied the knowledge on the later introduced ETR450.

The break-through for actively tilted trains came around 1990 when introduction of large series commercial trains, like the ETR450 in Italy and the X2000 in Sweden (Figure 2-3) started. At the same time the Series 2000 trains were introduced in Japan, which were the first naturally tilted trains with active tilt support. Today more than 5000 tilting vehicles, defined as tilting carbodies, have been produced world-wide by different suppliers.

Figure 2-3: The Swedish X2000.

The request for performance of trains has generally led to increased maximum speeds. The tilting trains are following this trend. The first tilting trains had a maximum speed of 120 km/h in service. Narrow track gauge trains in Japan have still only 130 km/h as maximum speed, whereas the tilting trains in Europe have at least 160 km/h as maximum speed. The Acela trains in USA have a top speed of 240 km/h, the Pendolino trains ETR450, ETR460 and ETR480 in Italy 250 km/h. The tilting Shinkansen Series N700 in Japan has a top speed of 300 km/h, Figure 2-4.

Figure 2-4: The Japanese Shinkansen N700, *photo by D.A.J. Fossett.*

Tilting trains do not always combine top speed with high cant deficiency; one example is the Italian Pendolino trains which run at the same speed as Italian non-tilting trains at speeds above 200 km/h, [Casini, 2005]. Another example is the tilting Shinkansen series N700 which only has a maximum cant deficiency of 154 mm over the whole speed range. Speeds above 250 km/h combined with high cant deficiencies are still at the research stage; one example is the Swedish high-speed tests where an X2000 train run at 275 km/h with 245 mm of cant deficiency.

3 Track – vehicle interaction

The track–vehicle interaction is today guided by standards. In Europe these standards are issued by European Committee for Standardization (CEN), some based on a UIC standard. These standards are widely used also outside Europe.

Comparison with older vehicles is another possibility to set limits. This technique was applied when SJ set certain limits for the tilting train that became X2000. Today this type of limits is found in the Technical Specification for Interoperability (TSI) for high-speed trains on the task of cross wind stability, issued by the European Association for Railway Interoperability (AEIF) [2006].

3.1 *Passenger Ride Comfort*

Passenger comfort can be several things, but is here limited to the passenger ride comfort excluding motion sickness. There are two important relations to passenger ride comfort where tilting trains differ from non-tilting ones;

1. Ride comfort as function of speed
2. Ride comfort as function of cant deficiency

Ride Comfort as Function of Speed

The ride comfort influenced by the vibrations and motion of the vehicle deteriorates with increased speed. This could be understood by looking at a typical description of the level of track irregularities as function of the spatial frequency Ω (1/m) of the irregularities issued by Office for Research and Experiments (ORE) [1989], Figure 3-1.

The level of track irregularities decreases with the spatial frequency, which means that the level of track irregularities increases with the wave length of track irregularities. As a result, the track irregularity magnitude at a certain frequency will be higher at increased speed, which will impact the ride comfort.

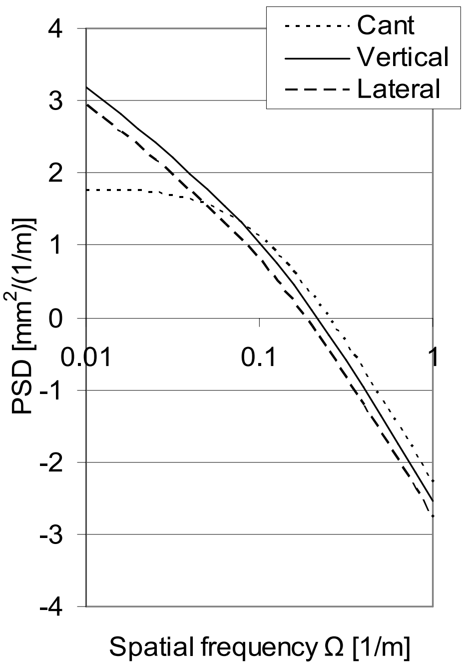

Figure 3-1: Magnitude of track irregularities as function of spatial frequency, [ORE, 1989].

A tilting train may run faster than a non-tilting train on the same track and the ride comfort may therefore be worse. Worse ride comfort does not fit well to passenger expectations of a faster train and must be counteracted by reduced magnitudes of track irregularities and / or by reduced vibration transfer from track to passenger, i.e. improved vehicle suspension.

Ride Comfort as Function of Cant Deficiency

Increased cant deficiency can impact the ride comfort in two ways; it can increase the vibrations and motions of the vehicle and it can increase the quasi-static lateral acceleration perceived by the passenger.

The relation to vibrations and movements of the vehicle is weak assuming that the suspension systems of the vehicle are properly designed for the cant deficiency in question.

The relation to the quasi-static lateral acceleration perceived by the passenger exists, but the negative impact of high cant deficiency in tilting trains is balanced by the carbody tilt. Criteria on quasi-static lateral acceleration and lateral jerk perceived by the passenger is given by CEN [1999, 2007] in the P_{CT} criteria.

The P_{CT} Comfort index for discomfort on curve transitions is calculated on the basis of Equation 3-1 with constants according to Table 3-1.

$$P_{CT} = 100 \cdot \left\{ \max\left[A \cdot \left| \ddot{y}_{1s} \right|_{\max} + B \cdot \left| \dddot{y}_{1s} \right|_{\max} - C);\ 0 \right] + (D \cdot \left| \dot{\varphi}_{1s} \right|_{\max})^{E} \right\} \qquad [3\text{-}1]$$

where:

- P_{CT} = Percentage of dissatisfied passengers
- $\ddot{y}_{1s}$ = Lateral acceleration in carbody (average over 1 second) [m/s^2]
- $\dddot{y}_{1s}$ = Lateral acceleration change over 1 second in carbody [m/s^3]
- $\dot{\varphi}_{1s}$ = Roll velocity in carbody (average over 1 second) [deg/s]

Table 3-1 Constants for P_{CT} comfort index.

Condition	A [s^2/m]	B [s^3/m]	C [–]	D [s/deg]	E [–]
In rest – standing	0.2854	0.2069	0.111	0.00185	2.283
In rest – seated	0.0897	0.0968	0.059	0.0012	1.626

Note that requirements on quasi-static lateral acceleration perceived by the passenger may lead to increased magnitudes for other motions, which may lead to increased risk of motion sickness.

3.2 *Wheel / Rail Forces*

Track Shift Force

The track shift force can be divided into two parts, one quasi-static part and one dynamic part. The quasi-static part has a dependence on cant deficiency, which for a tilting train is higher than for a non-tilting train. The dynamic part has a dependence on speed, which (for the same curve radius) is also higher for a tilting train than for a non-tilting train, presupposed that no improvement is made in the running gear and suspension.

Kufver [2000] and Lindahl [2001] have simulated track-vehicle interaction for high-speed tilting vehicles with the following data, Table 3-2.

Table 3-2: Vehicle properties used by Kufver and Lindahl.

Property	Kufver	Lindahl
Carbody length [m]	24.95	25.00
Carbody height [m]	3.8	3.6
Bogie centre distance [m]	17.7	18.0
Bogie wheel base [m]	2.9	2.7
Carbody mass [kg]	32 411	33 000
Carbody centre of gravity height [m]	1.61	1.55
Bogie frame mass, incl. drive [kg]	5 420	6 000
Wheelset mass [kg]	1 340	1 600

Both Kufver and Lindahl found that track shift forces can be safety critical for tilting vehicles at high speed. At 360 km/h Lindahl set the maximum permissible 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, an improved track standard must be considered for 275 - 300 mm of cant deficiency, in particular at speeds higher than 200 km/h. It should be noted that both Kufver and Lindahl presupposed rather soft wheelset guidance, allowing radial steering in representative curve radii. Also, the softer wheelset guidance reduces the dynamic content of the lateral force.

Derailment Criteria

The ratio between lateral and vertical track forces on a wheel is often used as derailment criterion, this ratio is also called flange climbing criterion. The lateral force on the flange is here balanced by the vertical force at the same wheel. The derailment ratio can be divided in two parts, one quasi-static part and one dynamic part. The quasi-static part has a dependence on cant deficiency, which for a tilting train is higher than for a non-tilting train, but both the lateral and vertical forces increase when the cant deficiency increases. However, the risk for derailment is higher at low speeds than in high speeds due to the impact from small curve radii and larger track irregularities. The tilt is normally inactive at these speeds making tilting trains no different from the non-tilting train in this critical case.

3.3 *Wheel / Rail Wear*

Wheel and rail wear may in a general sense be understood as deterioration of the surfaces on wheel and track. This deterioration can be divided in two groups of basic mechanisms, loss of material, i.e. abrasive wear, and Rolling Contact Fatigue (RCF). Burstow [2004] has shown that both the abrasive wear and the risk of RCF can be judged by the wear number (force times the relative velocity in the contact point).

Wheel and rail wear in curves has a relation to the vehicle's ability of radial steering. This could be achieved by reducing the primary suspension stiffness in longitudinal direction, a technique applied for example in Sweden since the 1980s. Reduced primary suspension stiffness in longitudinal direction may and has been applied on tilting vehicles. Negotiating curves at high cant deficiencies may influence wheel wear due to the increased lateral force that must be taken up by the wheels. However, the increased lateral force is normally accomplished by a decreased angle of attack for the leading wheelset, thus producing a tendency towards reduced wear. The total effect of higher cant deficiency on wheel and rail wear is therefore small regarding wear. Some reports on wheel wear problems on tilting trains are found in the literature, National corridors [2006] have reported excessive wheel (flange) wear on the tilting version of the Inter City Express (ICE) and Trainweb [2006] has reported the same for Acela. None of these tilting trains is believed to have any substantial radial steering ability.

From a vehicle point of view, the wheel profile development must also be considered. Flange wear leads to decreased flange thickness and need for reprofiling due to thin flange. Tread wear may lead to need for reprofiling due to poor running behaviour. The longest wheel turning interval is received when flange wear and tread wear is in balance with each other. However, these phenomena are not specific for tilting trains only.

Rolling Contact Fatigue (RCF) has, for models described by Ekberg, Kabo & Andersson [2002], a dependence on vertical force magnitudes. The increased cant deficiency will result in increased vertical force on the curve outer wheel, which will increase the risk for RCF. The increased vertical force on the curve outer wheel can be counteracted by modest static axle load and low centre of gravity. The risk of RCF may also be counteracted by careful optimisation of the utilized friction coefficient. Important ingredients are appropriate brake blending and longitudinal primary suspension stiffness.

3.4 *Cross-Wind Stability*

Cross-wind stability is an area where much research is in progress. Different calculation methods have been suggested and applied by different scientists. Flange climbing is not considered as safety critical for cross-wind, since an increased lateral force is accomplished by an increased vertical force on the potentially climbing wheel. Cross-wind stability is rather considered by the risk of over-turning the vehicle. The most commonly used criteria is based on the Vector Intercept (*VI*) calculated for a bogie, i.e. the intercept between the track plane and resultant vector of the vertical and lateral force components in relation the distance from track centre to the rail centre line, Figure 3-2. *VI* may also be expressed in vertical forces only as in Equation 3-2. The vertical wheel forces are usually filtered with a low-pass filter with 1.5 Hz limit frequency, [Andersson, Berg & Stichel, 2005]. The criteria on *VI* may be set to 0.9 to have some safety margin against overturning.

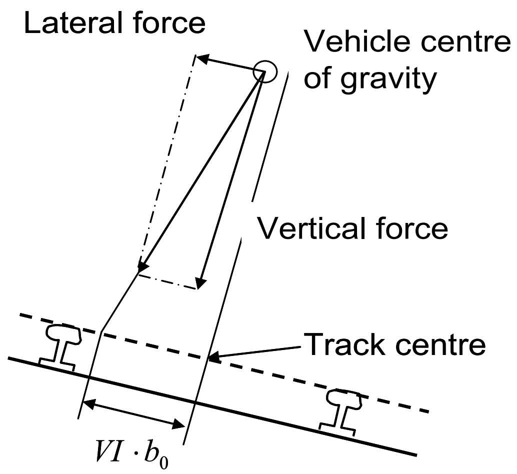

Figure 3-2: The Vector Intercept.
Note the influence from the lateral shift of centre of gravity.

$$VI = \frac{\left|\sum Q_l - \sum Q_r\right|}{\sum Q_l + \sum Q_r} \qquad [3\text{-}2]$$

where:

Q_l = vertical wheel force on the left wheel of a wheelset
Q_r = vertical wheel force on the right wheel of a wheelset

AEIF has included guidance on cross-wind stability in a working draft, [AEIF, 2006]. The draft does not explicitly treat tilting vehicles at enhanced speed. A comparative technique based on Characteristic Wind Curves (CWC) is described though. The CWCs show the maximum cross-wind as function of speed, Figure 3-3, where the wheel unloading criterion, Equation 3-3, is fulfilled. The selected reference vehicles are; the ICE-3, the Train á Grande Vitesse (TGV) Duplex and the ETR500. Any other vehicle used on the interoperable lines must have better or equal CWCs than the reference vehicles. The vertical wheel forces are in this proposal filtered with a low-pass filter with 2 Hz limit frequency.

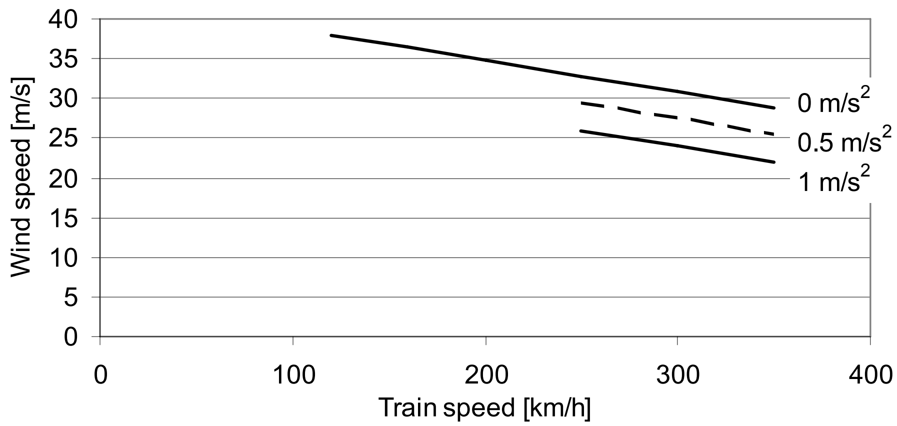

Figure 3-3: Characteristic Wind Curves as function of speed,
for different track plane accelerations in the flat ground case.
Note: 1 m/s² is equal to 153 mm of cant deficiency at standard gauge (1435 mm).

$$\left(\frac{\Delta Q}{Q_0}\right)_{\max,\lim} = 0.9 \qquad [3\text{-}3]$$

where:

ΔQ = Average (dynamic) vertical wheel force reduction on the two unloaded wheels of a bogie
Q_0 = Static vertical wheel force

AEIF [2002], states that the infrastructure manager must for each interoperable line ensure that the conditions on the line are not more severe than what the reference vehicle can handle.

Suggested measures in infrastructure and operations to ensure the safety are:

- locally reduced train speed, possibly temporary during periods at risk of storms,
- installing equipment to protect the actual track section from cross winds,
- or taking other necessary steps to prevent vehicle overturning or derailment.

Diedrichs, Ekequist, Stichel & Tengstrand [2004] showed the relation between different properties of a vehicle and cross-wind stability. Studied properties for vehicles cross-wind stability were:

- train height,
- train width,
- carbody vertical centre of gravity,
- mass of leading bogie,
- nose shape, cross section shape and other properties that affect the aerodynamic coefficients of the vehicle,
- train speed,
- density of air (depending on air pressure and temperature).

The property with the strongest relation to cross-wind stability is the train height.

Lindahl [2001] has simulated cross-wind stability for tilting vehicles at very high speed using the vector intercept criteria with vehicle data according to Table 3-1. Based on these simulations Lindahl finds a relation between wind velocity and cant deficiency for the vehicle. As an example, at a speed of 350 km/h the vehicle can sustain a constant cross-wind of 23 m/s at 250 mm of cant deficiency.

Andersson, Häggström, Sima & Stichel [2004] have 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. Based on the vector intercept criteria Andersson et al. came to the same limit as Lindahl, thus the vehicle can sustain a constant cross-wind of 23 m/s at 250 mm cant deficiency, however at a lower speed. The difference in speed compared to what Lindahl showed was due to a less advanced vehicle than in used by Lindahl.

The relation between speed and permissible cant deficiency can be derived from Lindahl [2001] and from AEIF [2006], Figure 3-3, where the difference in wind speed between a track plane acceleration of 0 m/s^2 and 1 m/s^2 is approximately equal to the difference in wind speed between a train speed of 200 km/h and 360 km/h. Expressing the 1 m/s^2 track plane acceleration as 153 mm cant deficiency, gives the simple rule of thumb: 1 mm reduced permissible cant deficiency for 1 km/h of increased speed, for the same vehicle.

4 Evidence of motion sickness

4.1 *Signs and symptoms*

Motion sickness can generally be explained as being dizzy or nauseated caused by a real and/or apparent motion. Some definitions limit the area to motions in vessels or vehicles, but is here taken in its wider perspective.

Many different symptoms of motions sickness are mentioned in the literature. Gathering the signs and symptoms in groups may help to understand the overall picture, but the split is not obvious and several different proposals have been given, Table 4-1 shows one possible grouping. The examples in Table 4-1 indicate what type of signs and symptoms that may be expected. The “objective group” is interesting as these signs and symptoms may be used as an objective mean to describe the degree of motion sickness. Descriptions of the human receptors are found in Section 5.1.

Table 4-1: Example of signs and symptoms of motion sickness in the literature.

Gastro-related	Somatic	Objective	Emotional
Stomach awareness	Dizziness	Skin humidity	Anxious
Nausea	Exhausted	Pulse rate	Nervous
Inhibition of gastric ability	Fatigue	Blood pressure	Scared / Afraid
Sick	Weak	Body temperature	Tense
Queasy	Tired	Respiration rate	Angry
Ill	Hot / Warm		Worried
Retching	Sweaty / Cold sweaty		Sad
Vomiting	Lightheaded		Upset
	Shaky		Confused
	Headache (especially frontal)		Butterflies
	Blurred vision		Panicky
	Like dying		Hopeless
	Short winded		Regret
	Yawing		Apathy
	Drowsiness		Disgusted
	Facial pallor		Gross
	Increased salivation		
	Swallowing		
	Malaise		

4.2 *Motion sickness questionnaires and scales*

4.2.1 General

Questionnaires with a selection of signs and symptoms and different scales play an important role to judge the degree of motion sickness. These questionnaires can be divided in "one-dimensional well-being scales" or "multi-dimensional symptoms lists". Recent research combines scales with symptoms lists as they have different advantages. An example of motion sickness questionnaire used by FACT is given in Annex B.

4.2.2 Symptoms lists

Graybiel, Wood, Miller & Cramer [1968] developed the Pensacola Diagnostic Index (PDI) which is an example of a multi-dimensional symptoms list. Graybiel et al. use nausea, skin pallor, cold sweating, increased salivation and drowsiness and call them *the big five* within symptoms. They scale and add the symptoms to a total sickness score. The score is finally transferred to a severity expression ranging from frank sickness to slight malaise.

Kennedy, Lane, Berbaum & Lilienthal [1993] developed a subjective motion sickness scale for motion sickness in simulators called the *Motion Sickness Symptom Checklist* later referred to as the *Motion Sickness Questionnaire* or just MSQ. A more recent development made by Gianaros, Muth, Mordkoff, Levine & Stern [2001] divides descriptions of motion sickness in four categories, Table 4-2. Gianaros et al. used a scale from 1 (not at all) to 9 (severe) to rate how accurately the statements in the questionnaire describe the experience of test subjects.

Table 4-2: The Motion Sickness Assessment Questionnaire, *[Gianaros et al, 2001].*

Descriptor	Gastro-related	Central	Peripheral	Sopite-related
Sick to stomach	X			
Queasy	X			
Nauseated	X			
May vomit	X			
Dizzy		X		
Spinning		X		
Faint-like		X		
Lightheaded		X		
Disorientated		X		
Sweaty			X	
Clammy – Cold sweat			X	
Hot – Warm			X	
Annoyed – Irritated				X
Drowsy				X
Tired – Fatigued				X
Uneasy				X

4.2.3 Well-being scales

Well-being scales, also called nausea rating scales, have been particularly used at field tests since they condense information from large data in a convenient way. Lawther and Griffin [1986] 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 [1993] modified the scale to have 5 levels for improved resolution, Table 4-3.

Table 4-3: ***Modified illness rating (IR),*** *[Turner, 1993].*

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

The Misery Scale (or simply MISC) developed by Human Factor Research Institute (TNO) [De Graaf, Bles, Ooms & Douwes, 1992] is an example of a one-dimensional well-being scale with many levels, Table 4-4.

Table 4-4: ***The Misery Scale,*** *[De Graaf et al, 1992].*

Label	Scale
No problems	0
Stuffy or uneasy feeling in head	1
	2
Stomach discomfort	3
	4
Nauseated	5
	6
Very nauseated	7
	8
Retching	9
Vomiting	10

Note that motion sickness scales are of the ordinal type, i.e. a scale in which *a higher number corresponds to a higher degree of a given property*. An ordinal scale provides no other information than the order between its items. Numerical differences between the positions on the scale have no particular significance and interpretation of the average is scientifically doubtful. Still the average is commonly used. One possibility to avoid the interpretation problem is to take the proportion of test subjects reaching a certain level on the well-being scales.

Förstberg [2000a] developed the Symptoms of Motion Sickness Incidence (SMSI), defined as the ratio between subjects having selected symptoms and the total number of subjects. Förstberg used the symptoms dizziness and nausea from the symptoms lists and all other answers than *I feel alright* from the well-being scale. A person having a symptom at start was omitted from the evaluation. That is, SMSI is the percentage of test subjects that have changed its well being from well to not feeling well or becoming dizzy or nauseated during the test. Note that SMSI is an interval scale, where it is mathematically correct to calculate the average.

4.3 *Motion sickness reports*

4.3.1 General

Evidence of motion sickness has been reported in air, in space, at sea, on cars, on trains, at skating, at fairground rides etc. and there are plenty of examples for most of them. Dobie, McBride, Dobie & May [2001] report on nausea caused by motion sickness of 443 children from 9 to 18 years old for 13 different modes of transportation, Figure 4-1. The values given by Dobie et al. are average values for US children that have travelled with each mode of transportation, but the number of travel experiences with trains and cruise ships are significantly lower than for the other modes of transportation.

Note that Dobie et al. takes the average over ordinal type scales which are scientifically doubtful. This figure is here given to show where motion sickness can be expected.

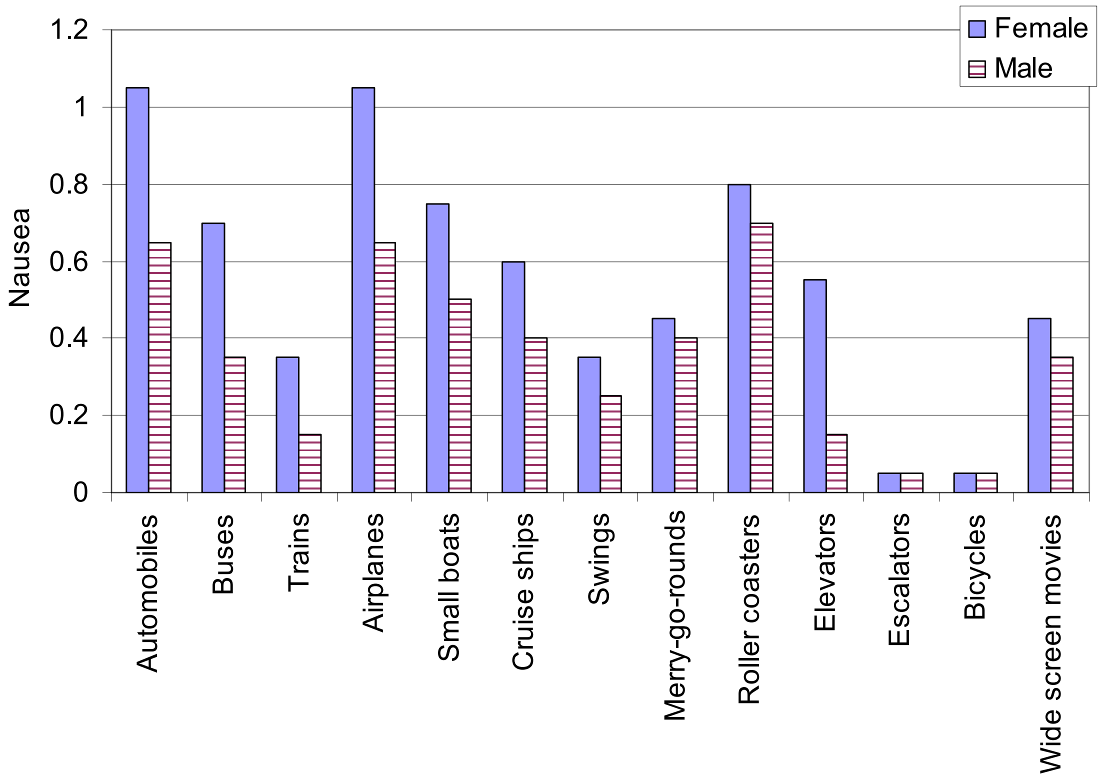

Figure 4-1: Average nausea experience of 9 to 18 years old children in the US,
[Dobie et al, 2001], 0 = never, 1 = rarely, 2 = frequently, 3 = always.

4.3.2 Non-tilting trains

Reports of motion sickness on non-tilting trains are quite rare, but have been reported. Kaplan [1964] reported that 0.13% of the passengers got motion sick among 370 thousand passengers on the Baltimore and Ohio Railroad. Kaplan reported more cases of motion sickness for females than for males and more for children than for adults, Figure 4-2.

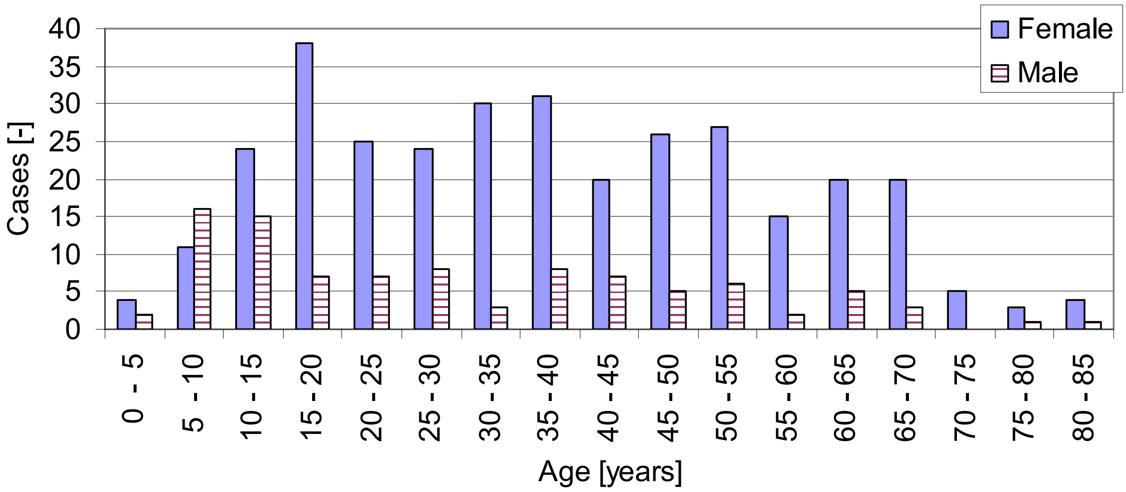

Figure 4-2: Number of motion sick cases on the Baltimore and Ohio Railroad, *[Kaplan, 1964].*

Kaplan also found that susceptible individuals tended to fall ill (become motion sick) within the first four hours of the journey with a marked decrease in cases towards the end of the travel, Figure 4-3.

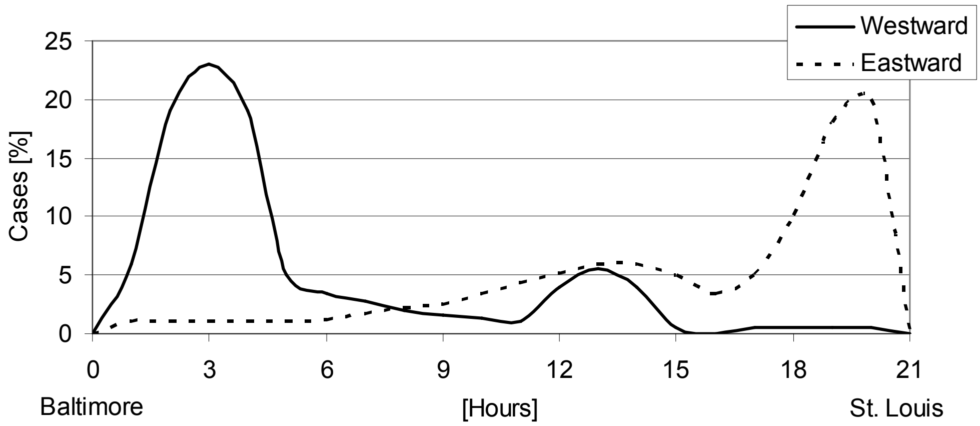

Figure 4-3: Motion sick case distribution as function of travelled time (100% = all cases), *[Kaplan, 1964]. The westward trains start in Baltimore and the eastward trains in St. Louis.*

Rough terrain (gradients and curves) increased the susceptibility when it coincided with wakening and eating hours. Kaplan found a significant decrease in reported cases during sleeping hours. Kaplan finally point out translational acceleration combined with rotational motion of the head as the prime cause of motion sickness on trains.

Suzuki, Shiroto & Tezuka [2005] report 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 trains on the conventional narrow-gauge Japanese network. Bromberger [1996] reports that 2 % of the passengers on the TGV-Duplex trains experiences motion sickness. Evidence of motion sickness in non-tilting trains has also been reported in the US by Money [1970], in the UK by Turner [1993] and in Sweden by Kottenhoff [1994].

4.3.3 Tilting trains

Evidence of motion sickness on tilting trains has been reported in Japan by Ueno, Ogawa, Nakagiri, Arisawa, Mino, Oyama, Kodera, Taniguchi, Kanazawa, Ohta & Aoyama [1986] and Suzuki et al. [2005], in Sweden by Förstberg [1996], in Switzerland by Hughes [1997], and in

France by Gautier [1999]. Suzuki et al. report that as much as 27% of the passengers experience motion sickness on the tilting trains. Förstberg [1996] reports 6% motion sickness at a test on X2000 in Sweden and 8 – 15% motion sickness in a test involving different tilt control strategies, Förstberg [2000a]. Tilting trains generally cause more motion sickness than non-tilting trains. However, the speed of the tilting trains was higher than for the non-tilting trains in reports where both types were considered. Bromberger [1996] states there is more reported motion sickness in passively tilted trains than in actively tilted ones.

Donohew & Griffin [2007] report from tests made in France on a tilted version of TGV, where they found significantly more motion sickness on morning runs than on afternoon runs independent of test case, Figure 4-4.

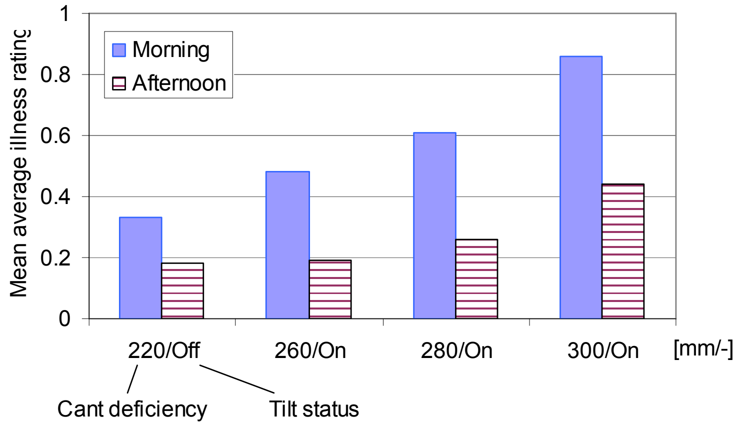

Figure 4-4: Mean average illness rating for morning and afternoon runs, *[Donohew & Griffin 2007].*

Förstberg [2000a], Donohew & Griffin [2005b] and Förstberg, Thorslund & Persson [2005] are examples of reports indicating females being more susceptible for motion sickness than males in tilting trains. Förstberg [2000a] also reported females to have sensitivity for travel direction, backwards giving significantly less motion sickness. Förstberg [2000b] reported more motion sickness for travelling backwards. This contradiction can possibly be due to experience, as the latter report came for tests made in Norway, where turning the seats in travelling direction is common in non-tilting trains.

4.4 *Motion sickness during laboratory tests*

Motion sickness as a result of provocative experiments in laboratories is one very important key in finding the cause of motion sickness as the provocative sensations in laboratories may be simplified compared with the real environment. The main interest here is whole-body oscillations, but also tests with head movements contribute to the knowledge. It is important to note under what conditions each test is made, in particular whether support to upper body and/or head is provided.

4.4.1 Longitudinal motions

Golding, Müller & Gresty [1999] 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 the head against the headrest providing some support of the test subjects' upper body and head. The amplitudes ranged from 0.19 to 3.98 m/s^2, and they found a sensitivity peak at 0.2 Hz indicating a similar weighting function as in vertical direction, see Figure 4-6. Griffin & Mills [2002] have shown that there is no significant difference between longitudinal and lateral motion sickness sensitivity at frequencies between 0.2 Hz and 0.8 Hz. The velocity amplitude was 0.5 m/s peak for all frequencies. The result was based on laboratory tests with pure longitudinal and pure lateral motions. The test subjects were seated in an upright position oscillating back and forth and side to side.

4.4.2 Lateral motions

Donohew & Griffin [2004b] proposed a different weighting function in lateral direction than used in vertical. The result was based on laboratory tests with pure lateral motions. The test subjects were seated in an upright position oscillating side to side at frequencies between 0.0315 Hz and 0.8 Hz. The backrest on the chair was low giving little support to the upper body and no support to the head of the test subject. 30% of the test subjects report motion sickness at a frequency of 0.125 Hz and an amplitude of 0.56 m/s^2 (r.m.s) after half an hour of exposure. Mild nausea incidence was used as a base. The weighting function in lateral direction has the greatest sensibility between 0.02 Hz – 0.25 Hz and is in this paper called W_g, Figure 4-5.

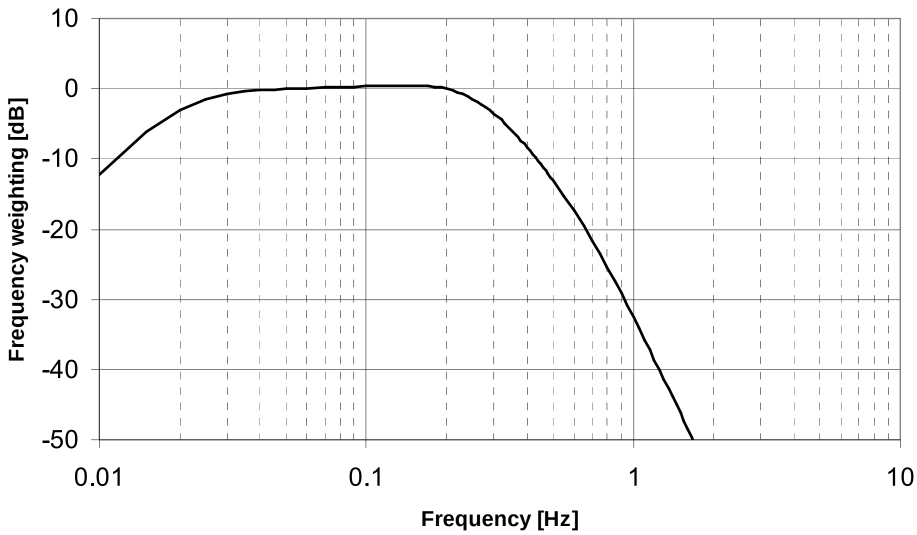

Figure 4-5: Normalized weighting function, W_g, for pure lateral acceleration,
[Donohew & Griffin, 2004b].

4.4.3 Vertical motions

O'Hanlon & McCauley [1973] made comprehensive tests in vertical direction with seated subjects. O'Hanlon & McCauley used aircraft seats and instructed the subjects to keep the head against the headrest providing some support of the test subjects' upper body and head. 50% of the test subjects report motion sickness at a frequency of 0.1 Hz and an amplitude of 0.30 m/s^2 (r.m.s.) 25% of the test subjects report motion sickness at a frequency of 0.1 Hz and an amplitude of 0.16 m/s^2 (r.m.s.) 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, for pure vertical acceleration causing motion sickness, documented by International Standards Organization (ISO) [1997]. The weighting function has the greatest sensibility between 0.1 and 0.25 Hz, Figure 4-6. The function is primarily applicable to standing or seated passengers exposed by motions in ships and other sea vessels. However, it has been used in other applications and even in other directions.

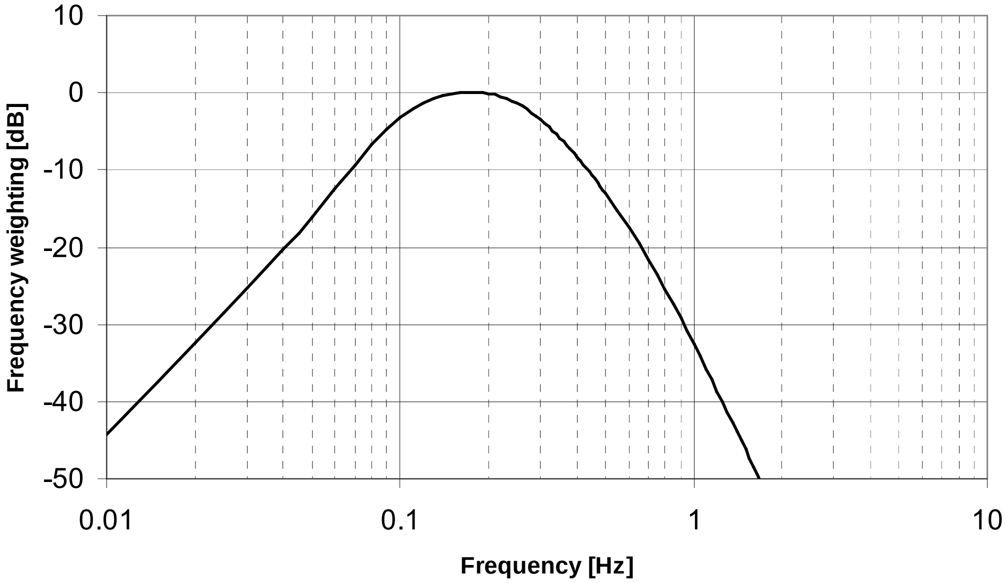

***Figure 4-6: Normalized weighting function, W_f, for pure vertical acceleration**, [ISO, 1997].*

4.4.4 Roll motions

McCauley, Royal, Wylie, O'Hanlon & Mackie [1976] have shown in laboratory tests that *pure roll* at 0.345 Hz does not generate motion sickness at an amplitude of 7 deg. They used aircraft seats and instructed the subjects to keep the head against the headrest providing some support of the test subjects' upper body and head. The pure roll case was a reference case then McCauley et al. combined roll with vertical acceleration, Table 4-6. Förstberg [2000a] has shown in laboratory tests that pure roll at 0.167 Hz does not give motion sickness at an amplitude of 4.8 deg (0 to peak). The pure roll case was one of several cases Förstberg made with tilting trains in focus, Table 4-8.

Howarth [1999] report from laboratory tests with *pure roll* at frequencies ranging from 0.025 Hz to 0.40 Hz, at an amplitude of 8 deg. The backrest on the chair was low giving little support to the upper body and no support to the head of the test subject. 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 to displacement instead of acceleration.

4.4.5 Pitch motions

McCauley et al. [1976] have shown in laboratory tests that *pure pitch* at 0.345 Hz gives motion sickness to 9% of the test subjects at amplitude of 7 deg. They used aircraft seats and instructed the subjects to keep the head against the headrest providing some support of the test subjects' upper body and head. The pure pitch case was a reference case when McCauley et al. combined pitch with vertical acceleration, Table 4-6. They concluded that pure pitch motion is not the prime cause of motion sickness on sea.

4.4.6 Yaw motions

There are ample examples of tests that use constant yaw velocity (typically rotation around an Earth-vertical axis) combined with at least one other motion. Many of these tests use the pure yaw motion as reference case like Eyeson-Annan, Peterken, Brown & Atchison [1996]. Constant yaw velocity does not provoke motion sickness.

Guedry, Benson & Moore [1982] used yaw oscillation. They found that 0.02 Hz at 155 deg per second peak velocity provoke motion sickness, but not 2.5 Hz at 20 deg per second peak velocity, when the subjects at the same time try to find a certain value in a head fix matrix display. Guedry et al. do not provide any description of the seat.

Bubka, Bonato, Urmey & Mycewicz [2006] compared constant yaw velocity at 30 and 60 deg per second with changing yaw velocity between 30 and 60 deg per second and found that changing yaw velocity cause more nausea than constant yaw velocity. The subject's head was immobilized in the centre of a drum that rotated about an Earth-vertical axis.

It should be noted that the used conditions are far from what is usual on trains.

4.4.7 Combined motions

A test with combined motions generally involves two motions, these tests may be divided in two groups depending on whether both motions are changing or just one is changing. The laboratory tests with combined motions are summarized in Table 4-5.

Table 4-5: Summary of combined tests.

	Roll	Pitch	Yaw (constant)
Longitudinal		Golding et al. [2003]	
Lateral	Förstberg [2000a] Donohew & Griffin [2004a]	Golding et al. [2003]	
Vertical	McCauley et al. [1976] Wertheim et al. [1995] Dahlman [2007]	McCauley et al. [1976] Wertheim et al. [1995]	
Roll		Wertheim et al. [1995]	Purkinje [1820] Eyeson-Annan et al. [1996] De Graaf et al. [1998]
Pitch			Purkinje [1820]

Early combined motion tests involved just one changing variable like Purkinje [1820], who used constant yaw velocity combined with roll or pitch movements to provoke motion sickness. This combination of motions was also the base to Cox’s chair developed to treat mentally ill persons by provoking nausea. One such chair can be seen in Vadstena hospital museum (Sweden).

McCauley et al. [1976] combined pitch or roll with vertical motions, Table 4-7. They used aircraft seats and instructed the subjects to keep the head against the headrest providing some support of the test subjects' upper body and head. The number of subjects participating in each case was 20 or more. McCauley et al. also made reference tests with pitch only, vertical only and roll only, Table 4-6.

Table 4-6: **_Vomiting incidence in percent, pure motion cases,_** *[McCauley et al, 1976].*

Frequency [Hz]	Pitch velocity (r.m.s) 33.3 [deg/s]	Vertical acceleration (r.m.s) 1.1 [m/s^2]	Roll velocity (r.m.s) 33.3 [deg/s]
0.250 [1)]		31%	
0.345	9%		0%

1) It is unclear to the author why the frequency in the reference case differs from that of the combined cases.

Table 4-7: **_Vomiting incidence in percent, vertical acceleration, with 1.1 m/s^2 (r.m.s) at 0.23 Hz, combined with pitch or roll velocity,_** *[McCauley et al, 1976].*

Frequency	Pitch velocity (r.m.s) [deg/s]			Roll velocity (r.m.s) [deg/s]		
[Hz]	5.51	16.7	33.3	5.51	16.7	33.3
0.115	36%			14%		
0.230	40%	40%		43%	40%	
0.345	24%	25%	38%	35%	8% [1)]	48%

1) McCauley et al. realized that this value deviated from the other results, but could not give any other explanation than it was due to chance variation.

McCauley et al. 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. It should be noted that the limited number of subjects resulted in a large statistical uncertainty, so McCauley et al. could not prove the difference in vomiting incidence between vertical only and vertical combined with pitch or roll to be statistically significant.

Wertheim, Wientjes, Bles & Bos [1995] combined pitch motions of 0.08 Hz to 0.13 Hz with roll motions with the same frequency. The amplitude was 11 deg (r.m.s.) in both directions. This combination of movements gave significantly more motion sickness than pure roll. Wertheim et al. also combined roll and pitch motions at 10 deg (r.m.s.) with *vertical acceleration* of 0.1 Hz at 0.22 m/s^2 (peak) with even higher degrees of motion sickness than the motion without vertical acceleration. This conclusion is in contrast to the results of McCauley et al. [1976]. The difference could possibly be explained by the head support provided by McCauley et al.

Dahlman [2007] combined vertical acceleration with roll motions in a test with sea sickness in focus. He found that the case with combined motions gave significantly more motion sickness than cases with pure vertical acceleration and pure roll motion. Dahlman was using car type seats with high backrests so that the test subjects had some support of the movement of their upper body.

Förstberg [2000a] 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. Also, typical lateral and vertical high-frequency vibrations found in trains were added. The backrest on the chair was high so the test subjects had some support of the movement of their upper body, Figure 4-7.

***Figure 4-7: Interior view of cabin with test subject**, [Förstberg, 2000a].*

The exposure time was 30 minutes. Förstberg used a motion sickness rating scale where 0 is no motion sickness and 4 is strong motion sickness (but no retching or vomiting). A result summary is given in Table 4-8.

***Table 4-8: Average motion sickness rating at combined motions**, [Förstberg, 2000a]. The value in parenthesis gives the ratio of the horizontal acceleration compensated by roll.*

Horizontal acceleration (peak) [m/s^2]	Roll angle (peak) [deg] 0	3.6	4.8	6.4
0			0.19 (-)	
0.8		0.42 (75%)	0.89 (100%)	
1.1	0.64 (0%)	0.68 (55%)	1.13 (75%)	1.34 (100%)

Förstberg 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 horizontal motions.

Donohew & Griffin [2004a] combined horizontal acceleration with roll in a test with tilting trains in focus. They used the same motion sickness rating as Förstberg and the exposure time was also the same, 30 minutes. The ratio of the horizontal acceleration compensated by roll was always 100% when roll applied. The backrest on the chair was low giving little support to the upper body and no support to the head of the test subject. The result as function of frequency and amplitude is shown in Figure 4-8.

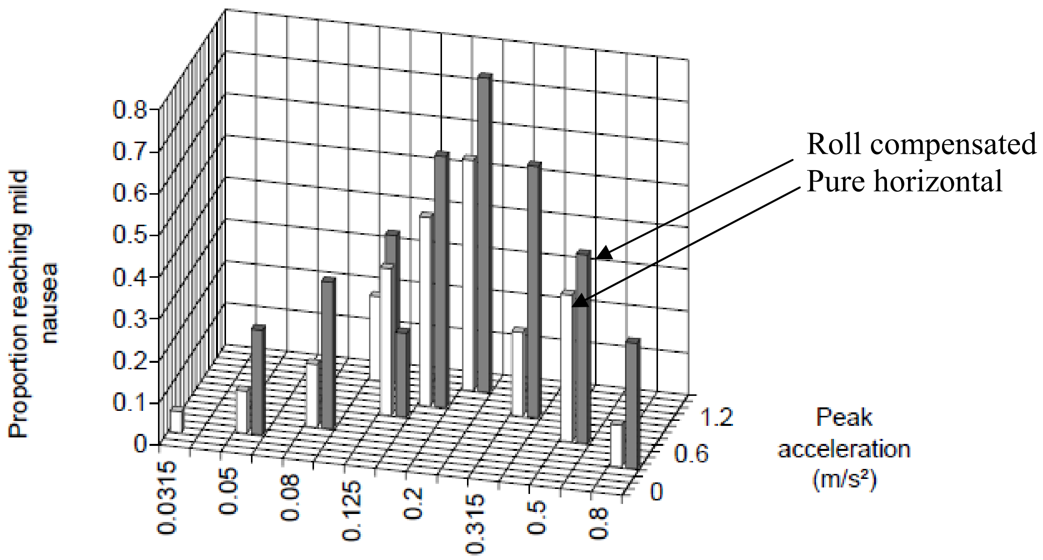

Figure 4-8: The effect of roll compensated horizontal acceleration,
[Donohew & Griffin 2004a],
(white = pure horizontal, grey = roll compensated) as proportion reaching mild nausea.

Donohew & Griffin [2004a] came to the conclusion that roll motions increase the incidence of sickness when combined with lateral motions, particularly at frequencies above 0.2 Hz; this conclusion is in accordance with Förstberg.

Golding, Bles, Bos, Haynes & Gresty [2003] combined pitch movements with longitudinal and lateral motions. They found longitudinal and lateral motions equal to cause motion sickness when combined with pitch movements. Golding et al. used a frequency of approximately 0.2 Hz and amplitudes from 2.0 to 3.1 m/s^2 (peak). They used seats with high backrests and instructed the subjects to keep the head against the headrest providing some support of the test subjects' upper body and head.

Eyeson-Annan et al. [1996] combined yaw rotation with roll motions and found them to cause motion sickness; pure yaw rotation did not cause any motion sickness. However, no motion sickness was observed as long as the test subject has correct visual reference. De Graaf, Bles & Bos [1998] combined yaw rotation at 180 deg per second with visual roll stimuli at 30 deg per second without any signs of motion sickness. The used conditions are far from what is usual on trains, but even at these high amplitudes, yaw combined with roll motion do not cause motion sickness.

4.4.8 Posture

Manning & Stewart [1949] studied the effect of posture in a test based on swing motion and a large group of subjects, Table 4-9. Manning & Stewart used seats with backrests providing some support of the tests subjects' upper body. They found that lying passengers received much less motion sickness than seated subjects.

Golding & Kerguelen [1992] studied the effect of posture by comparing vertical motion for sitting subjects with horizontal motion for lying subjects, which give the same information to the organs of equilibrium. The lying subjects received much less motion sickness and Golding & Kerguelen came to the conclusion that the direction of the motion in relation to gravity is important.

Table 4-9: The effect of posture and visual reference, *[Manning & Stewart, 1949].*

Attitude of subject	Percent vomiting in less than 30 minutes		
	External reference	No reference	Internal reference
Lying	5	11	No data
Sitting	28	51	64

Golding, Markey & Stott [1995] compared pure longitudinal motion with seated subjects with lying test subjects exposed with pure vertical motion, which give the same information to the vestibular organs. The lying subjects received much less motion sickness and also Golding et al. came to the conclusion that the direction of the motion in relation to gravity is important. The relation to maintaining the human body in upright position in the sitting case but not in the lying is believed to explain the difference in sensitivity due to posture.

4.4.9 Visual reference

Manning & Stewart [1949] studied the effect of visual reference in the same test as the studied the effect of posture, Table 4-9. They found that subjects without reference received much more motion sickness than subjects with external reference and that internal reference was more provocative than both external reference and the case without reference.

Howarth, Martino & Griffin [1999] studied the effect of visual scene on motion sickness caused by lateral oscillation. They found that external reference has significant beneficial effect, producing less motion sickness than an internal reference. However, the external view must be distant to get the positive effect.

4.4.10 Head movements

The movement of the head relative to the body has received interest in several research reports referred in the present report. Kaplan [1964] pointed out translational acceleration combined with rotational motion of the head as the prime cause of motion sickness on trains. Most scientists try to control the relative motion by offering head support, but there are also examples where the relative motion is part of the manipulation in the experiment.

Tests during parabolic flights have been used to simulate weightlessness. The subjects perform self controlled motions during the zero gravity periods. Graybiel [1978] reports on one such test where the subjects performed pitch and roll movements with their heads. A strong correlation between head movements and motion sickness was found.

Bles, de Graaf & Krol [1995] made tests after periods with enhanced gravity. Three times normal gravity was achieved by a human centrifuge. The subjects performed self controlled head motions after periods with enhanced gravity, resulting in motion sickness. Typically the centrifuge run with constant yaw velocity and it was found that head motions in pitch and roll provoke motion sickness but not head motions in yaw. They concluded that head motions in the same direction as the centrifuge run caused no motion sickness, but head movements in other directions provoke motion sickness.

Also National Aeronautics and Space Administration (NASA) has acknowledged the importance of head movements. The designers of the real-life International Space Station and the Space Shuttle have used different methods to establish a common sense of “up”. For example, all of the modules have a consistent “up”-orientation, and the writing on the walls points in the same direction, NASA [2001]. Astronauts are also advised to limit their head movements and to keep in the “up”-orientated direction when symptomatic.

4.4.11 Conclusions on motion sickness during laboratory tests

The knowledge shown and the references given to laboratory tests in the present study is huge. This section is an attempt to summarize the knowledge. The summary is given as statements with supporting evidence, Table 4-10.

Table 4-10: Evidence of motion sickness during laboratory tests.

Statement	Reference
Translations cause motions sickness. Reports for extensive laboratory tests have shown correlation between translations and motion sickness. The relations are well established.	O'Hanlon & McCauley [1973] Golding et al. [1999] Donohew & Griffin [2004b]
Pure rotations are less provocative than translations. Reports from laboratory tests made with rotations show that rotations cause motion sickness. However, the magnitudes must be higher than what is possible in a train.	McCauley et al. [1976] Eyeson-Annan et al. [1996] Förstberg [2000a]
Combined motions are provocative. Combining two rotations or a translation and a rotation is significantly more provocative than pure motions.	Purkinje [1820] Eyeson-Annan et al. [1996] De Graaf et al. [1998]
External visual reference reduces motion sickness. Internal visual reference is worse than no reference at all.	Manning & Stewart [1949]
Head movements are provocative if performed in unfamiliar force field.	Bles et al. [1995]

One pure motion is not the likely cause to the motion sickness experienced in tilting trains. A combination of motions is more provocative and much more likely the cause. It is also likely that head rotations contribute, as these may be performed at much higher amplitudes than performed by the train itself.

4.5 *Motion sickness during on-track tests*

This section gives a short description of reported motion sickness on-track tests and passenger surveys made on tilting trains.

Andersson & Nilstam [1984] reported on a test made in Sweden in 1979 with X15, an experimental tilting train. The main objective was to verify the comfort of the train, but the risk of motion sickness was also assessed. The most important result on motion sickness from this test was the recommendation to reduce the *tilt compensation* from 100 % to 65 - 70 %.

Ueno et al. [1986] reported on a passenger survey made on both natural tilting trains and non-tilting. A large difference on motion sickness was experienced between the tilting trains and the non-tilting. This was claimed to be due high magnitudes of 0.5 – 1.0 Hz *lateral accelerations* in the tilting trains.

Harborough [1986] reported on tests made in the UK in 1983 – 84 with APT, an experimental tilting train. The main objective was to verify the comfort of the train. The most important result was the comfort criteria on curve transition (P_{CT}) and the comfort criteria on discrete events (P_{DE}). He also found that the comfort was equally good in a train with 50% tilt compensation as a train with 100%.

Ohno [1996] reported on a passenger survey made on the conventional narrow-gauge Japanese network. The main objective was to verify the effect of the limits on *roll velocity* (5 deg/s) and *roll acceleration* (15 deg/s^2). The problems with motion sickness have decreased after introduction of these limits, but are not eliminated.

Förstberg [2000a] reported on a test made in Sweden in 1995 on X2000. The speed was up to 200 km/h combined with a cant deficiency up to 245 mm. The main objective was to assess the risk of motion sickness. The most important result from this test was the clear correlation between *tilt compensation* and motion sickness. Reduced roll velocity was also favourable.

Förstberg [2000b] reported on a test made in Norway in 1999 on BM73. The speed was up to 120 km/h combined with a cant deficiency up to 280 mm. The main objective was to assess the risk of motion sickness. No significant correlation between tilt compensation and motion sickness was found. Travelling backward was found more provocative for motion sickness than forward.

Suzuki et al. [2005] reported on a large passenger survey made on 14 different types of trains (both tilting and non-tilting) on the conventional narrow-gauge Japanese network. They correlate measured motions with experienced motion sickness. The most important result from this evaluation was the strong correlation between increased *lateral acceleration* and increased experienced motion sickness. Suzuki et al. are also proposing a weighting curve for lateral acceleration. No correlation between vertical acceleration and motion sickness was found.

Donohew & Griffin [2005a] reported on tests made in France in 1998 and 2000 on the tilting TGV, the evaluation was part of FACT. The tests were made on conventional lines with a cant deficiency up to 300 mm. The degree of motion sickness in the tests was extremely high with several cases of vomiting. The most important result derives from the test made in 2000 as this was the first time when correlation between *vertical acceleration* and motion sickness was reported. Models 4, 5 and 6 used in Chapter 9 come from this report.

Donohew & Griffin [2005b] reported on tests made in Slovenia in 2004 on Pendolino series ETR470 as part of FACT. The speed was up to 130 km/h combined with a cant deficiency up to 270 mm. The reported level of motion sickness was low. The result supported the results from the tests made in France 2000.

Förstberg et al. [2005] reports on tests made in Sweden and Norway in 2004 on BM73 as part of FACT. The speed was up to 200 km/h combined with a cant deficiency up to 280 mm. A description of the test is given in Chapter 7. The result supported the result from France 2000 by showing correlation between *vertical acceleration* and motion sickness. Models 7 and 8 used in Chapter 9 come from this report. The evaluation and analysis made in Chapter 8 and 9 is based on the same tests.

5 Hypothesis of motion sickness

5.1 *Human receptors*

The human body can receive information about posture and movements by:

1. Sensory information, from the inner ear,
2. Visual information, from the eyes,
3. Proprioceptive information, from muscles.

The sensory information is sensitive for translational and rotational accelerations. The information of translational acceleration comes from the otolith organs and rotational acceleration from the semicircular canals. The response for a sustained motion (constant velocity) will fade out with a time constant of approximately 15 seconds, which corresponds to a cut-off frequency of approximately 0.025 Hz, Förstberg [2000a].

The visual information is sensitive for position which may be derived to velocity. The visual information has an upper frequency limit of approximately 5 Hz, Verstraten, Cavanagh & Labianca [2000].

The proprioceptive information comes from muscles and is sensitive for force, which combined with the vestibular information is sensitive for accelerations with an upper frequency limit of 5 to 10 Hz, [Förstberg & Ledin, 1996].

The central nervous system summarizes the information from the receptors to posture and movements.

5.2 *The sensory conflict theory*

The sensory conflict is the most common explanation of motion sickness. The different sensitive capabilities of different motion information sources give a sensory conflict, like;

1. a passenger sitting in a moving train and looking inside train feels the movements but can not see any,
2. a subject in a simulator without moving platform sees movements on displays, but can not feel any,
3. a passenger, sitting in a turning aircraft, making head movements (pitch and roll) feels the turning of the aircraft but can not see any.

The theory has developed over the years from Claremont [1931] and Reason & Brand [1975] to today being able to explain most motion sickness cases. Benson [1988] has included the central nervous system and expresses the conflict as:

> *That in all situations where motion sickness is provoked, there is a sensory conflict not only between signals from the eyes, vestibular organs and other receptors susceptible to motion, but also that these signals are in conflict with what is expected by the central nervous system.*

One model of the conflict theory is shown in Figure 5-1.

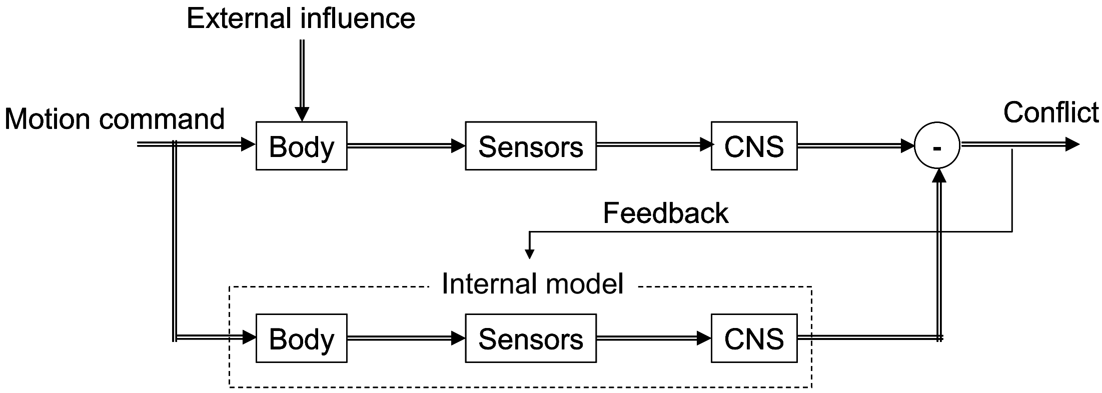

Figure 5-1: Model of the conflict theory, *modified from Bles, Bos & Kruit [2000], CNS = Central Nervous System.*

The model of the conflict theory consists of two paths, the top path represents the actual information from the sensors processed by the Central Nervous System (CNS), and the lower path represents the internal model, which estimate the effect of a given motion command (active motions). The estimated and the actual information are compared, and a conflict signal will be generated if they differ. Passive motions (without motion command) are in the model represented by external influence; these can by themselves create conflict as the external do not have any direct flow to the internal model. Habituation is represented by the feedback from conflict to updating the internal model.

The vestibular system plays a role in motion sickness, since humans with defect vestibular function are immune to stimuli that normally cause motion sickness, i.e. there is no sensory conflict. This includes cases where the stimuli are purely visual.

Some scientists have claimed that the Coriolis cross-coupling may be reason for the conflict, but others claim that the Coriolis force is too small to be the cause. A more likely scenario is that rotations in two directions cause a believed rotation around the third axis by exciting the sensors in the inner ear and activating the velocity storage mechanism. The latter scenario is suggesting that the velocity storage mechanism is important for the production of motion sickness. This theory is supported recent studies, DiZio & Lackner [1991], Bos, Bles & de Graaf [2002] and Dai, Kunin, Raphan & Cohen [2003].

The conflict can also be described by the difference between the sensed direction and the expected direction of vertical. The conflict is by Bles, Bos, de Graaf, Groen & Wertheim [1998] described as:

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

The conflict theory described as difference between the sensed direction and the expected direction of the g-vector is verified by comparing the frequency/amplitude response to test results derived by O'Hanlon & McCauley [1973]. This description is in line with Kaplan [1964] who pointed out translational acceleration combined with rotational motion of the head as the prime cause of motion sickness on trains.

Bubka & Bonato [2003], Bonato, Bubka & Story [2005] and Bubka et al. [2006] argue that the variance between the subjective vertical and the real vertical as described by Bos & Bles [1998, 2004] can not explain the result in a Bonato and Bubka's tests, where stand-still test subjects surrounded by a rotation drum with vertical stripes received motion sickness at head pitch movement. Bonato and Bubka explain that there is no variance between the subjective vertical and the real in this experiment, so the theory proposed by Bos and Bles can not be correct. Bonato and Bubka conclude that only the pure sensory conflict theory can explain their findings.

5.3 *Competing theories*

Most scientists have today accepted the sensory conflict theory, but there are also competing theories;

The over-stimulation theory
The over-stimulation theory is based on over-stimulation of sensors rather than conflict between different sensors. Supporters of the theory give examples where no conflict is involved like low-flying fighter aircrafts where the only input comes from the vision. According to this theory a large amount of signal information is transferred from sensors to the central nervous system. This over-stimulation is treated as poison and a defence mechanism is triggered.

The ecological theory
Riccio & Stoffregen [1991] proposed the ecological theory of motion sickness. Riccio & Stoffregen claim that no sensory conflict exists and suggests 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. Low frequencies have a destabilizing effect but not high frequencies as these are filtered out by the human body inertia. Low-frequency vibration is claimed to be the prime cause of motion sickness due to its relation to destabilizing the postural control system. Instability persists until a new pattern is learned.

5.4 *Time dependence of motion sickness*

Oman [1990] set up a mathematical model of time dependence of motion sickness based on the conflict theory. This time dependence starts with the conflict signal and ends with the magnitude of nausea. Oman's time dependence have two paths with two different time constants, one fast path with time constant less or equal to 60 seconds and one slow path with 600 seconds time constant, Figure 5-2. The time constant is a measure on how fast the output (nausea) responds to a change on input. A single conflict stimulus can at high levels of nausea produce a virtually instantaneous increment in nausea. Observe that the output from the slow path controls the amplification of the fast path. A graphic visualizing of Oman's time dependence is shown in Figure 5-3.

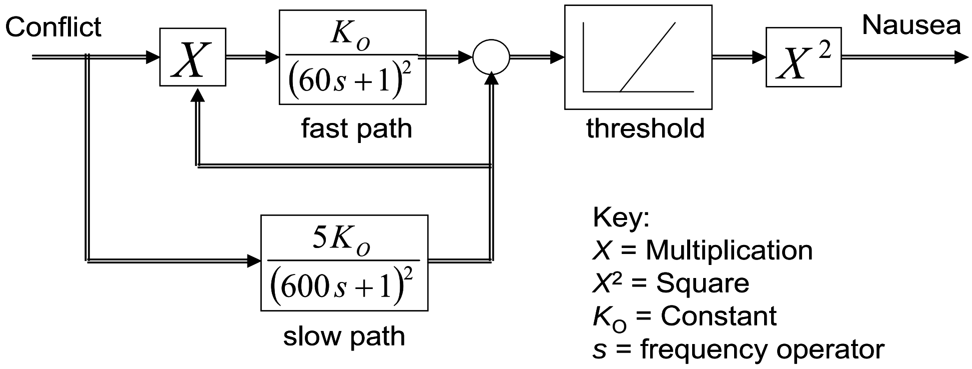

***Figure 5-2: Mathematical model for motion sickness path symptom dynamics**, Oman [1990]. The fast / slow path elements are second order low-pass filters.*

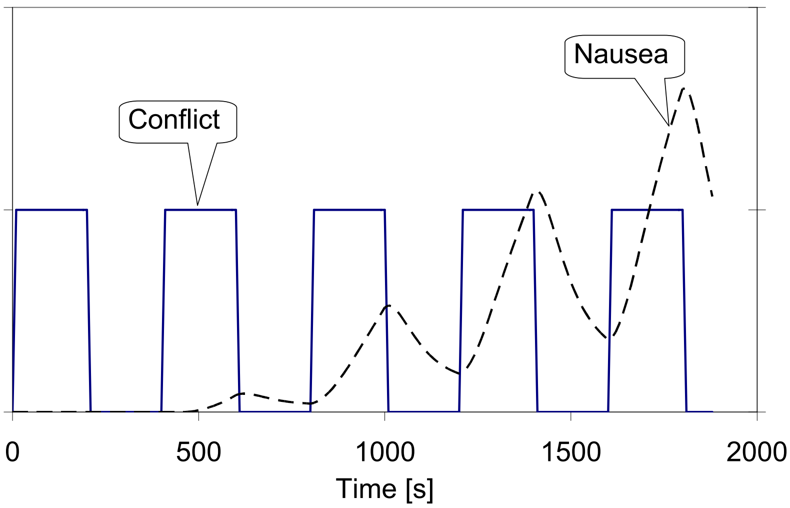

Figure 5-3: Graphic visualizing of Oman's time dependence.
The conflict input toggles between on and off.

The approach taken by Oman is rather difficult to apply on track testing due to its complexity. ISO [1997] has taken a more practical approach in the *Motion Sickness Dose Value* (MSDV) dependence of time indicating the *vomiting* frequency in percent, Equation 5-1. Theoretically, this equation can take values above 100%, but such high values are above the interesting range of application.

$$MSDV_z(t) = \quad k_{MSDV} \cdot \sqrt{\int_0^t a_{wf}^2(\tau) \cdot d\tau} \qquad [5\text{-}1]$$

where $a_{wf}(t)$ is the frequency-weighted vertical acceleration [m/s^2] and $k_{MSDV} = \frac{1}{3}$ [s^{1,5}/m] for a mixed population of male and female adults. Griffin [1990] has, based on the $MSDV_z(t)$, derived the *Illness Rating* $IR(t)$, Equation 5-2.

$$IR(t) = \frac{MSDV_Z(t)}{50} \qquad [5\text{-}2]$$

where $IR(t)$ is applied on a scale from 0 (feel all right) to 3 (feel dreadful).

Motion sickness dose value can be used with other descriptions of motion than the weighted vertical acceleration, but will always give a value increasing with time.

Kufver & Förstberg [1999] derived the Net-Dose time dependence *ND*(t)*,* which only has one first order path, Figure 5-4.

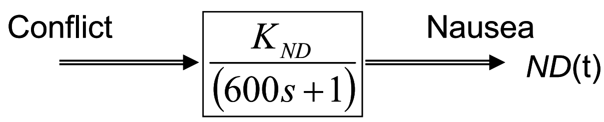

Figure 5-4: Mathematical model for the Net Dose time dependence.
The path element is a first order low-pass filter, here with a time constant of 600 seconds (10 minutes), K_{ND} = constant and s = frequency operator.

ND(t) can be applied on any description of conflict, but lateral acceleration and roll velocity are most common. The capability to depict increasing and decreasing motion sickness makes it, together with its simplicity useful for evaluation of on-track testing.

Förstberg [2000a] suggests 12 minutes as time constant, a value taken from the recovery after being motion sick. Förstberg et al. [2005] report a time constant in the same range, but indicate that the values vary at lot. The variation could be depending on the sensitivity threshold. This threshold corrupts the time constant at fall ill, and was the reason why Förstberg used the recovery only when he calculated the time constant. Förstberg et al. [2005] reported time constants taken from variable exposures derived at tilting train tests.

There are also indications that the time constant is depending on the degree of motion sickness. Golding et al. [1995] report time constants in the range of 3 to 5 minutes for low degree of motion sickness. Golding & Stott [1997] found a clear difference between subjective reports and objective measurements on motion sickness. The subjective reports gave much shorter time constants at recovery, about 4 minutes, than the objective measurements, which gave about 15 minutes.

5.5 *Habituation*

The human has the ability to recalibrate its *balance system* when information from the different receptors does not correspond. This ability is called *habituation* or *adaptation* and has been observed since long time at sea. Habituation is made to one specific environment while other motions may still cause motion sickness. Habituation to space environment may be an exception which seems to give immunity to other motions. The time constant for habituation has been the subject of several scientists. McCauley et al. [1976] made a test where they selected persons that gave motion sickness incidence (vomiting) in an initial test. They followed up with the same exposures for five consecutive days. The habituation series resulted in a decrease in motion sickness incidence ending at 30% on day 5. McCauley used vertical acceleration at 0.25 Hz and 0.22 m/s^2 (r.m.s.) in two hours as exposure. Förstberg [2000a] came to similar results with subjects exposed to lateral acceleration combined with roll in an experiment simulating tilting train conditions in 30 minutes at four different occasions at four different test days, Figure 5-5.

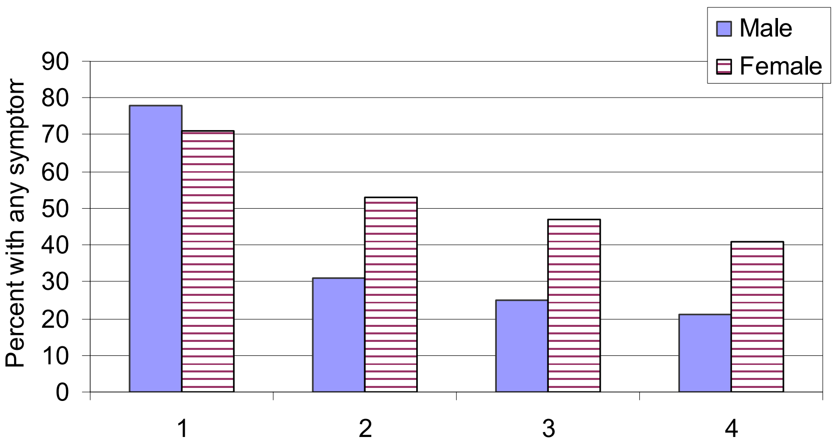

Figure 5-5: Percent of test subjects with any symptom as function of test day, *Förstberg [2000a]. The tests were performed in four different days.*

Most scientists have reported time constants for habituation in the range of 3 to 5 days, but the effect can also be observed after a few hours, Kaplan [1964]. Habituation has been observed at motion sickness tests on tilting trains where test subjects recover from motion sickness at maintained stimuli.

Other scientists have taken a more theoretical approach to habituation by seeking the base behind habituation. DiZio & Lackner [1991] have shown good correlation between velocity storage time constant and habituation, habituation lowers the time constant. There is also evidence that the time to get habituated is much less than the time to get weaned, Dai et al. [2003]. Figure 5-6 shows the relation between velocity storage time constant and habituation as function of test day. The subject performed horizontal head movements.

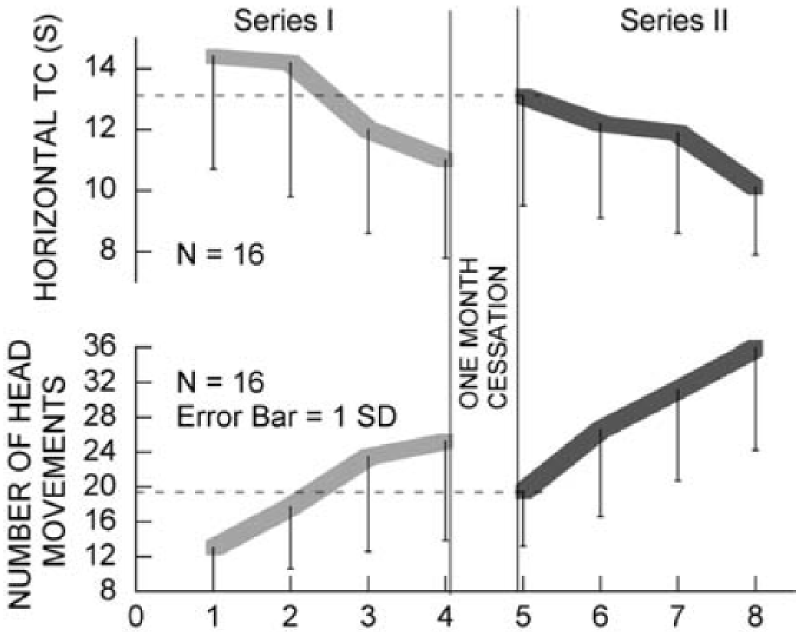

***Figure 5-6: The relation between velocity storage time constant and habituation**, Dai et al. [2003], expressed as number of head movements before reaching a certain level of motion sickness. The tests within a series were performed in four consecutive days with one month cessation between the two series. TC(s) = time constant [s], SD = standard deviation.*

Part 2: Analysis

6 Services suitable for tilting trains

6.1 *General*

This section shows running time simulation performed on representative Swedish tracks. Running times are dependent on many factors. Cant deficiency, top speed and tractive performance are key factors which are like a chair with their legs, where a change on one leg must go together with changes on the other legs to make a good chair, Figure 6-1.

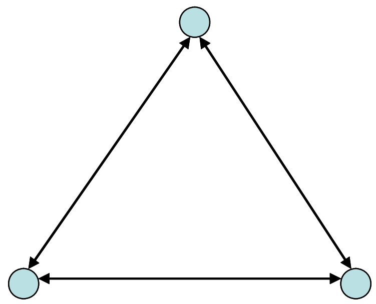

Figure 6-1: Cant deficiency, top speed and tractive performance.

Simulations of running times given in this chapter are performed at 3% lower speeds than allowed from the equilibrium cant and maximum speed points of view. This is made in order to achieve a running time margin due to non-optimum performance of the train driver. Further running time margins and dwelling times must be added to receive running times suitable for time tables.

Assumptions for the calculations are:

- Enhanced speed is allowed at the same track sections as today,
- The maximum speed is set depending on the equilibrium cant, i.e. the track cant and length of transitions of today may be changed where needed,
- Maximum permissible cant excess for freight trains is 110 mm at 90 km/h,
- Maximum permissible cant deficiency is 300 mm up to 225 km/h, and above that reduced with 1 mm per 1 km/h due to cross-wind effects.

6.2 *The track*

The Stockholm – Gothenburg relation is suitable as an example, as this is one of the most important services in Sweden. The track may be characterized by the curve distribution which may be given as percentage of the total length of the track. The curve radius indicated is the mean radius in that group, e.g. the curves in group 1000 m range from 900 to 1100 m.

The Stockholm – Gothenburg line has a variety of curves ranging from 352 m radius and up. The curve distribution for the line is shown in Figure 6-2. The length of the circular curves (transition curves are excluded) with radii less than 6000 m constitutes in total 19 % of the line. The total length of this line is 457 km.

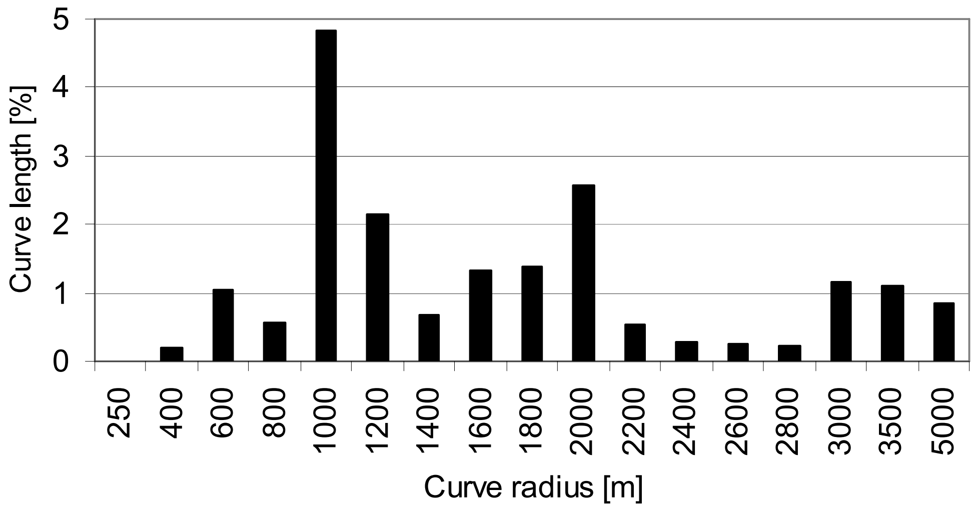

Figure 6-2: Distribution of circular curves** (curve transitions excluded) **with radii less than 6000 m as function of the total length of the line Stockholm – Gothenburg.

6.3 *The train*

The basis for the running times is a future train with key performance factors as shown in Table 6-1. The tilting and the conventional train only differ on the permissible cant deficiency.

Table 6-1: Key performance factors, future train.

Performance factor	Value
Number of vehicles	6
Cant deficiency [1)]	150 - 300 mm
Weight with seated passengers	360 ton
Top speed in service [1)]	180 – 280 km/h
Short-term power [1)]	2.7 – 9.0 MW
Starting acceleration [1)]	0.6 – 1.0 m/s^2
Braking deceleration	0.6 m/s^2
Running resistance	$R = 2400 + 60 \cdot v + 6.5 \cdot v^2$ [N] where v is the speed [m/s]

1) This factor is part of the optimisation

6.4 *Running time influence of cant deficiency*

The relation between cant deficiency, top speed and tractive performance is strong as mentioned above, but still it is possible to study them one at a time. The first parameter to be studied is the cant deficiency, or rather the equilibrium cant which is the sum of the track cant and cant deficiency. Service with future tilting trains is studied in relation to service with non-tilting trains. Four different combinations of track cant and cant deficiencies can be distinguished based on the situation today in Sweden and what could likely be achieved in the near future, say until 2012 - 2014, Table 6-2.

Table 6-2: Possible equilibrium cant.

Vehicle & Track	Track cant [mm]	Cant deficiency [mm]	Equilibrium cant [mm]
Non-tilt, today	150	150	300
Non-tilt, 2012 - 2014	160	165	325
Tilt, today	150	245	395
Tilt, 2012 - 2014	160	300	460

The result of the running time simulations on Stockholm – Gothenburg can be seen in Figure 6-3 where the running times are given as function of equilibrium cant. The stopping pattern includes 8 intermediate stops, but this has a quite limited impact on the difference between the different combinations. The four graphs represent four trains with low and high top speed and low and high tractive power. The running times improves with increased equilibrium cant independently of maximum speed and tractive power.

One interesting conclusion is that a non-tilting vehicle, with maximum equilibrium cant of 300 mm, will have longer running times than a tilting train with today's maximum speed and tractive power. This statement is independent of top speed and tractive power of the non-tilting vehicle.

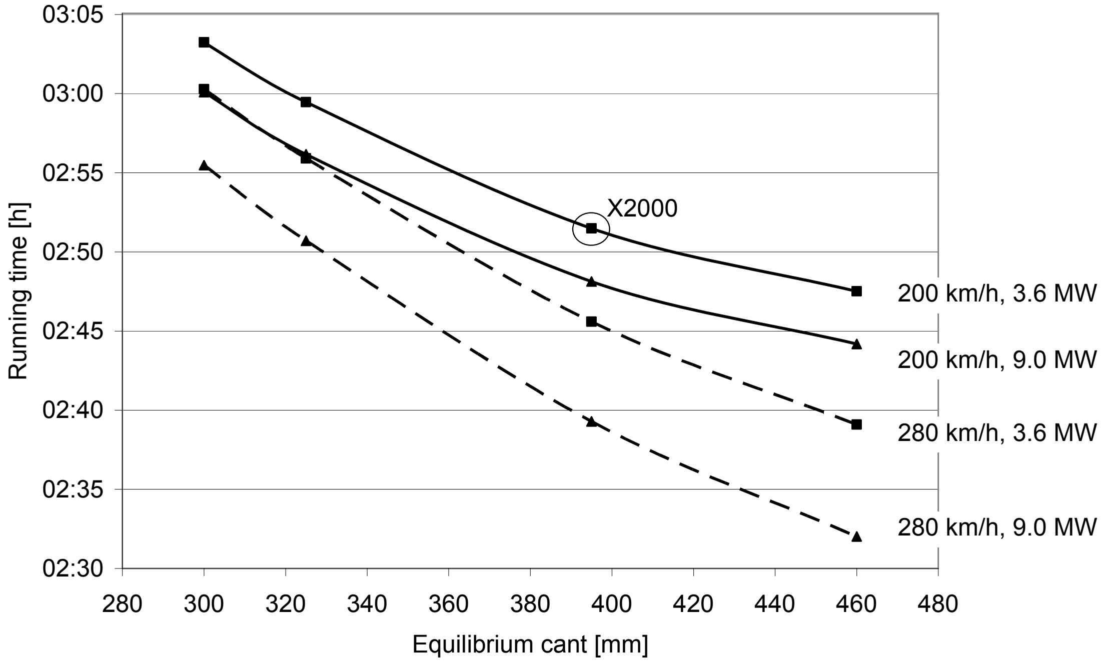

***Figure 6-3: Simulated running times Stockholm – Gothenburg as function of equilibrium cant** (=track cant + cant deficiency) with 8 intermediate stops.*

6.5 *Running time influence of top speed*

In the previous section it became clear that high equilibrium cant is beneficial for the running time. If an equilibrium cant of 460 mm is selected, the relation between top speed and running time can be studied. The studied top speeds range from 200 km/h to 280 km/h.

The result is displayed in Figure 6-4. A top speed of 240 - 250 km/h seems to be close to an optimum. Higher top speed can not significantly improve the running time even if high tractive power is selected. The stopping pattern includes 8 intermediate stops.

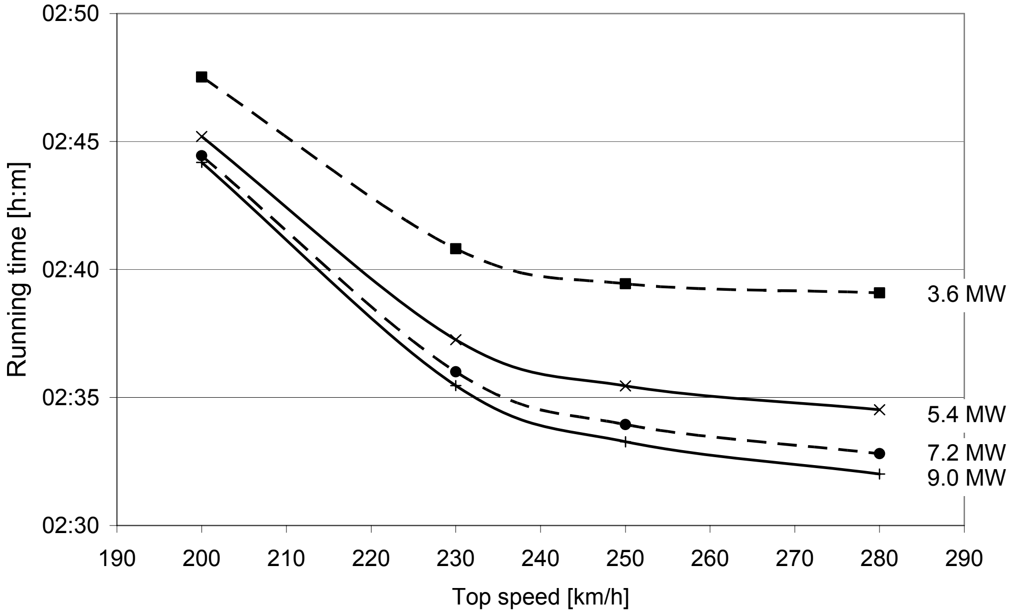

Figure 6-4: Simulated running times Stockholm – Gothenburg as function of top speed, *at 460 mm equilibrium cant with 8 intermediate stops.*

6.6 *Running time influence of tractive power*

In the previous section it became clear that increased maximum speed is, up to a certain level, beneficial for the running time. This level is about 250 km/h at the Stockholm – Gothenburg line. If an equilibrium cant of 460 mm, according to CEN [2006] is selected, the relation between tractive power and running time can be studied. The studied tractive power ranges from 2.7 MW to 9.0 MW. The basis for the running times is here a future tilting train with key performance factors as shown in Table 6-1.

The result is displayed in Figure 6-5. Tractive power of 4 – 6 MW seems to be close to an optimum, which is to some degree depending on the number of stops, more stops requires more power. It should be noted that the optimum of tractive power is from the running time point of view only and that other parameters, like regeneration braking, may influence the choice of tractive power.

The effect of increased starting acceleration is shown for the case with 4 stops, a starting acceleration of 1.0 m/s^2 is compared with the otherwise used 0.6 m/s^2. Increased starting acceleration is mainly effective at start, the benefit is therefore larger the more stops and starts there are.

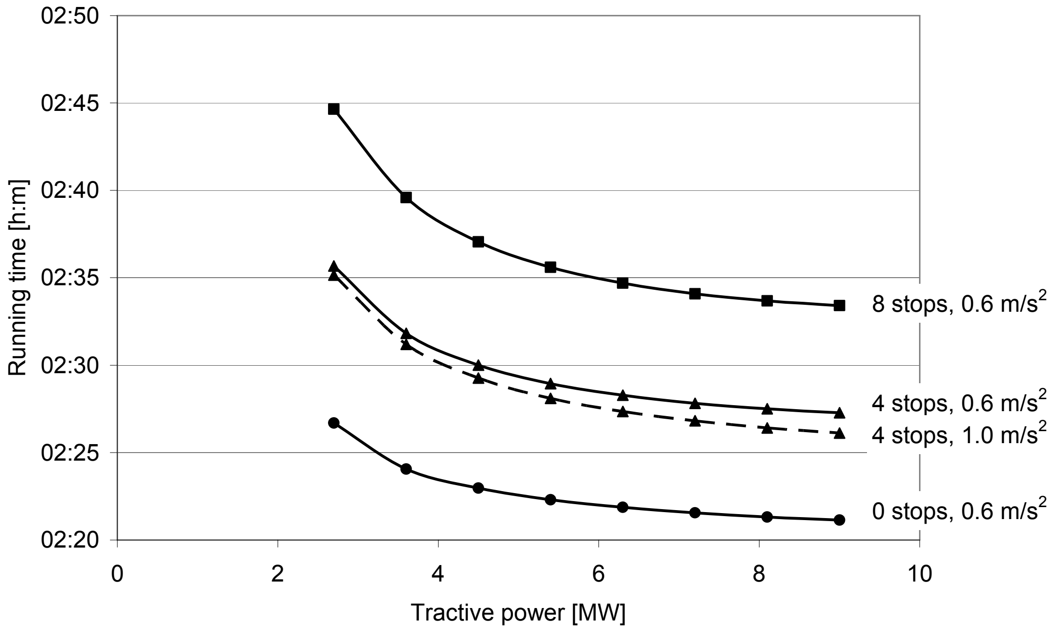

Figure 6-5: Simulated running times Stockholm – Gothenburg as function of tractive power, *at 460 mm equilibrium cant and 250 km/h top speed.*

6.7 *Summary*

The relation between cant deficiency, top speed and tractive performance is important to get the best performance out of a tilting train. The running times improves with increased cant deficiency, top speed and tractive performance; however the benefit of increased top speed and tractive performance is small above a certain level.

15 minutes running time (9%) may be gained on the Stockholm – Gothenburg line, if cant deficiency, top speed and tractive performance are improved compared with existing tilting trains. One interesting conclusion is that a non-tilting very high-speed train will, independent of top speed and tractive power, have longer running times than a tilting train with today's maximum speed and tractive power on the studied line.

7 Motion sickness on-track test setup

One of the aims in the EU funded research project FACT was to develop a model for predicting motion sickness on tilting trains. FACT performed field tests in three regions of which one was the Nordic field test, carried out 2004 in Sweden and Norway. The test was reported by Förstberg et al. [2005]. However, much of the data was never evaluated. Further evaluation and model analysis is reported in Chapter 8 and 9. This chapter gives for convenience a description of the test train, the test lines, the test conditions, the measured parameters and the test subjects.

7.1 *Test train*

A four car long-distance tilting train, class BM73, from Norwegian State Railways (NSB) was used as test train, Figure 7-1. This electrical multiple unit has a first class car (BM), a second class car with bistro in the middle (BFR), a second class saloon car (BMU) and a second class family car (BFM). Maximum speed is 210 km/h and the permissible cant deficiency is 280 mm. The cars were numbered 1 to 4 starting from the BM car. Cars 1 to 3 were used for test subjects.

Figure 7-1: The Norwegian tilting train, class BM73, used in the Nordic field test by FACT, *[Förstberg et al. 2005].*

7.2 *Test lines*

Three test lines were chosen with different characteristics, two in Norway and one in Sweden, Table 7-1. A schematic drawing of test track locations is shown in Annex A. The original purpose with three track sections was to reduce the correlation between motion variables. The track section between Kristiansand and Vegårdshei contains numerous curves with approximately 300 m radii; the track section between Linköping and Järna contains numerous curves with 1000 to 1200 m radii and the track section between Hamar and Vinstra contains a mixture of curves. Also the length of the curve transitions differs between the test lines. Typically the curve transitions take two seconds to pass on the Norwegian lines and three seconds on the Swedish.

Table 7-1: Description of test lines used by FACT in the Nordic field test, *[Förstberg et al, 2005].*

Test Line	Length [km]	Typical travel time (one way) [min]	Typical speed [km/h]
Kristiansand – Vegarshei (on South-West Main Line Stavanger – Oslo)	104	60 – 65	80 – 120
Hamar – Vinstra (on Dovre Main Line Oslo – Trondheim)	140	100 – 110	70 – 130
Linköping – Järna (on South Main Line Stockholm – Malmö)	180	70 – 80	180 – 200

7.3 *Test conditions*

Three speed levels were used, giving a maximum cant deficiency of 280, 215 or 150 mm, respectively. A cant deficiency of 280 mm corresponds to the maximum speed level used in tilting services, cant deficiency of 150 mm corresponds to the maximum speed level used in non-tilting services and a cant deficiency of 215 mm is an intermediate condition.

For each speed level, two different tilt compensations could be utilised at the same time, one in each half of the train, one giving a maximum effective tilt angle of 6.2 deg and the other giving a maximum lateral carbody acceleration of 1.0 m/s^2 for all three track plane acceleration levels. The six test conditions are shown in Table 7-2.

Table 7-2: Test conditions used by FACT in the Nordic field test, *[Förstberg et al, 2005].*

Cant deficiency [mm]	Tilt compensation [%]	Carbody acceleration [m/s^2]
280	57	0.8
280	44	1.0
215	79	0.3
215	28	1.0
150	100	0.0
150	0	1.0

The tests were carried out in June 2004 according to Table 7-3. Most tests started about 9:00 in the morning, the exceptions were test 1 which started about noon and tests 6, 8 and 10 which started about 13:00. All tests were run as return trips. 15 minutes stop was planned at the turning station, where the subjects were free to leave the train and stretch their legs. No other stops were planned, but tests 1, 2 and 11 got one or more unplanned stops in respect to other train services.

Table 7-3: ***Test plan used by FACT in the Nordic field test,*** *[Förstberg et al, 2005].*

Test run	Track location	Cant deficiency [mm]	Tilt compensation[1)] [%] Car 1 & 2	Tilt compensation[1)] [%] Car 3 & 4	Carbody acc. [m/s²] Car 1 & 2	Carbody acc. [m/s²] Car 3 & 4
1	Hamar - Vinstra	280	57	44	0.8	1.0
2	Linköping – Järna	215	79	28	0.3	1.0
3	Linköping – Järna	280	44	57	1.0	0.8
4	Linköping – Järna	150	100	0[2)]	0	1.0
5	Kristiansand – Vegårshei	280	57	44	0.8	1.0
6	Kristiansand – Vegårshei	215	79	28	0.3	1.0
7	Kristiansand – Vegårshei	150	100	0[2)]	0	1.0
8	Kristiansand – Vegårshei	280	44	57	1.0	0.8
9	Kristiansand – Vegårshei	215	28	79	1.0	0.3
10	Kristiansand – Vegårshei	150	0[2)]	100	1.0	0
11	Hamar - Vinstra	280	44	57	1.0	0

1) Part of cant deficiency compensated by the carbody tilt
2) The carbody tilt is compensating the suspension sway

7.4 *Measured parameters and signal processing*

Motion environment was monitored through a comprehensive set of transducers in all three cars used for test subjects (cars 1, 2 and 3). The complete measurement setup is shown in Table 7-4.

Table 7-4: ***Measurement setup,*** *[Förstberg et al, 2005].*

	Car 1				Car 2				Car 3				Car 4			
	b1	m	b2	tc	b1	m	b2	tc	b1	m	b2	tc	b1	m	b2	tc
Lateral acceleration	x	x	x		x		x		x	x	x			x		
Vertical acceleration		x	x		x		x		x	x	x			x		
Longitudinal acceleration		x				x				x				x		
Roll velocity (a)		x				x				x				x		
Yaw velocity (a)						x				x						
Tilt angle								x				x				
Train speed								x				x				
Track plane acceleration													x			
Number of signals:				7				9				11				5

Key: (a) = rate gyro, b1 = above bogie 1, m = carbody middle, b2 = above bogie 2, tc = tilt computer.

The signals were recorded by two 16-channel “Comet” measuring systems. The recording was digital with 400 Hz sample frequency and the anti-aliasing low-pass filters were set at 100 Hz limit frequency.

Signal processing:

1. The signals were re-sampled with 40 Hz sample frequency and with the anti-aliasing low-pass filters set at 10 Hz limit frequency.
2. Yaw acceleration was calculated from lateral acceleration above the bogies. Pitch acceleration was calculated from vertical acceleration above the bogies. An extended set of signals were calculated as products of other signals, see Section 9.4. The full list of signals is given in Annex C.
3. The signals were filtered, details in Annex C.
4. The Net Dose values were created and all data for one test run was gathered in one file.
5. Net Dose values were picked corresponding to the time when the subjects reported motion sickness.

7.5 *Test subjects*

The test subjects were mostly recruited from nearby universities and schools in Linköping, Kristiansand and Hamar. Also athletic and Christian societies were used for recruitment in Norway. The Swedish group was the most homogenous in age. Subjects applied via a web-site at VTI by stating gender, age, sensitivity to motion sickness, etc. In the train, the participants were informed about the test ride and signed a consent form. There was a small remuneration for participation.

The number of subjects were planned to be about 60 in each test. Some subjects participated more than once due to difficulties to recruit this large number of subjects, particularly in Kristiansand. No records were kept of how many, but the number was less than ten for each tests. Effect of participating more than once was not possible to study due to lacking records.

Subjects were divided into four groups, Figure 7-2. The groups were matched to have equal proportions female and equal self-estimated sensitivity of motion sickness. The subjects were advised a seat to ensure equal number of subjects in window seat and aisle seat. Sitting side by side was avoided to minimize influence from subject to subject.

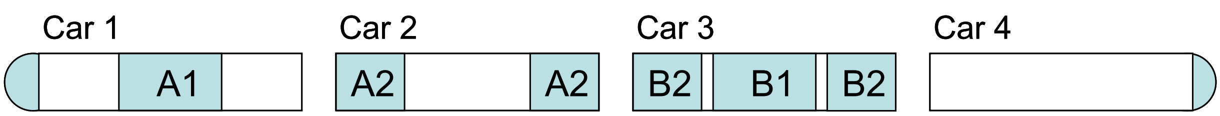

Figure 7-2: Localisation of the four test groups.

At the evaluation it was found that the motions, calculated as Net Dose values with 10 minutes time constant, were similar in cars with the same test conditions, see example in Figure 7-3. The difference within car 3, which carried two groups of test subjects, was even smaller.

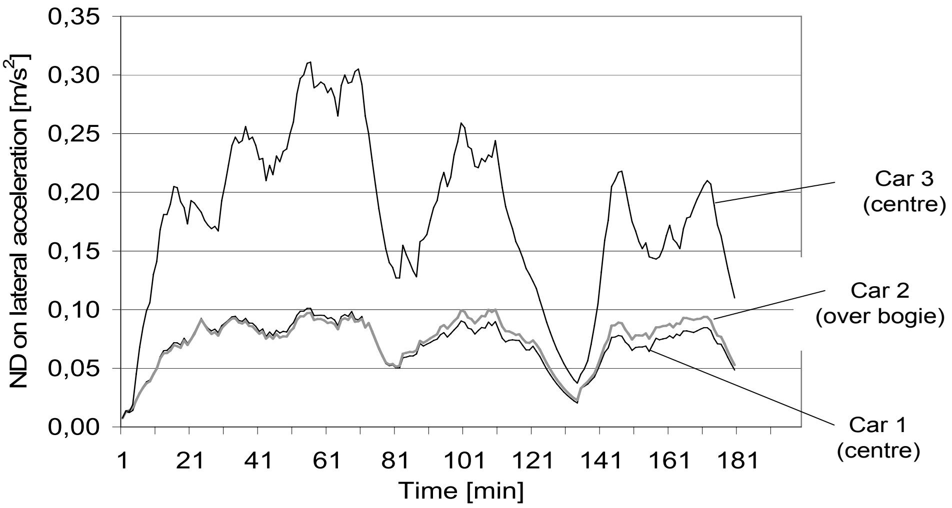

Figure 7-3: Net Dose-values on lateral acceleration as function of time in the three cars, *at run 2.*

It was decided to reduce the number of groups from four to two as the statistical benefit of larger groups was judged to be larger than the disadvantage of only one motion reference. The two evaluation groups with about 25 - 30 test subjects each became:

Group A: Consisting of all subjects in car 1 and 2, the Net Doses calculated as the average between the centre of car 1 and over bogie 1 in car 2.

Group B: Consisting of all subjects in car 3, the Net Doses taken from the centre of car 3.

The first check of data also showed that some subjects were not feeling well from start and that other had *taken medicine to prevent motion sickness*. These subjects (approximately 20%) where kept out of the evaluation. Data over test subjects used in the evaluation per test run are shown in Table 7-5. Data over test subjects used in the evaluation per test site are shown in Table 7-6.

Table 7-5: Test subjects used in the evaluation per test run.

Test run	Males		Females		Total
	Number	Age (mean)	Number	Age (mean)	Number
1	46	28	15	31	61
2	38	23	16	21	54
3	35	29	21	24	56
4	30	27	20	24	50
5	26	35	19	38	45
6	27	29	17	31	44
7	28	30	19	38	47
8	25	25	19	34	44
9	30	30	16	31	46
10	38	26	15	26	53
11	37	24	14	27	53

Table 7-6: Test subjects used in the evaluation per test site.

Test site	Males		Females		Total
	Number	Age (mean)	Number	Age (mean)	Number
Kristiansand	174	29	105	34	279
Hamar	83	26	29	29	112
Linköping	103	26	57	23	160
All	360	28	191	30	551

7.6 *Questionnaires*

The questionnaires consisted of three parts, where the first covered background information, travel frequency, motion sickness background and a subjective estimation on susceptibility to motion sickness.

The second part covered questions about ride comfort, nausea and motion sickness symptoms, which the participants answered every 5 min on the Kristiansand runs and every 10 min on the other runs. Both ride comfort and nausea were estimated on a seven-graded scale (0 – 6). For motion sickness symptoms, two different question schemes were used, one in Sweden and the other in Norway, see Annex B.

The third part covered general questions about the comfort (suggestions to improve comfort), comparison to a normal ride, discomfort due to tilt motions etc.

8 Motion sickness on-track test evaluation

FACT collected a large amount of data at the field tests, but only a limited set of data was used in the evaluation made and reported by FACT. This chapter and Chapter 9 complement earlier evaluation reported by Förstberg et al. [2005]. The test setup is described in Chapter 7.

8.1 *Reports of motion sickness*

The tested conditions were found to be provocative for motion sickness. 44% of all test subjects have any time of the test run felt sign of motion sickness. The proportion differs between the test runs and between the two test groups in each test run, Table 8-1. The highest proportions are found for test run 3, a run at the highest cant deficiency, and in particular for group A where 70% of the test subjects have any time of the test run felt sign of motion sickness. The lowest proportions are found for group B in test run 4, a run at the lowest cant deficiency, where 19% of the test subjects have any time of the test run felt sign of motion sickness.

Table 8-1: Reported Motion Sickness per test run.

	Group A			Group B		
Test run	Any time, any sign [%]	Average, any sign [%]	Average, ≥ 3 [%]	Any time, any sign [%]	Average, any sign [%]	Average, ≥ 3 [%]
1	57	12	2	29	8	1
2	55	19	2	48	18	1
3	**70**	37	9	48	24	7
4	46	16	2	**19**	8	1
5	41	7	0	39	19	8
6	48	15	2	52	10	0
7	26	10	3	32	8	0
8	63	18	4	40	16	1
9	43	10	1	40	15	1
10	50	10	0	31	7	0
11	29	6	1	43	13	3

Any time, any sign = Proportion of test subjects reporting any sign of motion sickness at any time of the test run
Average, any sign = Proportion (average over all voting occasions) of test subjects reporting any sign of motion sickness
Average ≥ 3 = Proportion (average over all voting occasions) of test subjects reporting 3 or higher on the seven-graded scale (0-6)

The reported motion sickness per test site is shown in Table 8-2. More motion sickness was reported at the Linköping site then fore the two other sites. It should be noted that only tests with a cant deficiency of 280 mm were made at the Hamar site.

Table 8-2: Reported Motion Sickness per test site.

Test site	Any time, any sign [%]	Average, any sign [%]	Average, ≥3 [%]
Kristansand	42	12	2
Hamar	40	10	2
Linköping	48	20	4

Any time, any sign = Proportion of test subjects reporting any sign of motion sickness at any time of the test run
Average, any sign = Proportion (average over all voting occasions) of test subjects reporting any sign of motion sickness
Average ≥ 3 = Proportion (average over all voting occasions) of test subjects reporting 3 or higher on the seven-graded scale (0-6)

The reported motion sickness per test condition is shown in Table 8-3. Significantly less motion sickness was reported at cant deficiency of 150 mm compared to the others. The reported motion sickness for each voting occasion is shown in Annex D, Figure D-1 to D-3.

Table 8-3: Reported Motion Sickness per test condition.

Cant deficiency [mm]	Tilt compensation [%]	Any time, any sign [%]	Average, any sign [%]	Average, ≥ 3 [%]
280	57	47	14	2
280	44	46	17	5
215	79	45	16	2
215	28	51	12	1
150	100	35	10	1
150	0	32	9	0

Any time, any sign = Proportion of test subjects reporting any sign of motion sickness at any time of the test run
Average, any sign = Proportion (average over all voting occasions) of test subjects reporting any sign of motion sickness
Average ≥ 3 = Proportion (average over all voting occasions) of test subjects reporting 3 or higher on the seven-graded scale (0-6)

The reported motion sickness per age group is shown in Table 8-4. The reported motion sickness is surprisingly similar between the age groups. A gender analysis is shown in Section 9.4.

Table 8-4: Reported Motion Sickness per age group.

Age	Any time, any sign [%]	Average, any sign [%]	Average, ≥ 3 [%]
16 – 18	47	13	2
19 – 24	44	13	2
25 – 40	50	13	2
41 – 78	21	13	2

Any time, any sign = Proportion of test subjects reporting any sign of motion sickness at any time of the test run
Average, any sign = Proportion (average over all voting occasions) of test subjects reporting any sign of motion sickness
Average ≥ 3 = Proportion (average over all voting occasions) of test subjects reporting 3 or higher on the seven-graded scale (0-6)

8.2 *Measured motion quantities*

Table 8-5 shows the average motion magnitudes measured in car 1 (tilting) at test run 5 (280 mm of cant deficiency) and in car 3 (non-tilting) at test run 7 (150 mm of cant deficiency). The largest differences are shown found for vertical and roll accelerations where the tilting case shows increased magnitudes. The tilting case has reduced magnitudes of lateral acceleration at frequencies below 0.1 Hz. Figure 8-1 to 8-3 shows Power Spectral Density (PSD) –diagrams of the motion quantities with the largest differences between tilting and non-tilting. PSD-diagrams for all six directions are shown in Persson [2008].

Table 8-5: Measured carbody accelerations on the track between Kristiansand and Vegårdshei.

Direction (rel. carbody)	Frequency weighted[1)] r.m.s accelerations		Dominant frequency [Hz]
	Tilting (280 mm of cant deficiency)	Non-tilting (150 mm of cant deficiency)	
Longitudinal	0.04 m/s^2	0.03 m/s^2	< 0.1
Lateral	0.35 m/s^2	0.45 m/s^2	< 0.1
Vertical	0.07 m/s^2	0.04 m/s^2	< 0.1
Roll	0.93 deg/s^2	0.40 deg/s^2	≈ 0.1
Pitch	0.09 deg/s^2	0.06 deg/s^2	None
Yaw	0.59 deg/s^2	0.42 deg/s^2	≈ 0.1

1) Frequency weighing W_f is applied on all motions except lateral where W_g is used. See Sections 4.4.2 and 4.4.3 for description of the frequency weighting.

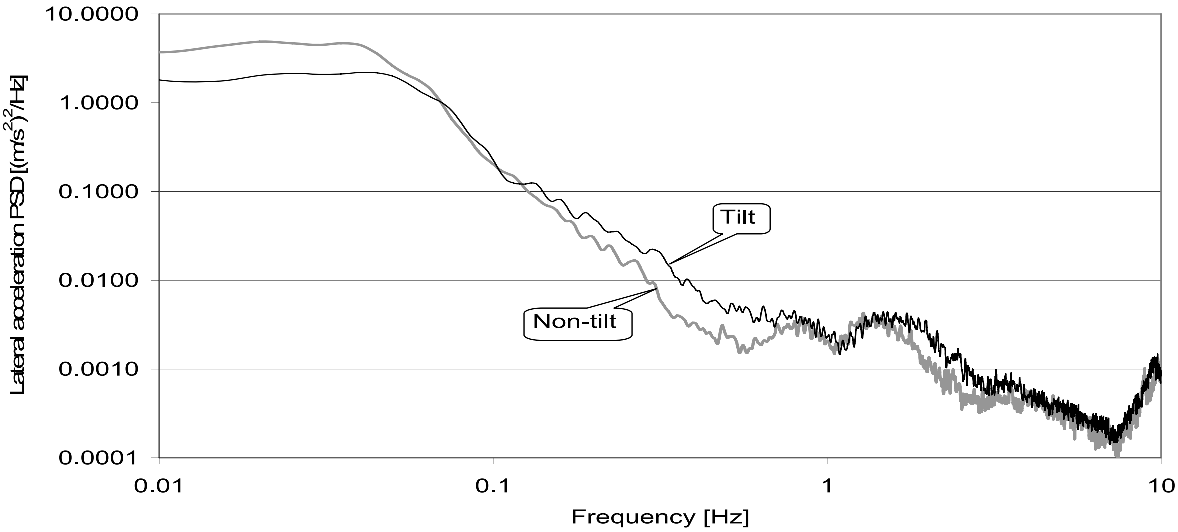

Figure 8-1: Carbody lateral acceleration in tilting and non-tilting test case.

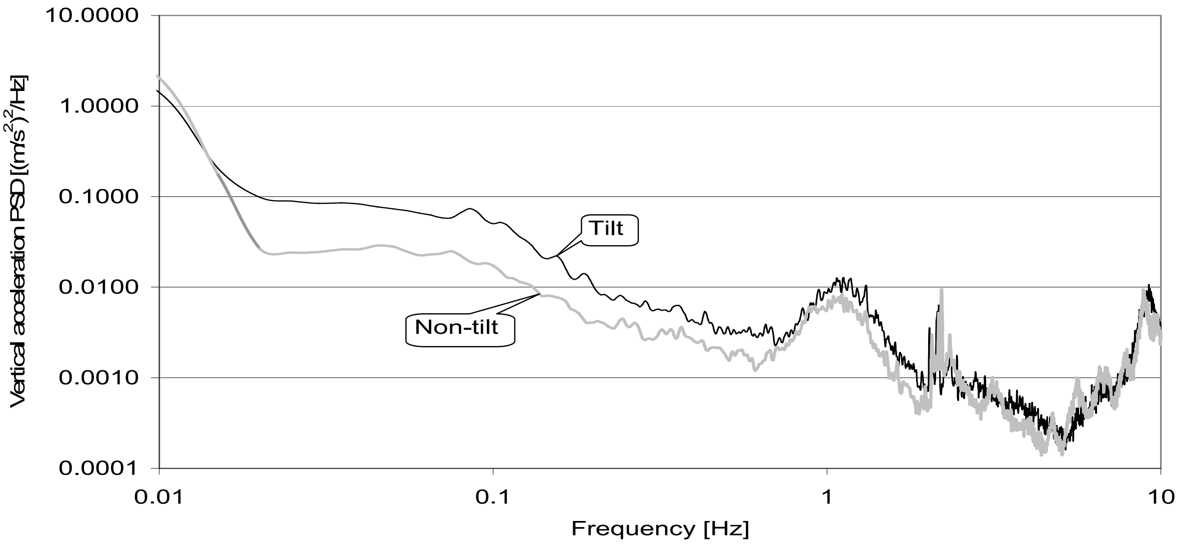

Figure 8-2: Carbody vertical acceleration in tilting and non-tilting test case.

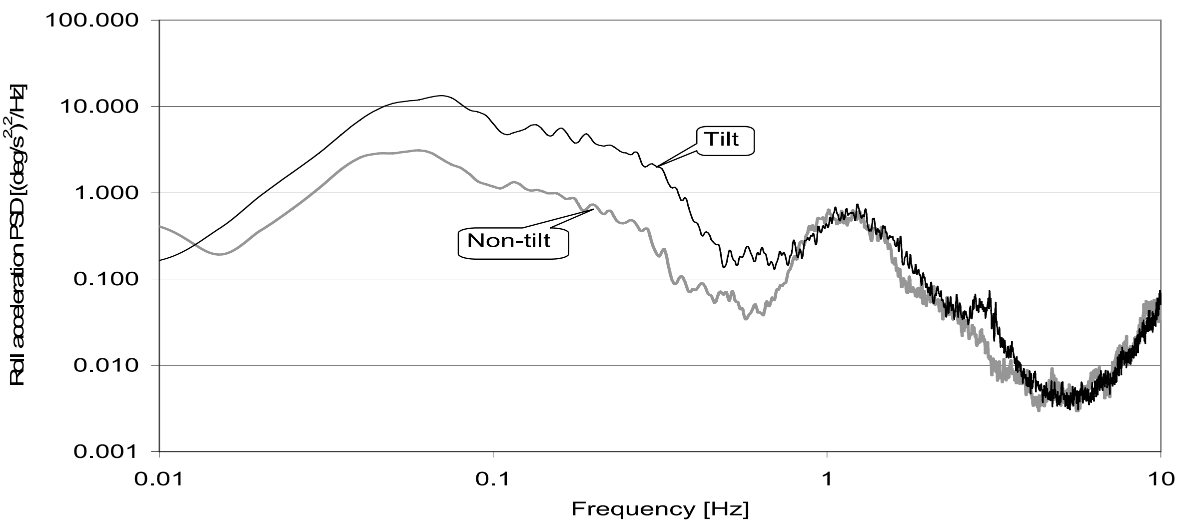

Figure 8-3: Carbody roll acceleration in tilting and non-tilting test case.

8.3 *Motion quantities – experienced motion sickness*

One interesting issue is whether motion quantities specifically measured in tilting trains have caused motion sickness in laboratories. The comparison here is made to laboratory tests where the test subjects were seated in a similar way as in trains. The measured motion quantities are taken from car 1 (tilting) at test run 5 (280 mm of cant deficiency).

The result of this comparison is shown in Table 8-6. All the laboratory tests causing motion sickness have been performed at amplitudes higher than measured in the test train, which is believed to representative for tilting trains. In particular this is the case for rotations. The lateral accelerations used in laboratory by Donohew & Griffin [2004b] and vertical accelerations used in laboratory by O'Hanlon & McCauley [1973] were only 60 – 70% higher than measured in tilting trains on the track section between Kristiansand and Vegårdshei. However, the non-tilting train, which causes less motion sickness, has even higher lateral acceleration (frequency below 0.1 Hz) than in the tilting train.

Table 8-6: Comparison between laboratory and tilting train tests.

Motion quantity	Laboratory				Tilting train (car 1, test run 5)
	Ref 1)	Frequency [Hz]	Amplitude (r.m.s.) [m/s², deg/s]	Sickness	Amplitude (r.m.s.) [m/s², deg/s]
Lateral acceleration	D	0.125	0.56	30% nausea (½h exposure)	0.35 2)
	F	0.167	0.78	37% nausea (½h exposure)	
Vertical acceleration	M	0.10	0.12	25% vomiting (2h exposure)	0.07 3)
	W 4)	0.10	0.12	No sickness (2h exposure)	
Roll velocity	W	0.07	10	26% nausea (2h exposure)	1.0 3)
	F	0.167	4	17% nausea 5) (½h exposure)	
Yaw velocity	G	0.02	110	8% vomiting (5m exposure)	0.7 3)

1) D) Donohew & Griffin [2004b]
F) Förstberg [2000a]
G) Guedry et al. [1982]
M) O'Hanlon & McCauley [1973]
W) Wertheim et al. [1995]

2) Weighting curve W_g applied [Donohew & Griffin, 2004b]

3) Weighting curve W_f applied [ISO, 1997]

4) Wertheim et al. repeated the O'Hanlon & McCauley test, but without head support

5) Laboratory tests always cause some nausea independently of motion, Förstberg did not consider this case to cause motion sickness

9 Analysis of motion sickness models

The analysis of motion sickness models made in this chapter is based on data collected by FACT at the field tests and complements analysis reported by Förstberg et al. [2005]. Models proposed by other scientists are taken are hypothesis to be tested. The test setup is described in Chapter 7.

9.1 *Measures of motion sickness*

The reported motion sickness may be measured in different ways:

1) Average Motion Sickness Score (MSS), the average of scores given on the motion sickness scale (0 – 6), see Annex B
2) Motion Sickness Proportion (MSP), the proportion of test subjects not feeling well, taken as answers different from 0 on the motion sickness scale,
3) Motion Sickness Incidence (MSI), the proportion of test subjects who have felt incidence of motion sickness any time from start, taken as answers different from 0 on the motion sickness scale.

The difference between the three measures is shown in Figure 9-1. MSS and MSP give a picture of the actual degree of motion sickness, when MSI is an ever increasing number. MSI and MSP follow each other from start, but at 40 minutes one test subject recovers from motion sickness.

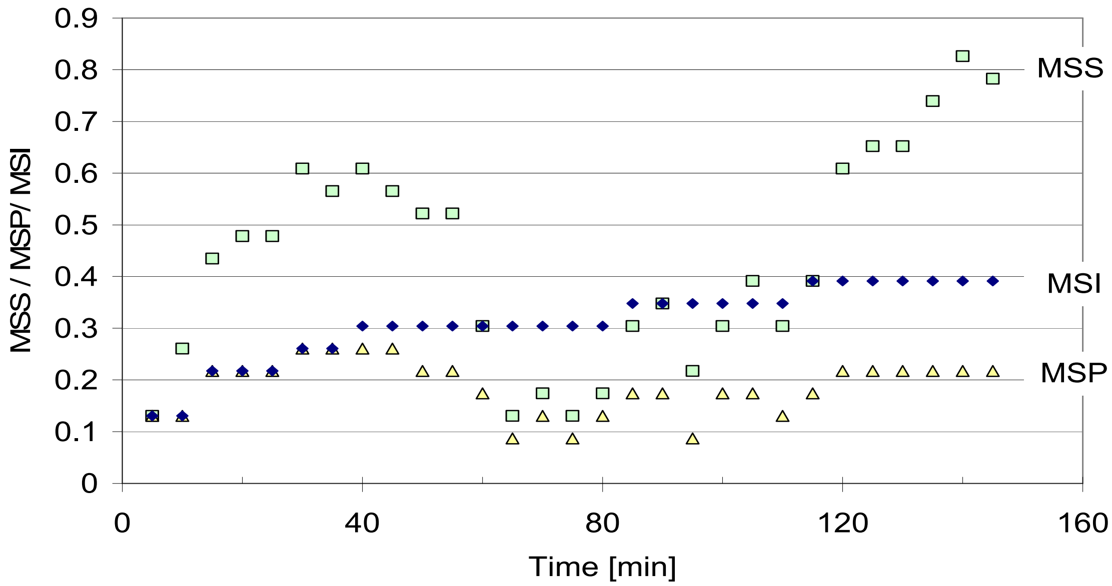

Figure 9-1: Experienced motion sickness as function of time.
Example: Group B at test run 5.

Estimation of motion sickness may also account for the time dependence. Three possible time dependencies were given in Section 5.4, their typical behaviour are shown in Figure 9-2, here based on vertical acceleration as stimuli.

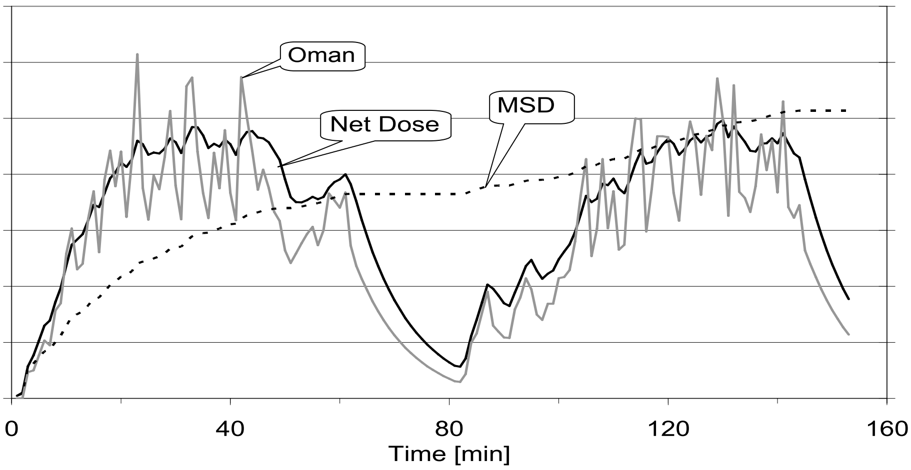

Figure 9-2: Typical behaviour of the Oman, Net Dose and MSDV time dependences. *Example: Vertical acceleration for group B at test run 5.*

The Oman and the Net Dose time dependences correlate with MSS and MSP as these give a picture of the actual degree of motion sickness, Figure 9-3. Generally the MSS gives slightly higher correlation (R^2) to the motion sickness models than the MSP. This statement is independent of gender, see Table 9-1.

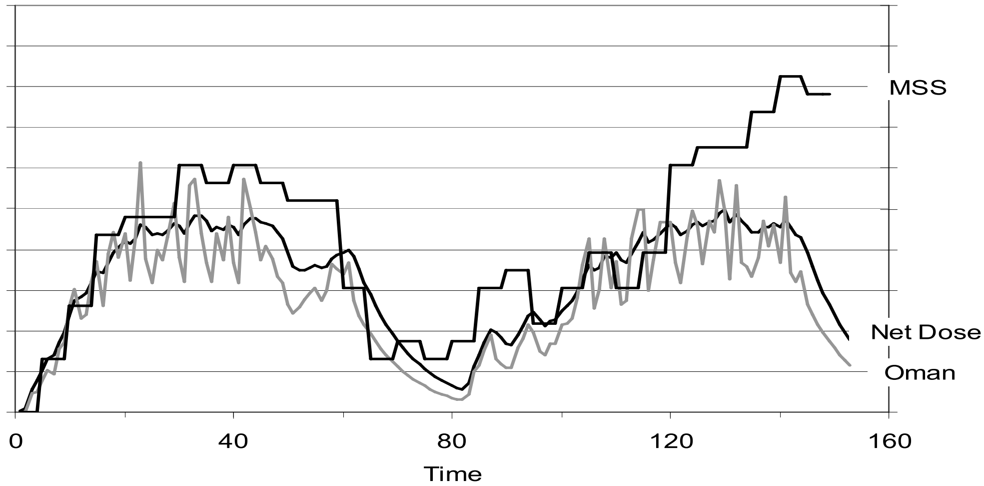

Figure 9-3: Typical behaviour of the Oman and Net Dose time dependences and the reported MSS. *Example: Vertical acceleration for test group B at test run 5.*

Table 9-1: Correlation (R^2) between MSS / MSP and the Net Dose time dependence. *Here calculated on vertical acceleration for all test runs.*

Gender	MSS	MSP
Males	0.219	0.206
Females	0.228	0.153
Males and females	0.373	0.345

MSDV correlate with MSI as these give a percentage of test subjects that have felt motion sickness, their typical behaviour are shown in Figure 9-4.

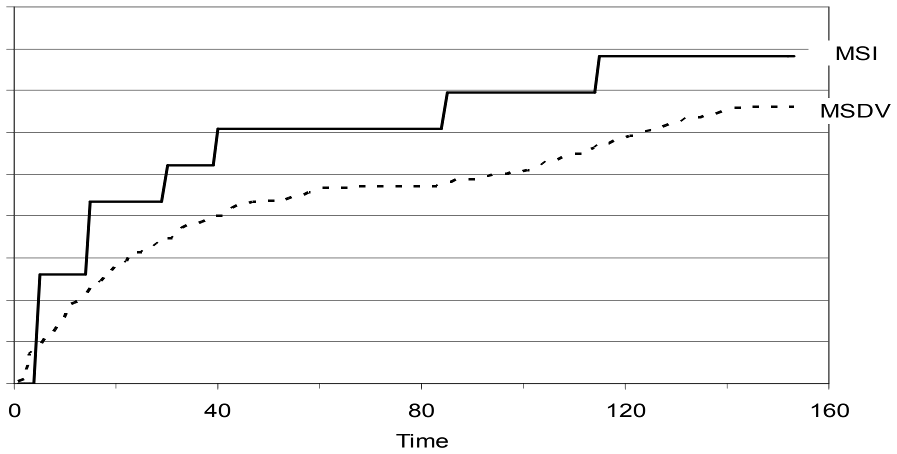

Figure 9-4: Typical behaviour of the MSDV time dependences and the reported MSI.
Example: MSDV calculated on vertical acceleration for test group B at test run 5.

The evaluation in the present study is based on the Net Dose time dependence and the MSS. This choice is motivated by:

- The Net Dose and Oman time dependences give better possibilities for locating problematic track sections than the MSDV time dependence, this excludes use of MSI.
- The Net Dose time dependence is less time consuming at the evaluation than the Oman time dependence as any combination of motions in the stimuli models can be handled after the calculation of the Net Dose values. The calculation of the time dependence must in case of the Oman be performed for every combination of motions.
- MSS gives higher correlation to the motion sickness models than MSP.

9.2 *Correlation between motion variables*

Correlation between motion variables is a known problem at evaluation of motion sickness tests made on-track. Correlation excludes the possibility to, based on measurements in trains, judge which motion quantity is the main cause of motion sickness. Knowing the main cause is the key to reduce motion sickness as there are different means to reduce different motion quantities. Table 9-2 shows the correlation between motion variables after frequency weighting and ND-calculation. The correlation between vertical acceleration and the three rotations is particularly high. Using motion variables with high mutual correlation in a model may lead to models with lacking robustness as one variable can be replaced with another with similar result. Motion variables with high mutual correlation should be avoided in models.

Table 9-2: Correlation between motion quantities (ND-doses) for all Nordic field tests.

Direction (rel. carbody)	Longitudinal $\ddot{x}$	Lateral $\ddot{y}$	Vertical $\ddot{z}$	Roll $\ddot{\varphi}$	Pitch $\ddot{\chi}$	Yaw $\ddot{\psi}$
Longitudinal	1					
Lateral	0.430	1				
Vertical	0.499	0.525	1			
Roll	0.518	**0.338**	0.875	1		
Pitch	0.614	0.544	0.888	0.911	1	
Yaw	0.604	0.626	0.759	0.889	0.893	1

Motion variables created as products of other motion variables, like vertical acceleration times roll acceleration, has generally a high correlation to the base variables, here vertical acceleration and roll acceleration. The exception is when the two base variables have low mutual correlation; the product may then have low correlation to the base variables. One example of the exception is lateral acceleration times roll acceleration, where the base variables have low mutual correlation (0.338), resulting in a product with medium correlation to the base variables.

The generally high correlation between the product and its base variables may lead to the conclusion that the products are useless, but this is false as the product can have significant higher correlation to motion sickness than any of the base variables.

9.3 *Motion sickness models*

Scientists have tried to find models that can describe motion sickness based on one or more motion quantities. The models of motion sickness are derived either by tests in laboratories or by tests on train. In mathematical statistical evaluations these models may be used as hypotheses to be tested. Models can also be derived from the data directly, but this method has less strength as the hypothesis to test comes from the data itself. However, most models have been identified from data one way or another. As a result, models can be set in two groups, Table 9-3; models derived from another set of data (No: 1 – 6) and models derived from the present evaluation data (FACT Nordic field tests) (No: 7 – 9). For the first group it is valid to talk about hypothesis to be tested.

Table 9-3: Motion sickness models.

Proposed by	No:	Model stimuli [1)]	Data source
Förstberg [2000a]	1	$k_{11} \cdot a_h + k_{12} \cdot \dot{\varphi}^2$ [2)]	Laboratory in Sweden
Bles et al. [1998]	2	$k_{21} \cdot a_h$ [3)]	Laboratory in the Netherlands
Suzuki et al. [2005]	3	$k_{31} \cdot \ddot{y} + k_{32} \cdot \dot{\varphi}$	On-track test in Japan
Donohew & Griffin [2005a]	4	$k_{41} \cdot \ddot{z}$	FACT field test in France
	5	$k_{51} \cdot \dot{\varphi}$	
	6	$k_{61} \cdot \ddot{y} \cdot \dot{\varphi} - k_{62} \cdot \ddot{y} - k_{63} \cdot \dot{\varphi}$	
Förstberg et al. [2005]	7	$k_{71} \cdot \ddot{z} - k_{72} \cdot \dot{\varphi}$	FACT field test in Sweden / Norway
	8	$k_{81} \cdot \ddot{y}^2 + k_{82} \cdot \dot{\varphi}^2$	
The present study	9	$k_{91} \cdot \ddot{z}^2$	

Where: a_h = Horizontal acceleration, $\ddot{y}$ = Lateral acceleration in carbody,
$\ddot{z}$ = Vertical acceleration in carbody, $\dot{\varphi}$ = Roll velocity of carbody, k_{ij} = positive constant

1) The given signs reflect the signs as given by the proposer.

2) Förstberg used roll acceleration instead of roll velocity, but this change has no significant impact as the correlation between roll velocity and roll acceleration is strong.

3) Interpreted by the author from Bles et al. [1998] "Situations which provoke motion sickness are characterized by a condition in which the sensed vertical as determined on the basis of integrated information from eyes, the vestibular system and the non-vestibular proprioceptors is at variance with the subjective vertical as expected from the previous experience".

9.4 *Motion sickness model analysis*

The method chosen for this analysis was to use linear regression between combinations of the collected motion data during the run and the passengers reported level of nausea. The methods of these analyses are based on earlier similar analyses, but here applied on an extended set of data, Annex C, including:

- The three transversal accelerations
- The three rotational velocities/accelerations
- The lateral and vertical accelerations in square
- The three rotational velocities/accelerations in square
- The three products between lateral acceleration and rotational velocities/accelerations
- The three products between vertical acceleration and rotational velocities/accelerations
- The three products between rotational velocities/accelerations
- The product between speed and yaw velocity (approximate horizontal acceleration)

A first check of data discovered differences in motion sickness between the three test sites. Test subjects in Linköping were more prone to motion sickness than test subjects in Kristiansand. This statement is based on the relation between experienced motion sickness and measured motions, and is independent of which motion is taken as reference. The test subjects in Hamar show sensitivities between those in Linköping and Kristiansand. Evaluating all tests as one group without any action leads to weak correlation between motion and motion sickness, and may also lead to models rather explaining the differences between test subjects than the relation to motion. The reason for the differences is discussed in Chapter 11. Three approaches could be taken:

1) Evaluate the sites separately
2) Allow a scaling factor on Motion Sickness between the test sites
3) Allow a constant term on Motion Sickness between the test sites

The first approach gives good correlation between motions and motion sickness, but results in three independent models which may have little in common. The second approach gives only a small improvement in correlation to motion sickness compared with disregarding the differences. The third approach gives almost as high correlation as the first without the drawback of three independent models, and was therefore applied.

A first check of data also discovered differences between the two genders, as expected. Female test subjects were more prone to motion sickness than male ones. This statement is independent of which motion is taken as reference. If a model for both genders are requested an average must be created, and this could be made in three different ways:

1) Take the average of the male average and the female averages.
2) Take the average over all test subjects.
3) Take the average over all test subjects after considering the average difference between the two genders.

The result of the average procedures differs due to different proportion of males and females in the tests. The first averaging procedure takes no notice of the number of male / females, and as the number of females was low the result is sensitive to how these females answered. The second average procedure gives a result for an undefined proportion of males and females as the ratio differs from test to test. The third average procedure is time consuming as the average difference must be calculated for each motion. The second average procedure is used in this evaluation as the proportion of males and females were similar in the tests.

The best hypothesis (the best model of the six first) is model 4, based on vertical acceleration, Table 9-4. The 9th model is the best model overall and adding further stimuli can not increase the correlation to MSS significantly. Correlation between a model and motion sickness is important, but it is not the only criteria for a good model. Model 7 is an example of a model where the internal correlation between the stimuli is high, resulting in an uncertain model.

Table 9-4: Models and their correlation to MSS.

Gender	Tests	Model		Correlation (R^2)
		No: 2)	Stimuli 1)	
m + f	All	1	$0.0014 \cdot a_h + 0.15 \cdot \dot{\varphi}^2$	0.219
m + f	All	2	$0.0054 \cdot a_h$	0.198
m + f	All	3	$0.17 \cdot \ddot{y} + 6.4 \cdot \dot{\varphi}$	0.225
m + f	All	4	$8.3 \cdot \ddot{z}$	0.311
m + f	All	5	$6.8 \cdot \dot{\varphi}$	0.217
m + f	All	6	$2.3 \cdot \ddot{y} \cdot \dot{\varphi} - 0.17 \cdot \ddot{y} + 3.2 \cdot \dot{\varphi}$	0.256
m + f	All	7	$11 \cdot \ddot{z} - 3.2 \cdot \dot{\varphi}$	0.320
m + f	All	8	$0.45 \cdot \ddot{y}^2 + 0.21 \cdot \dot{\varphi}^2$	0.253
m + f	All	9	$97 \cdot \ddot{z}^2$	0.373

Where: a_h = Horizontal acceleration, $\ddot{y}$ = Lateral acceleration in carbody,
$\ddot{z}$ = Vertical acceleration in carbody, $\dot{\varphi}$ = Roll velocity of carbody, k_{ij} = positive constant

1) Given signs reflect the calculated signs
2) The model numbers are the same as in Table 9-3.

9.5 *Influence of high cant deficiency*

An evaluation of tests performed on the high cant deficiency tests only, may contain information particularly important for tilting trains as this is the normal condition for tilting trains. A separate model estimate is therefore made on the tests at a cant deficiency of 280 mm, Table 9-5. Comparing the result from this selection of tests with the result for all tests shown in Table 9-4 reveals some differences.

1. The correlation to MSS is higher.
2. Model 3, 6 and 8 show better correlation to MSS than model 9, which was the best when all tests were considered. The influence from roll velocity in model 8 is small and can be omitted with no significant impact on correlation to MSS.
3. The stimuli for models containing more than one stimulus are all very different compared to those shown in Table 9-4; notice model 6 which has different signs on all terms!

Table 9-5: Models and their correlation to MSS, tests at 280 mm of cant deficiency.

Gender	Tests	Model No: 2)	Model Stimuli 1)	Correlation (R^2)
m + f	1, 3, 5, 8, 11	1	$0.006 \cdot a_h - 0.04 \cdot \dot{\varphi}^2$	0.581
m + f	1, 3, 5, 8, 11	2	$0.0055 \cdot a_h$	0.580
m + f	1, 3, 5, 8, 11	3	$1.64 \cdot \ddot{y} - 3.3 \cdot \dot{\varphi}$	0.634
m + f	1, 3, 5, 8, 11	4	$6.3 \cdot \ddot{z}$	0.576
m + f	1, 3, 5, 8, 11	5	$6.6 \cdot \dot{\varphi}$	0.570
m + f	1, 3, 5, 8, 11	6	$1.64 \cdot \ddot{y} - 3.3 \cdot \dot{\varphi} - 0.02 \cdot \ddot{y} \cdot \dot{\varphi}$	0.634
m + f	1, 3, 5, 8, 11	7	$5 \cdot \ddot{z} + 1.4 \cdot \dot{\varphi}$	0.577
m + f	1, 3, 5, 8, 11	8	$2.4 \cdot \ddot{y}^2 - 0.03 \cdot \dot{\varphi}^2$	0.659
m + f	1, 3, 5, 8, 11	9	$62 \cdot \ddot{z}^2$	0.558

Where: a_h = Horizontal acceleration, $\ddot{y}$ = Lateral acceleration in carbody,
$\ddot{z}$ = Vertical acceleration in carbody, $\dot{\varphi}$ = Roll velocity of carbody, k_{ij} = positive constant

1) Given signs reflect the calculated signs
2) The model numbers are the same as in Table 9-3.

9.6 *Gender differences*

The gender difference on susceptibility to motion sickness has been a subject for several scientists, and most scientists have found that females are more prone to motion sickness than males. The higher susceptibility to motion sickness for females is found also in the present evaluation, Figure 9-5.

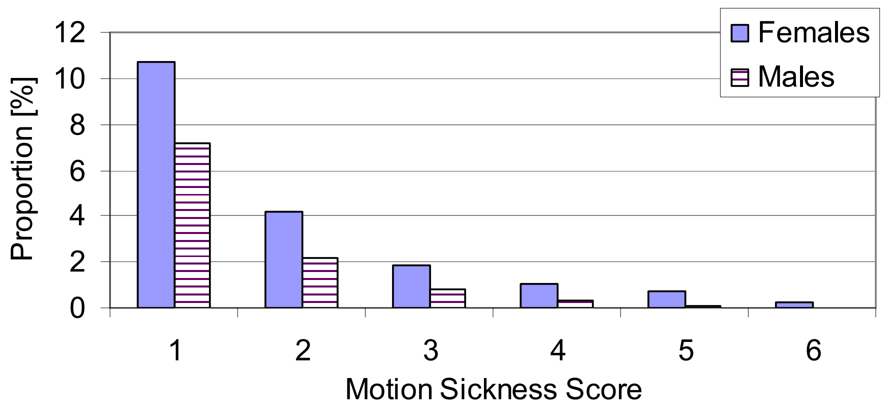

Figure 9-5: Average MSS for females and males, *all tests.*

An evaluation of the nine models for females only is shown in Table 9-6. The stimuli expressions are surprisingly similar to the expressions for males and females together in Table 9-4; this statement is particularly valid for models containing one stimulus only. The correlation as R^2 is surprisingly similar and rather low for all the eight models, indicating that the deviations in MSS are larger for females than for females and males together.

Table 9-6: Models and their correlation to MSS, females only.

Gender	Tests	Model		Correlation (R^2)
		No: 2)	Stimuli 1)	
f	All	1	$0.0048 \cdot a_h + 0.15 \cdot \dot{\varphi}^2$	0.223
f	All	2	$0.0080 \cdot a_h$	0.210
f	All	3	$0.27 \cdot \ddot{y} + 9.1 \cdot \dot{\varphi}$	0.222
f	All	4	$9{,}9 \cdot \ddot{z}$	0.228
f	All	5	$9{,}7 \cdot \dot{\varphi}$	0.216
f	All	6	$0.14 \cdot \ddot{y} \cdot \dot{\varphi} + 0.25 \cdot \ddot{y} + 8.9 \cdot \dot{\varphi}$	0.222
f	All	7	$7 \cdot \ddot{z} + 3.0 \cdot \dot{\varphi}$	0.230
f	All	8	$0.62 \cdot \ddot{y}^2 + 916 \cdot \dot{\varphi}^2$	0.220
f	All	9	$104 \cdot \ddot{z}^2$	0.228

Where: a_h = Horizontal acceleration, $\ddot{y}$ = Lateral acceleration in carbody,
$\ddot{z}$ = Vertical acceleration in carbody, $\dot{\varphi}$ = Roll velocity of carbody, k_{ij} = positive constant

1) Given signs reflect the calculated signs
2) The model numbers are the same as in Table 9-3.

Females differ from males by having a small zero offset, such as even small motions generate some motion sickness. This effect is not shown in the models as any constant term is left out of the models. Calculated for model 4 on MSS for all tests, this constant is 0.15 and the constant is larger for test site Linköping than for the two other sites. For males this constant is insignificant.

9.7 *Time dependence*

Figure 9-6 shows how the MSS develops as function of time (average of all tests and both test groups in each test) for the Kristiansand site. The decline of MSS at the stand still between 65 and 75 minutes is clearly visible. The decline at the end is exaggerated as only the least provocative test cases lasted as long as 150 minutes.

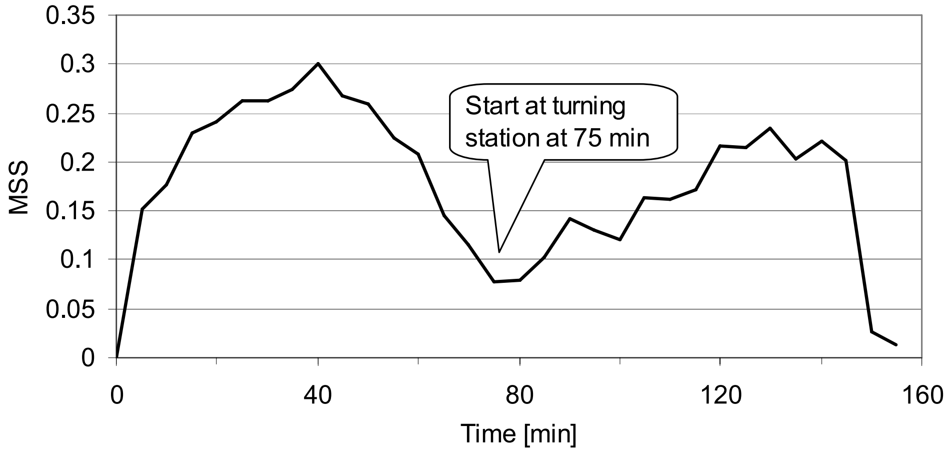

Figure 9-6: Average MSS as function of time for the Kristiansand site.
Average of both test groups in all tests.

The aim with a motion sickness model (earlier and present) is to show the development of motion sickness as closely as possible. A time constant of 10 minutes has been used as standard in the present study at Net Dose calculations. However, other time constants have been suggested by different scientists. Figure 9-7 shows the influence of different time constants from 2 to 20 minutes calculated on vertical acceleration in square.

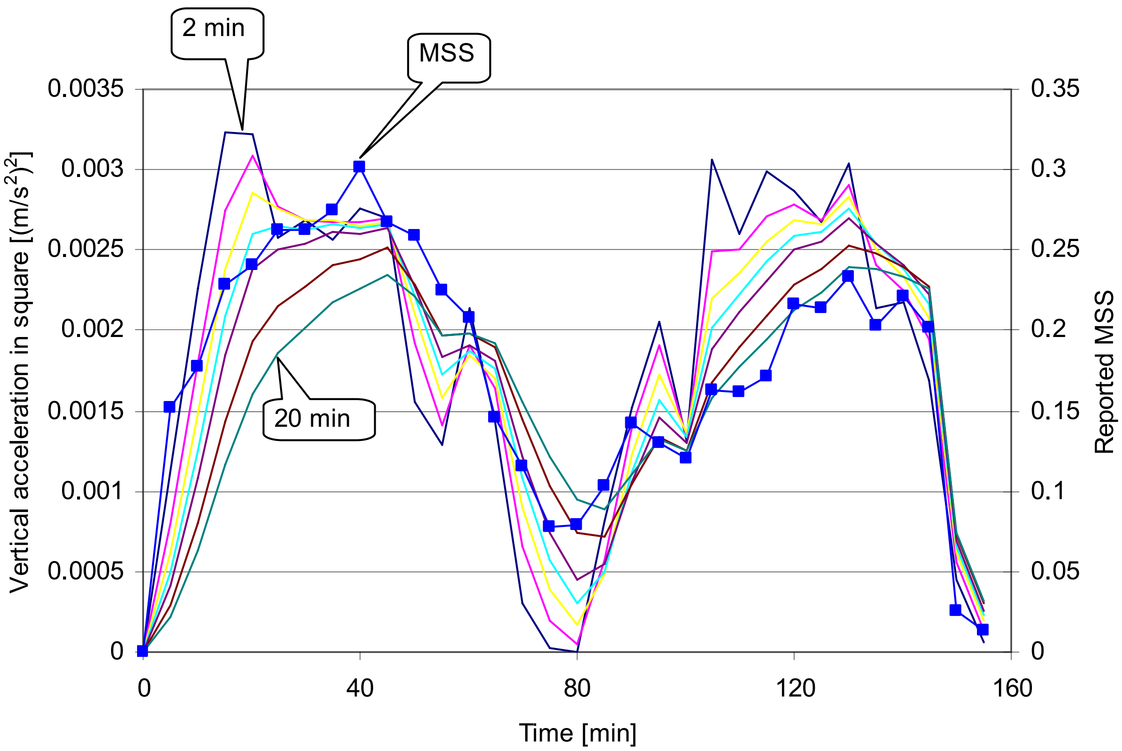

Figure 9-7: Average vertical acceleration in square as function of time for the Kristiansand site. *Average of all tests and both test groups in each test, the shown curves are for 2, 4, 6, 8, 10, 15 and 20 minutes time constants.*

From Figure 9-7 it can be concluded that the best fit is received with a time constant in between the two extremes of 2 and 20 minutes. In Figure 9-8 the best fit, as the time constant giving the highest correlation to MSS, can be identified to 10 minutes, which is the same as used as standard in the present evaluation.

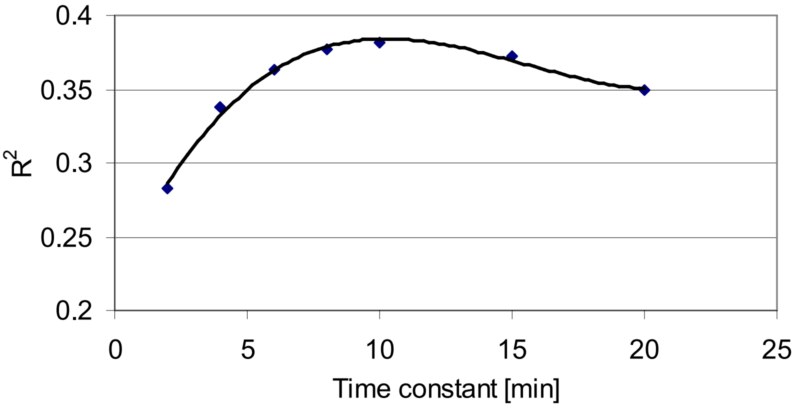

Figure 9-8: Correlation (R^2) as function of time constant in the Net Dose time dependence.
Applied on model 9 and compared to MSS.

The sensitivity to motion sickness can be calculated as the ratio between the reported motion sickness and the experienced motions. In the description of the ND-time dependence in Figure 5-4 this ratio was assumed to be a constant k_{ND}, but it can also be expressed as a function of time. In Figure 9-9 this sensitivity is calculated as the average reported MSS divided by the average ND-values (excluding the constant k_{ND}) calculated on vertical acceleration squared. The sensitivity is about 110 $(m/s^2)^{-2}$ before turning and about 80 $(m/s^2)^{-2}$ after. This reduction in sensitivity can be interpreted as habituation to the motions on the train. Two distinct peaks can also be seen; one shortly after start and one shortly after the turning. The interpretations of these peaks are discussed in Chapter 11.

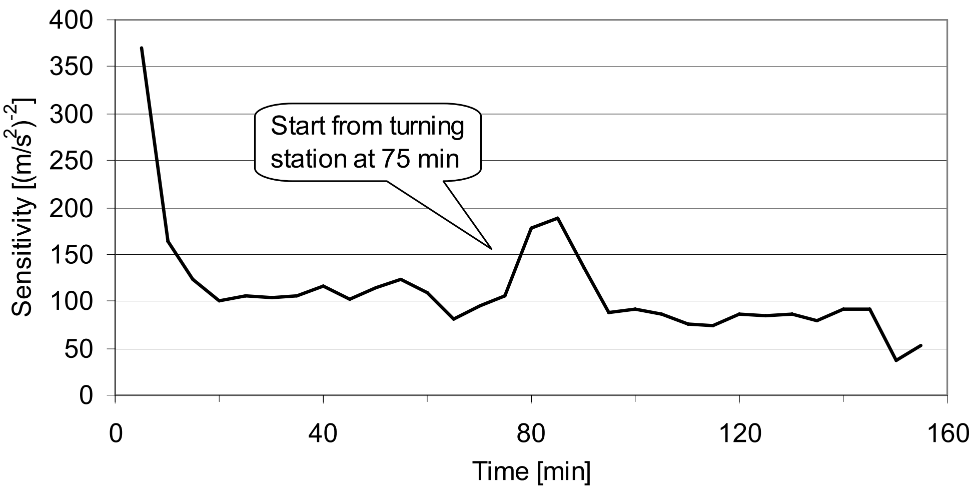

Figure 9-9: Average motion sensitivity as function of time at the Kristiansand site.
Calculated as the average reported MSS divided by the average ND-values
(excluding the constant k_{ND}) calculated on vertical acceleration squared.

9.8 *Frequency weighting*

Frequency weighting of motion signals is a central part of motion evaluation. The only available standardized frequency weighting function for motion sickness is the W_f-filter valid for vertical motions. This weighting function is in this evaluation applied on all motions except lateral accelerations where the W_g-filter is used, see Section 4.4.2. Weighting filters are generally derived though laboratory tests, but it is also possible to check the filter frequencies from the on-track test. The technique used here is extension of the pass band applied on vertical acceleration. The Net Dose time dependence with 10 minutes time constant is used and the correlation to MSS is calculated, the result is shown in Table 9-7. There is a slight tendency that an extension towards lower frequencies increases the correlation.

Table 9-7: Alternative frequency weighting of vertical acceleration.

Pass band [Hz]	Correlation (R^2)	Comment
0.02 - 0.25	0.334	
0.04 - 0.25	0.335	
0.08 - 0.25	0.331	The W_f-filter
0.08 - 0.50	0.324	
0.08 - 1.00	0.301	

The W_f-filter is often used also for roll velocity despite the filter is only validated for vertical acceleration (there is no other generally accepted filter for nausea caused by roll motions). The W_f-filter application on roll velocity is checked with extension of the pass band. The Net Dose time dependence with 10 minutes time constant is used and the correlation is calculated to MSS, the result is shown in Table 9-8. There is a slight tendency that an extension towards higher frequencies increases the correlation.

Table 9-8: Alternative frequency weighting of roll velocity.

Pass band [Hz]	Correlation (R^2)	Comment
0.02 - 0.25	0.243	
0.04 - 0.25	0.253	
0.08 - 0.25	0.262	The W_f-filter
0.08 - 0.50	0.263	
0.08 - 1.00	0.259	

9.9 *Alternative analysis*

Regression analysis based on linear models has been a standard in evaluations of motion sickness tests made on-track. This section presents an alternative analysis method. Just by looking at Figure 9-10 a clear pattern can be seen, which can be interpreted in different ways.

1. The line in the figure is a polynomial of second order (parabola) describing the relation between ND-values (excluding the constant k_{ND}) calculated on roll velocity and MSS. This second order polynomial has a better fit than a single order polynomial (the linear model).
2. There seems to be two groups of data, one below the ND-values (excluding the constant k_{ND}) calculated on roll velocity of 0.028 deg/s and one above. The MSS in the first group appears not to have any correlation to roll velocity, in the second group MSS increases with the roll velocity. 0.028 deg/s could be interpreted as a threshold, under which the roll velocity should be kept to avoid increased motion sickness. If this is true we could also interpret the MSS experienced below 0.028 deg/s as a *placebo* effect caused by making tests. Alternative, it could be influenced by other motion than roll velocity.

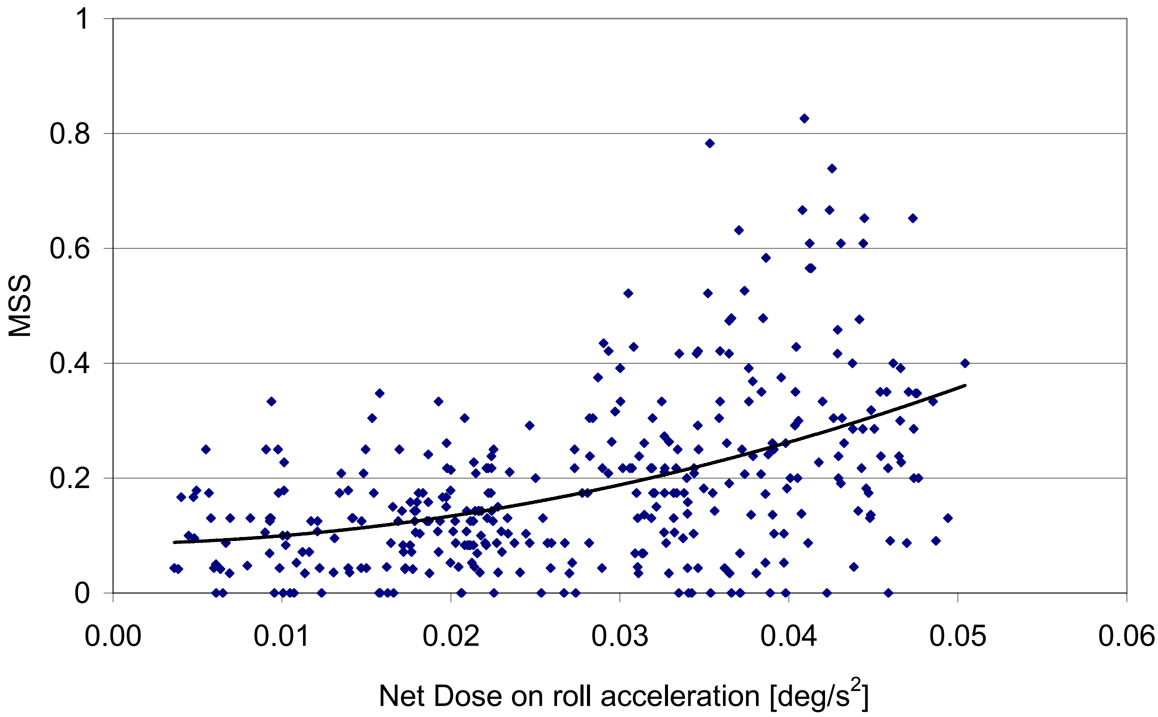

Figure 9-10: MSS as function of ND-values (excluding k_{ND}) calculated on roll velocity.
All tests at the Kristiansand site.

The threshold found for ND-values (excluding k_{ND}) calculated on roll velocity could also be expressed for ND-values (excluding k_{ND}) calculated on vertical acceleration to 0.026 m/s^2 or in any other motion with strong correlation to roll velocity. The evaluation made this way show less clear patterns for the other two test sites, Annex D, Figure D-4 to D-21.

9.10 *Conclusions on motion sickness during on-track tests*

The knowledge shown and the references given to on-track tests in the present study is huge. This section is an attempt to summarize the knowledge won during on-track tests, both previous tests according to Section 4.5 and the present evaluation of the FACT-tests. The summary is given as statements with supporting evidence, Table 9-9. A similar summary for laboratory tests was in made in Section 4.4.11.

Table 9-9: Conclusions on on-track tests.

Statement	Supporting reference
High cant deficiency cause more motion sickness than low. There are several reports indicating that cant deficiency has correlation to motion sickness. It is also consistent with the fact that tilting trains causes more motion sickness than non-tilting trains.	Figure 4.4 and Table 8-3.
High tilt compensation cause more motion sickness than low. There are several reports indicating that tilt compensation has correlation to motion sickness. It is also consistent with tilting trains causes more motion sickness than non-tilting trains. However, the statement is <u>in conflict with</u> the result in the present report on motion sickness at high cant deficiency, Table 9-5.	Andersson & Nilstam [1984] Förstberg [2000a]
Tilting trains show increased levels of vertical and roll motions at frequencies below 1 Hz compared with non-tilting.	Table 8-5 and Figures 8-2 and 8-3
Vertical acceleration correlates with motion sickness on trains with active tilt. It is consistent with increased levels of vertical motions in tilting trains compared with non-tilting ones.	Donohew & Griffin [2005a] Table 9-4
Vertical acceleration does not correlate with motion sickness on trains with natural tilt. This is a single source statement <u>in conflict with</u> several statements in this table.	Suzuki et al. [2005]
Lateral acceleration correlate with motion sickness. The statement is partly <u>in conflict with</u> correlation between vertical motions and motion sickness.	Förstberg [2000a] Suzuki et al. [2005] Table 9-5
Roll velocity correlate with motion sickness, particularly when combined with lateral acceleration. The statement is supported by the number of scientists having showed correlation between roll velocity and motion sickness, Wertheim et al. [1995], Dahlman [2007].	Ohno [1996] Suzuki et al. [2005] Förstberg et al. [2005] Table 9-4
Correlation is high between several motions. This is a known problem caused by the rules to design railways and how tilting trains acts today.	Table 9-2

Table 9-9 included statement on the some of the motion sickness model shown in Table 9-3. Table 9-10 gives some comments to all of the models and possible means to reduce motion sickness if the models were used for explaining the cause of motion sickness. The result is striking as conflicts between the models are common. However, most models point out *extended curve transitions*, *reduced tilt angle* and *reduced track cant* as a mean to reduce motion sickness. This conclusion is also consistent with Table 4-10 and Table 9-9.

Table 9-10: Comments of motion sickness models.

No:	Model stimuli [1)]	Possible means to reduce motion sickness if true
1	$k_{11} \cdot a_h + k_{12} \cdot \dot{\varphi}^2$ [2)]	Extend curve transitions, reduce track cant, reduce tilt angle.
2	$k_{21} \cdot a_h$ [3)]	None, except reduce speed or enlarge curve radii.
3	$k_{31} \cdot \ddot{y} + k_{32} \cdot \dot{\varphi}$	Extend curve transitions, influence from track cant and tilt angle depending on the constants.
4	$k_{41} \cdot \ddot{z}$	No influence from transition curves. Reduce track cant, reduce tilt angle, increase vertical curve radius.
5	$k_{51} \cdot \dot{\varphi}$	Extend curve transitions, reduce track cant, reduce tilt angle
6	$k_{61} \cdot \ddot{y} \cdot \dot{\varphi} - k_{62} \cdot \ddot{y} - k_{63} \cdot \dot{\varphi}$	Avoid high lateral acceleration and high roll velocity at the same time. 100% tilt compensation gives no motion sickness, but this is outside the validated area for the model.
7	$k_{71} \cdot \ddot{z} - k_{72} \cdot \dot{\varphi}$	Reduce track cant, reduce tilt angle, increase vertical curve radius and shorten transition curves (!)
8	$k_{81} \cdot \ddot{y}^2 + k_{82} \cdot \dot{\varphi}^2$	Only model giving optimum tilt angle and track cant different from the two extremes. Extend curve transitions.
9	$k_{91} \cdot \ddot{z}^2$	No influence from transition curves. Reduce track cant, reduce tilt angle, increase vertical curve radius.

Note: Reduced speed is not mentioned; this is a trivial measure in conflict with the main purpose of tilting trains.

10 Design of track geometry

10.1 *Track cant*

This section shows an attempt to optimize the contradictory requirements on low lateral acceleration perceived by the passengers in the non-tilting trains and low rick of motion sickness in the tilting trains. Tilting trains cause more motion sickness than non-tilting ones. Figure 8-2 and 8-3 indicate that the largest differences are vertical acceleration and roll acceleration. Minimizing roll will not only limit roll acceleration, but also vertical acceleration. Reducing the risk for motion sickness in tilting trains can thereby be achieved by minimizing the track cant. This study on track cant is made for Swedish conditions, where three different categories of trains are running:

Category A, with maximum cant deficiency of 100 mm
Category B, with maximum cant deficiency of 150 mm (passenger services, non-tilt)
Category S, with maximum cant deficiency of 245 mm (passenger services, active tilt)

In the design of track geometry, the choice between track cant and cant deficiency does not have a simple answer. The track standards often give rather wide ranges of possible combinations. The choice gets even more complex when different train categories (running at different speeds and hence different cant deficiency) must be considered. The following choices can be made for a curve with an equilibrium cant of 220 mm for *category A* in Sweden:

1. Apply 150 mm track cant which currently is the maximum permissible in Sweden
2. Apply 120 mm track cant which gives 100 mm cant deficiency for category A.
3. Apply something between 1 and 2.

In the same curve as above there will also run trains of *category B* at about 10 % enhanced speed and trains in *category S* at about 30 % enhanced speed. The three choices are then modified to:

1. Apply 150 mm track cant which currently is the maximum permissible in Sweden
2. Apply 130 mm track cant which gives 245 mm cant deficiency for category S.
3. Apply something between 1 and 2.

The limitations on track cant to apply as function of equilibrium cant for trains in category A are shown in Figure 10-1. The range of possible track cant is wide for most cases of equilibrium cants.

There are some more relations to consider:

- The relation between the number of trains per day in each category,
- The shortest transition curve can be derived from the requirements on rate of change of track cant and rate of change of cant deficiency,
- The passenger comfort has a strong relation to cant deficiency (as well as rate of change of cant deficiency). Cant deficiency above a certain level leads to discomfort,
- Certain carbody tilt systems uses track cant information to improve performance,
- *Cant excess* for slow trains (freight).

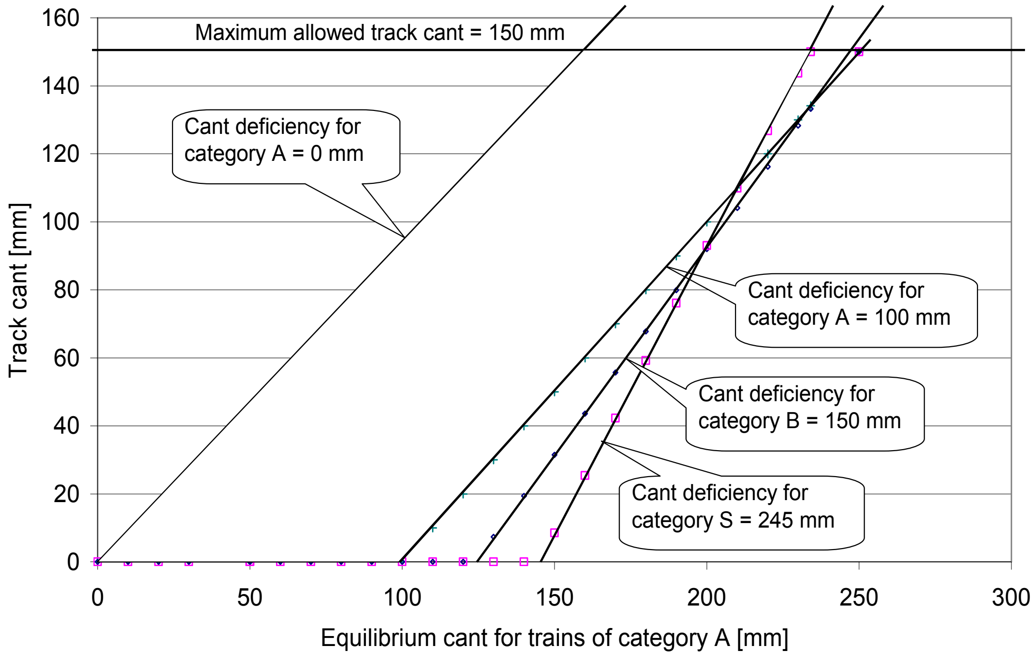

Figure 10-1: Possible track cant as function of equilibrium cant for trains of category A.

With all limitations on track cant considered there still remains a wide range, and it might be proper to suggest some *guidelines* for selection of track cant on lines with all categories of trains. The guidelines are given as function of equilibrium cant for category A trains. The tilting trains are here assumed to apply a fixed ratio between cant deficiencies and tilt angles. Kufver & Persson [2006] have shown how a variable ratio between cant deficiencies and tilt angles can be used to optimize comfort and limit risk of motion sickness. The guideline derived here is a balance between comfort according to the P_{CT} criterion and the risk for motion sickness as function of roll motions. The P_{CT} criterion consists of two parts (with constants for seated passengers), Equation 10-1 and 10-2.

The lateral portion: $$100 \cdot \left\{ \max\left[0.0897 \cdot \left|\ddot{y}_{1s}\right|_{\max} + 0.0968 \cdot \left|\dddot{y}_{1s}\right|_{\max} - 0.059); \ 0 \right] \right\}$$ [10-1]

The roll portion: $$100 \cdot \left\{ (0.0012 \cdot \left|\dot{\varphi}_{1s}\right|_{\max})^{1,626} \right\}$$ [10-2]

where:

P_{CT} = Percentage of dissatisfied passengers
$\ddot{y}_{1s}$ = Lateral acceleration in carbody (average over 1 second) [m/s^2]
$\dddot{y}_{1s}$ = Lateral acceleration change over 1 second in carbody [m/s^3]
$\dot{\varphi}_{1s}$ = Roll velocity in carbody (average over 1 second) [deg/s]

The choice of track cant can be summarised in a guideline divided in four parts as function of equilibrium cant. The result is given in words below and as a diagram in Figure 10-2.

Low equilibrium cant (0 – 49 mm)
The low equilibrium cant results in a low lateral acceleration which will make the lateral part of the P_{CT} criterion zero for all train categories. The track cant may be set to 0 to minimize the roll part.

Medium equilibrium cant (50 – 149 mm)
Cant different from 0 is needed to make the lateral part of the P_{CT} criterion zero for category B. Carbody tilt is used to reduce the lateral acceleration for category S. The track cant is set to equilibrium cant minus 50 mm (resulting in a cant deficiency of 50 mm for train in category A).

High equilibrium cant (150 – 234 mm)
Considerations to motion sickness in tilting trains should be taken. The lateral part of the P_{CT} criterion will not be zero for category B. The track cant is set to 60 % of equilibrium cant for category A + 10 mm (this choice makes the guideline continuous to medium and very high equilibrium cant).

Very high equilibrium cant (235 - 250 mm)
Maximum track cant must be applied to meet requirements on cant deficiency. Large roll motions may contribute to motion sickness in tilting trains.

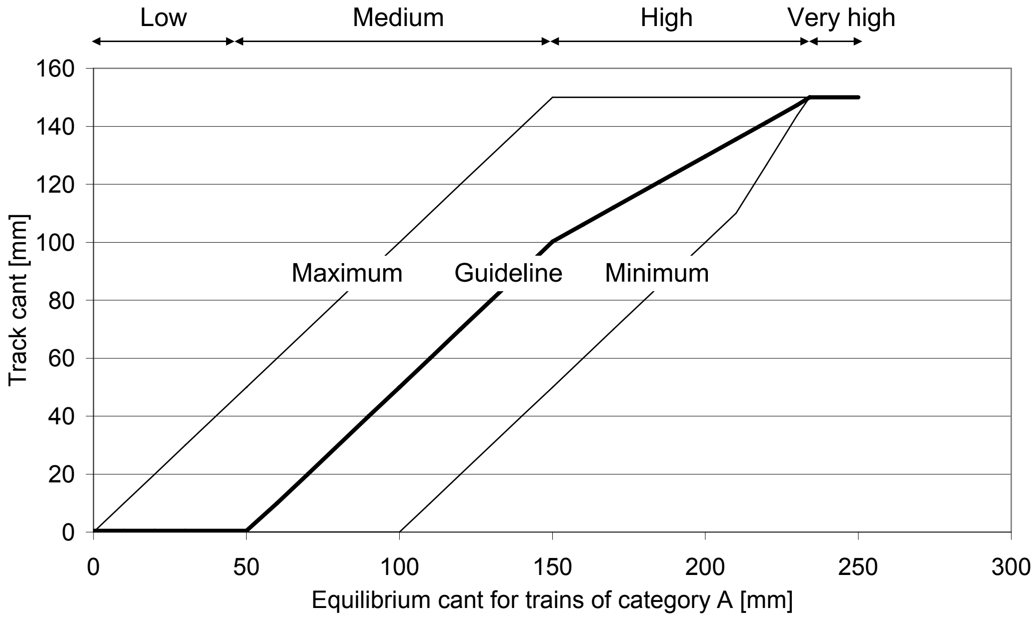

Figure 10-2: Track cant derived from the guidelines as function of equilibrium for trains of category A.

Figure 10-3 shows the applied track cant on the Stockholm – Gothenburg line as function of equilibrium cant for category A trains at today’s speeds. Some curves have applied track cant outside the possible area indicating that at least one train category has not been considered or that there are more to consider than in the scope of the present study.

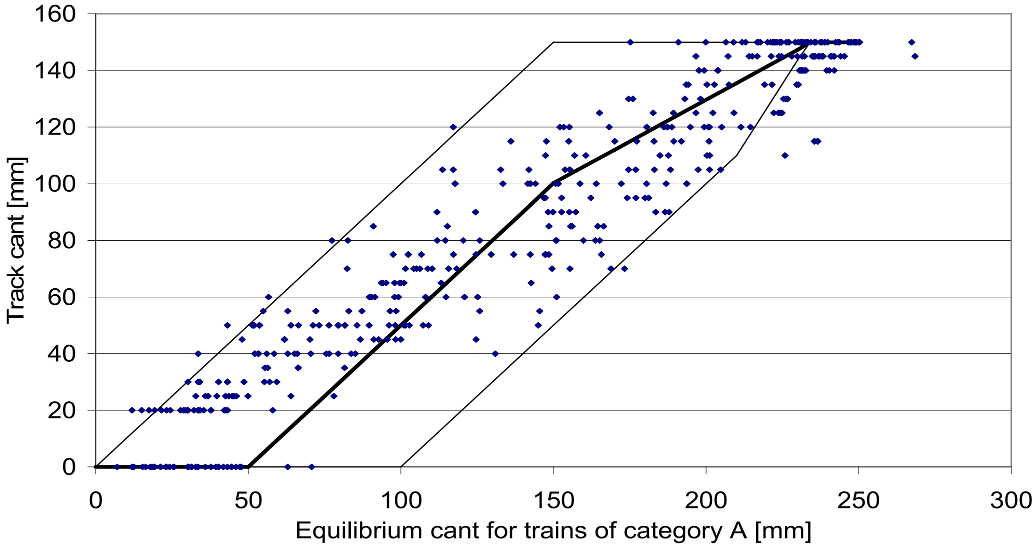

Figure 10-3: Applied track cant Stockholm – Gothenburg as function of equilibrium for trains of category A.

This study on optimal track was based on a fix relation between cant deficiency and tilt angle. Kufver & Persson [2006] has shown how a variable relation between cant deficiency and tilt angle can meet both requirements on good comfort for non-tilting trains and low risk for motion sickness on the tilting trains. Modern tilt control system makes this solution possible.

10.2 *Curve transitions*

Some of the motion sickness models showed good correlation between motion sickness and roll velocity. Roll velocity was in Section 10.1 limited by reduction of the roll angle, which gave implication on increased lateral acceleration perceived by the passengers in non-tilting trains. Roll velocities can also be limited by *extending the length of curve transitions*. However, extending the curve transitions on existing lines often result in a lateral shift of the track in the circular track and/or a reduction of the curve radius. The issue of extending the curve transition then became a complicated optimisation process and a possible area for further research.

10.3 *Vertical track geometry*

Some of the motion sickness models showed good correlation between motion sickness and vertical acceleration. The correlation may have two different causes, either directly to vertical acceleration or indirectly as a sign of difference between the sensed vertical and the subjective vertical as proposed by Bles et al. [1998].

Vertical acceleration was in Section 10.1 limited by reduction of the roll angle (cant angle), which gave implication on increased lateral acceleration perceived by the passengers in non-tilting trains. Vertical acceleration also has a relation to the vertical track geometry. The vertical acceleration due to the vertical track geometry has approximately the same magnitude as caused by the horizontal track geometry and carbody roll due to track cant and tilt angle. The vertical acceleration caused by vertical track geometry may be both negative and positive, which differs from the horizontal track geometry which only can cause an increase in vertical acceleration. Hence the variation of vertical acceleration may be in the order of twice as high due to vertical track geometry.

11 Discussion and conclusions

11.1 *Discussion on results and methods*

Studies on running time

In Chapter 6 studies on running time show that tilting trains is a good choice for existing lines where running time is in focus. The result is based on the main line between Stockholm and Gothenburg However, also the more curvy line between Gothenburg and Kalmar was studied in [Persson, 2007a], which showed similar result, and the result is therefore believed to be representative for existing lines in Sweden.

Motion sickness testing

Test subjects in Linköping (Sweden) were more prone to motion sickness than test subjects in Kristiansand (Norway). This statement is based on the ratio between experienced motion sickness and measured motions, and is independent of which motion is taken as reference. There could be one or more reasons for this difference, and examples are:

1. From Table 7-6 we know that the age of the subjects were higher for test site Kristiansand than for the test site Linköping. From earlier research it is known that sensitivity decreases with the age. On the other hand we know from Table 8-4 that the proportion reporting motion sickness is similar for all age groups.
2. From Section 9.4 we know that females differ from males on sensitivity to motion sickness. Females differ from males by having a small offset, such that even small motion doses generate some motion sickness. The offset is significant for test site Linköping, but not for site Kristiansand and accounts for a large part of the sensitivity difference. The reason is unclear; have the females in Kristiansand experienced more motions and got more habituated?
3. From Section 7.5 we know that some test subjects participated more than once and this statement particularly applies to Kristiansand. From Section 5.5 we know that the sensitivity decreases with the number of times.

Figure 9-9 showed the motion sickness sensitivity as function of time. The decline in sensitivity over time was interpreted as habituation to the motions in the train. There were also two distinct peaks in sensitivity; one shortly after start and one shortly after the turning. There could be one or more reasons for these peaks, and examples are:

1. It is a part of habituation to new motions. Human may be very sensitive the first minutes of a new exposure, but adopts quickly. Section 5.5 gives no support for this theory, but this may be depending on that such short times have not been studied.
2. The Net Dose time dependence is too simple. The Net Dose time dependence, used as standard in the present study, gives lower estimated motion sickness than reported the first minutes. It may be that the Net Dose time dependence should have <u>two</u> different time constants; one at increasing motion sickness and one at decreasing motion sickness.
3. It has psychological grounds. At the start the subjects worry about what experience they are going to meet, but after a while the subjects get more relaxed. As motion sickness and psychology go hand in hand, the subject can not separate these effects.

Comfort and motion sickness

The issue of selecting the tilt compensation is a main issue of interested parties. On-track tests from the 1970s until today have all showed the advantage of low tilt compensation to reduce the risk of motion sickness. This is also consistent with the result in the present study, at least for low levels of cant deficiencies (150 and 215 mm). For 280 mm of cant deficiency the results differs from previous experience by showing contradictory result. Excluding data from the Hamar site, since there were only tests made at one cant deficiency, the low tilt compensation (44%) condition gave 72% more MSS than the high tilt compensation (57%) condition. This is likely a result of mere chance; optionally this would mean trend change compared with previous experience gained at lower cant deficiencies. This would also mean that low risk of motion sickness goes hand in hand with comfort at high cant deficiencies.

Guidelines for application of track cant

In Chapter 10 guidelines for application of track cant are given. The basis for these guidelines is: *tilt just as much as necessary to avoid discomfort due to quasi-static lateral acceleration*. The result is therefore believed to be valid independent of the cause of motion sickness.

11.2 *Motion sickness on-track testing*

The evaluation made in the present study has high-lighted some key issues on the success of motion sickness on-track testing. These key issues are:

- Finding the source of motion sickness by on-track test only is not possible as the correlation between different motion variables is strong. FACT put a large effort in their design of the on-track test to reduce the correlation, but still the correlation was strong between several motion variables. However, it is possible to verify hypotheses of motion sickness. These hypotheses must be set in advance, and may then be verified or falsified in light of the measured data.
- FACT decided to use the test subjects once only (there were some exceptions) to avoid the influence of habituation. However, different test subjects participating in different tests risk that the motion sickness sensitivity differs from group to group. This was also the case for FACT, in particular differences between the three test sites were found. The cause to these differences was probably the recruitment process which differed from site to site, but there could be other reasons also as discussed in Section 11.1. Reuse of subjects could be an alternative as the influence of habituation is easier to handle than large differences between test groups. FACT originally used four groups of 15 subjects in each test (was reduced to two in the present evaluation). Technically this split in four groups was correct as the motions in a train differ from place to place, but the disadvantage with small test groups become evident in the evaluation. The test groups should be large to limit the influence of mere chance.
- Validity of the result is seldom discussed in the reports. The validity of the result can not be larger than the investigated field. Take motion sickness as function of tilt compensation as example. From Table 8-3 we found that intermediate tilt compensation gives more motion sickness than low and high. Extending this relation to tilting trains in general is nonsense as the low and high tilt compensation cases were run at lower cant deficiency. Looking at model 6 in Table 9-3 (which can be interpreted as intermediate tilt compensation gives more motion sickness than low and high), it is difficult to determine the validity range of the model.

11.3 *Conclusions*

Carbody tilting has today become a mature technology accepted by most operators, but not favoured by many. There are different reasons behind this fact: the non-tilting trains have increased their speed in curves, reducing the potential for travel time reduction by tilting trains to approximately 10 - 15 %. The attractiveness is also impacted by low reliability and motion sickness on certain services. The risk of motion sickness and the running time benefit compared with non-tilting trains are addressed in the present study.

Running times

There is a trend to apply more and more track cant. On lines with no freight traffic, 180 mm track cant is today allowed by some infrastructure managers. High track cant increases the permissible speed for both non-tilting and tilting trains, but the difference in running time between non-tilting and tilting trains is decreasing. There is also a trend to allow more and more cant deficiency for non-tilting passenger trains, which also decreases the difference in running time between non-tilting and tilting trains. The increased cant deficiency will for the non-tilting train result in increased lateral acceleration perceived by the passenger. The small difference in permissible cant deficiency between a non-tilting train and an X2000, Figure 11-1, will at 160 mm of track cant give a speed difference of only 9 % up to 160 km/h.

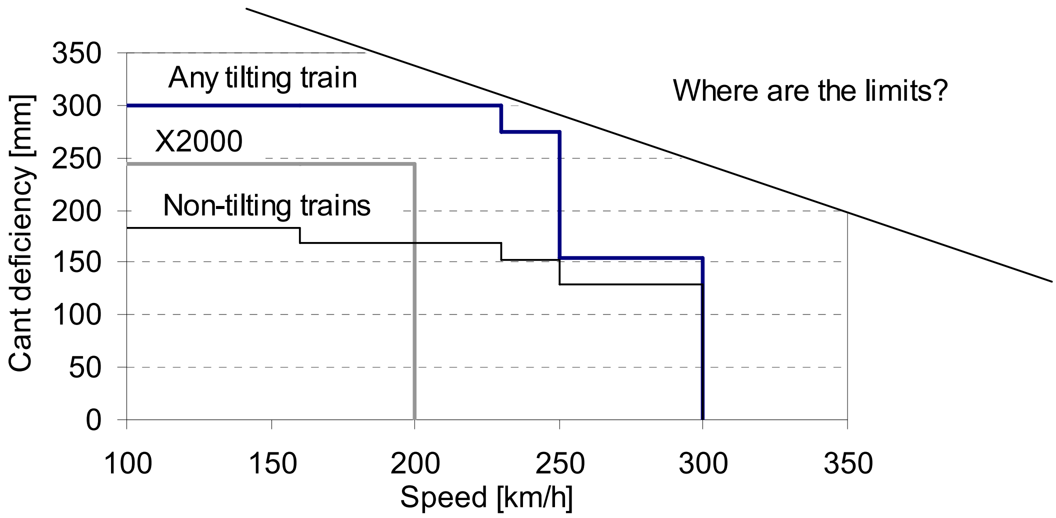

Figure 11-1: Permissible cant deficiency for different vehicles.
The cant deficiency for non-tilting trains is taken from CEN [2006].

Figure 11-1 shows the maximum permissible cant deficiency for any tilting train in the world as function of speed. This should be seen as an indication on the state of the art design. The values in speeds above 250 km/h come from the Shinkansen N700, a train with a maximum tilt angle of 1 deg. Using trains with larger maximum tilt angle gives potential for increased cant deficiency. However, potential limitations on permissible cant deficiency at speeds above 250 km/h have been identified to:

- Cross-wind stability
- Lateral track shift forces

Exactly where the limits are is depending on what improvements can be done on both vehicle and infrastructure. The inclined line in Figure 11-1 is one possible limit. Setting these limits is identified as one area for further research.

The relation between cant deficiency, top speed and tractive performance is important to get the best performance out of a tilting train. 15 minutes running time (about 9%) may be gained on the line Stockholm – Gothenburg (457 km) if cant deficiency, top speed and tractive performance are improved compared with existing tilting trains.

Motion sickness

Evidence of motion sickness has been reported in air, in space, at sea, in cars, in trains, at skating, at fairground rides etc. and there are reports. Motion sickness is most common in cars and on cruise ships. Dominant frequencies for vehicles experiencing motions sickness are often at 0.2 Hz or below.

Laboratory tests have proven that translations in all directions can cause motion sickness; it is only a question of magnitude and duration. Weighting curves exist as results from the laboratory tests, with sensitivity peaks at frequencies of 0.2 Hz or below. Pure rotations seem to have less correlation to motion sickness than translations. Combinations of motions, in particular translation combined with rotation, are highly effective in creating motion sickness.

All the laboratory tests causing motion sickness have been performed at amplitudes higher than measured in tilting trains. In particular this is the case for rotations. O'Hanlon & McCauley [1973] showed that vertical accelerations at amplitudes 60 – 70% higher than measured in tilting trains on the track section between Kristiansand and Vegårdshei cause motion sickness. Vertical acceleration also shows the highest correlation to MSS of the tested models estimating motion sickness based on measured motions. High correlation to motion sickness does not necessary mean that vertical acceleration is the cause of motion sickness in tilting trains, it is likely that combinations with rotations contribute. Already Purkinje [1820] pointed out movement of the head as one good combination candidate.

Motion quantities measured in tilting trains differ from motion quantities measured in non-tilting trains by increased levels of vertical and roll motions at frequencies below 1 Hz. These increased levels of motions may contribute to the difference in experienced motion sickness between non-tilting and tilting trains. Correlation between vertical, roll and other motions exists, which excludes the possibility to, based on measurements in trains, judge which motion quantity is the main cause of motion sickness.

The sensory conflict is the most common explanation of motion sickness. Most scientists have today accepted the sensory conflict theory, but there are also competing theories like the over-stimulation theory and the ecological theory.

Limiting the risk of motion sickness

It is possible to give some conclusions on how the risk of motion sickness shall be limited in tilting trains. These conclusions can be given despite lacking knowledge of the main cause to motion sickness. Tilting trains cause more motion sickness than non-tilting ones. The largest differences are vertical acceleration and roll velocity. Minimizing the roll angle will not only limit roll velocity, but also vertical acceleration. However, reduced roll angle may be in conflict with requirements on comfort (increased quasi-static lateral acceleration). Chapter 10 was an attempt to optimize these counteracting requirements by giving guidelines on track cant. Reduced roll motions without comfort implications may be achieved by continuous adjustment the ratio between cant deficiency and tilt angle, as proposed by Kufver & Persson [2006]. Reduced roll velocity and acceleration can also be achieved by extending the length of the curve transitions. Reduced vertical acceleration can be achieved by increasing the vertical curve radii.

12 Suggestions on further research

Further research should be carried out on areas where research can improve the competitiveness of tilting trains. The suggestions made here are based on the knowledge won in the present study.

- *Running time benefits*. The running times with non-tilting trains have been improved by increased applied track cant and increased cant deficiency. Tilting trains take advantage of the increased track cant, but the running time benefit in percent compared with non-tilting trains decays. Could the limitation on cant deficiency for tilting trains be updated? Would a limitation as function of speed be feasible? The present study has identified the existing types of limits; but at what levels should the limits be set? Particularly the limitation due to cross-wind is interesting to study.
- *Speed setting for good comfort and low risk of motion sickness*. Developing a guideline devoted to train operators and infrastructure owners as a best compromise between comfort and low risk for motion sickness. The guideline shall consider the influence of track cant and length of transition curves and the influence of perceived dose of motion sickness relevant motions (it might be a good idea to run slightly slower in track sections with many curves).
- *The choice of tilting as function of track cant and cant deficiency.* Developing a guideline devoted to train operators and manufactures as the best compromise between comfort and low risk for motion sickness (it might be a good idea to tilt slightly less than today in some curves).
- *Control of carbody roll motions.* Today’s tilt systems control the roll angle between the bogie frame and the tilting bolster. Modern control theory and practice would make control of the carbody roll possible. Control of carbody roll motions opens up for the possibility to minimize the dynamic contribution to carbody roll motions, which is believed beneficial for minimizing the risk of motion sickness.
- *Track geometry guidelines.* Today’s guidelines on track geometry consider safety and comfort, but it would also be possible to consider motion sickness. A first attempt to do so was made in Chapter 10.

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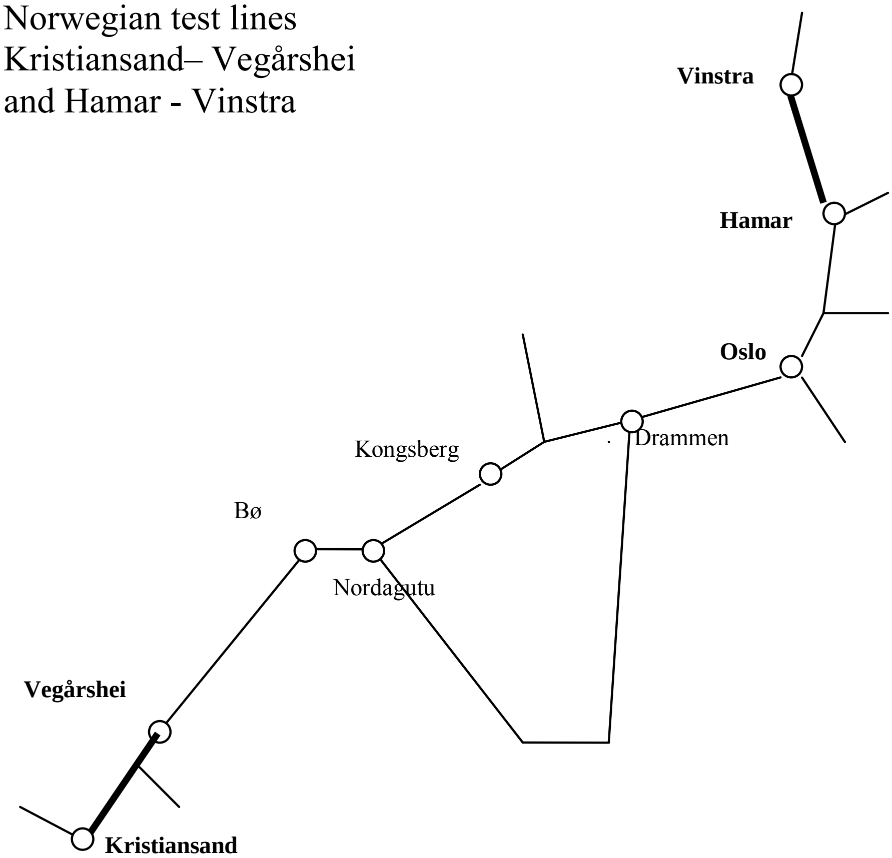
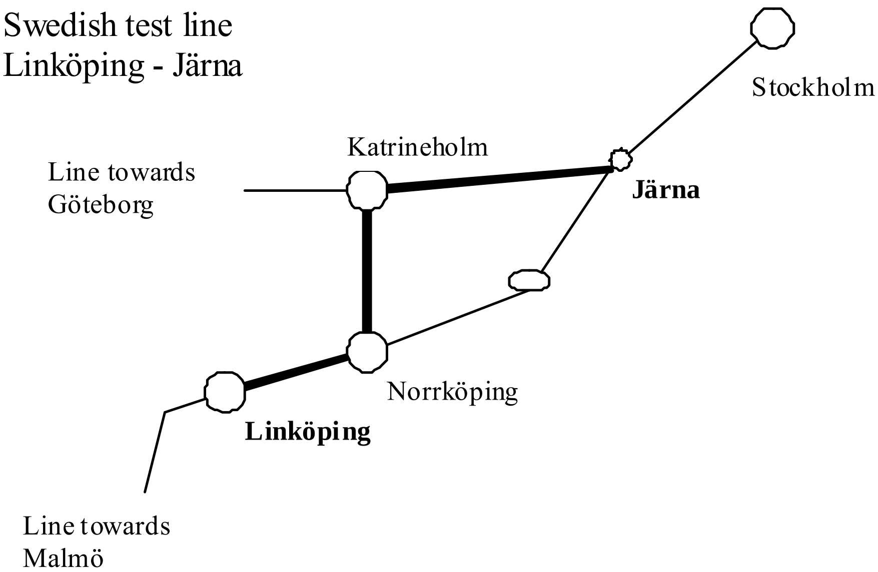
Annex A. Location of test lines

Norwegian test lines
Kristiansand– Vegårshei
and Hamar - Vinstra



Swedish test line
Linköping - Järna



Annex B. FACT Motion Sickness Questionnaire

How would you describe the ride comfort the last 5/10 minutes?

Very bad Very good

☐ ☐ ☐ ☐ ☐ ☐ ☐
1 2 3 4 5 6 7

How would you describe your feelings of nausea right now?

None Very strong

☐ ☐ ☐ ☐ ☐ ☐ ☐
0 1 2 3 4 5 6

And additionally the following question was asked on the Swedish and Norwegian runs respectively:

Swedish questions
How would you characterize your nausea, just now?
You may tick more than one box.

- ☐ Headache
- ☐ Tiredness
- ☐ Feeling hot
- ☐ Cold sweating
- ☐ Drowsiness
- ☐ Dizziness
- ☐ Nausea
- ☐ No motion sickness symptoms

Norwegian questions
How would you characterize your feeling of motion sickness, just now?
You may tick more than one box.

- ☐ No symptoms at all, I feel fine
- ☐ Some mild symptoms, but not nausea nor dizziness
- ☐ Mild dizziness
- ☐ Mild nausea
- ☐ Moderate nausea
- ☐ Dizziness
- ☐ Strong nausea
- ☐ I do not feel well

Annex C. List of signals

Car	Name	Direction	Type	Filter 1)	ND Tc 2)	Comments
Train	Speed	longitudinal	velocity			
1, 2, 3	ax	longitudinal	acceleration	Wf	10	
1, 2, 3	ay	lateral	acceleration	Wg	10	
1, 2, 3	az	vertical	acceleration	Wg	10	
1, 2, 3	az	vertical	acceleration	W004	10	Pass band 0,04 - 0,25 Hz
1, 2, 3	az	vertical	acceleration	Wf	10	
1, 2, 3	az	vertical	acceleration	W050	10	Pass band 0,08 - 0,50 Hz
1, 2, 3	az	vertical	acceleration	W100	10	Pass band 0,08 - 1,00 Hz
1, 2, 3	vf	roll	velocity	Wg	10	
1, 2, 3	vf	roll	velocity	W004	10	Pass band 0,04 - 0,25 Hz
1, 2, 3	vf	roll	velocity	Wf	10	
1, 2, 3	vf	roll	velocity	W050	10	Pass band 0,08 - 0,50 Hz
1, 2, 3	vf	roll	velocity	W100	10	Pass band 0,08 - 1,00 Hz
1, 2, 3	ak	pitch	acceleration	Wf	10	Calculated from vertical accelerations
1, 2, 3	ap	yaw	acceleration	Wf	10	Calculated from lateral accelerations
1, 2, 3	ay2	lateral	acceleration2	Wg	10	
1, 2, 3	ayvf	mix	mix	Wf	10	
1, 2, 3	ayak	mix	acceleration2	Wf	10	
1, 2, 3	ayap	mix	acceleration2	Wf	10	
1, 2, 3	az2	vertical	acceleration2	Wf	2	
1, 2, 3	az2	vertical	acceleration2	Wf	4	
1, 2, 3	az2	vertical	acceleration2	Wf	6	
1, 2, 3	az2	vertical	acceleration2	Wf	8	
1, 2, 3	az2	vertical	acceleration2	Wf	10	
1, 2, 3	az2	vertical	acceleration2	Wf	15	
1, 2, 3	az2	vertical	acceleration2	Wf	20	
1, 2, 3	azvf	mix	mix	Wf	10	
1, 2, 3	azak	mix	acceleration2	Wf	10	
1, 2, 3	azap	mix	acceleration2	Wf	10	
1, 2, 3	vf2	roll	velocity2	Wf	10	
1, 2, 3	vfak	mix	mix	Wf	10	
1, 2, 3	vfap	mix	mix	Wf	10	
1, 2, 3	ak2	pitch	acceleration2	Wf	10	
1, 2, 3	akap	mix	acceleration2	Wf	10	
1, 2, 3	ap2	yaw	acceleration2	Wf	10	
2, 3	ah	horizontal	acceleration	Wg	10	Calculated from yaw velocity
4	ay+	lateral	acceleration			Left axlebox of wheelset 2 of bogie 1

1) The abbreviation refers to the used weighting filter, for non-standard filter the abbreviation includes the change compared with standard and the pass-band is given in the comment column.
2) Net Dose time constant [min].

All signals are measured at carbody centre on floor except lateral and vertical acceleration in car 2 which were taken from a position above bogie 1 as this was considered more representative.

Annex D. Motion sickness test evaluation

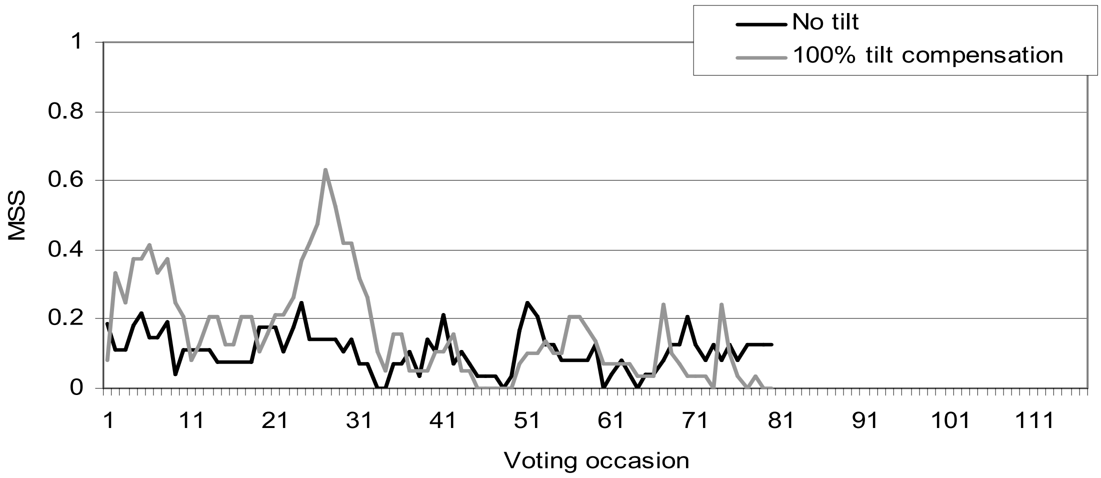


Figure D-1: MSS as function of voting occasion, 150 mm of cant deficiency.

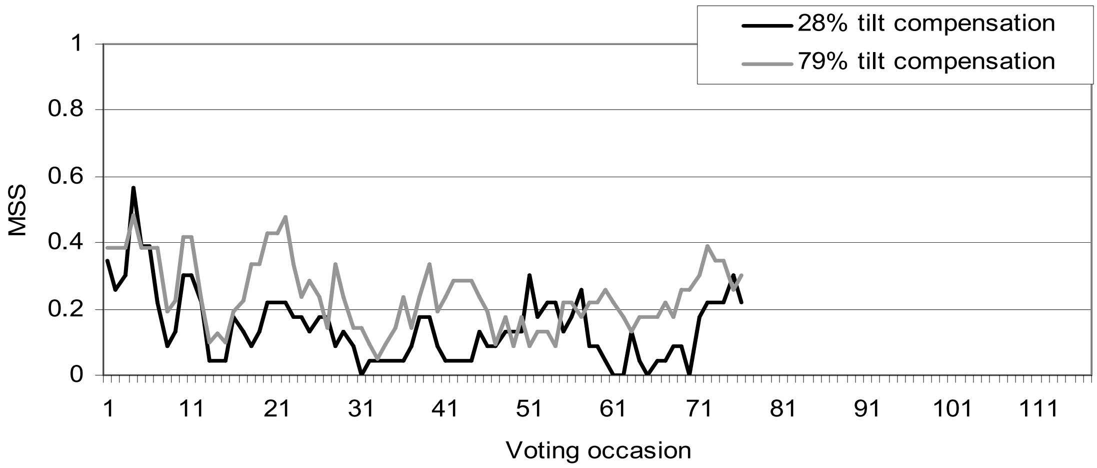


Figure D-2: MSS as function of voting occasion, 215 mm of cant deficiency.

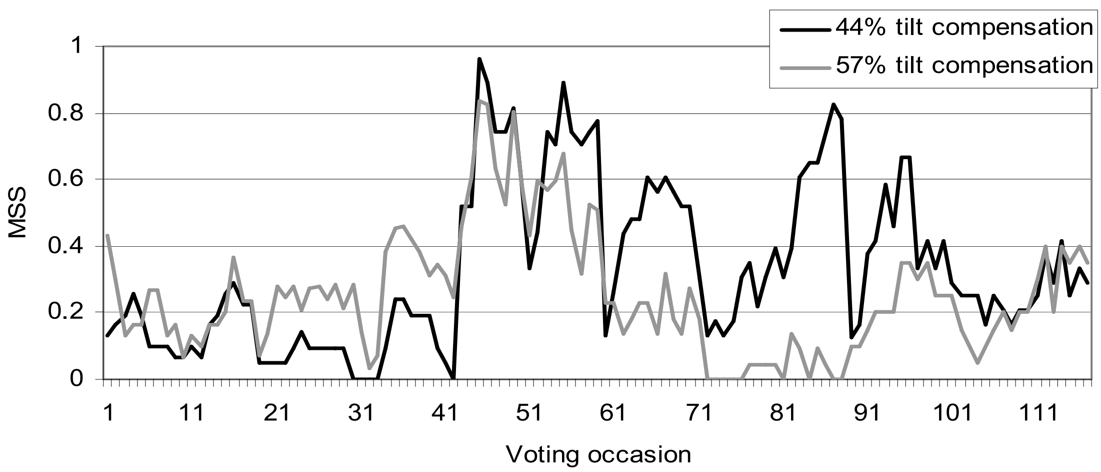


Figure D-3: MSS as function of voting occasion, 280 mm of cant deficiency.

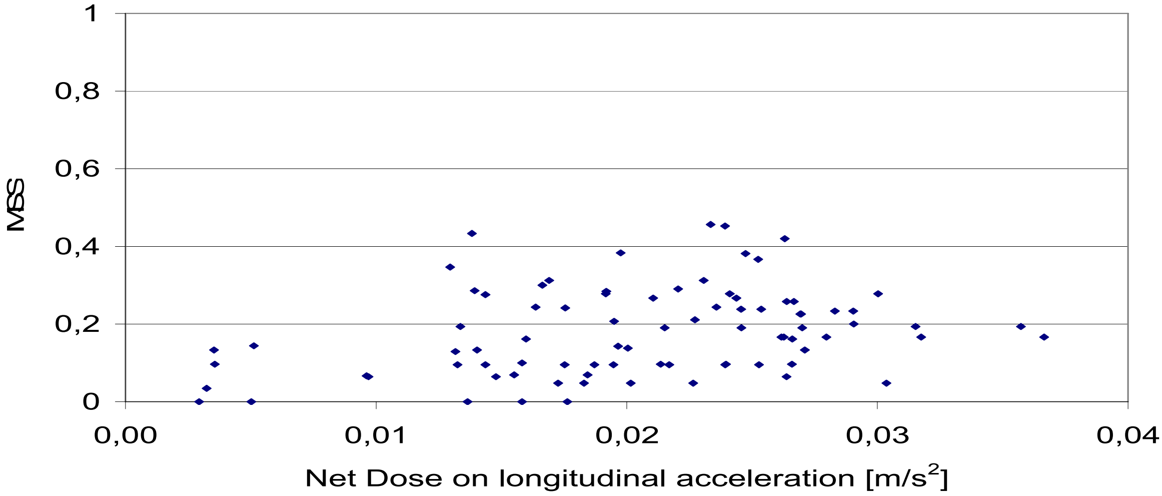


Figure D-4: ***MSS as function of ND (excl. k_{ND}) on longitudinal acceleration, Hamar.***

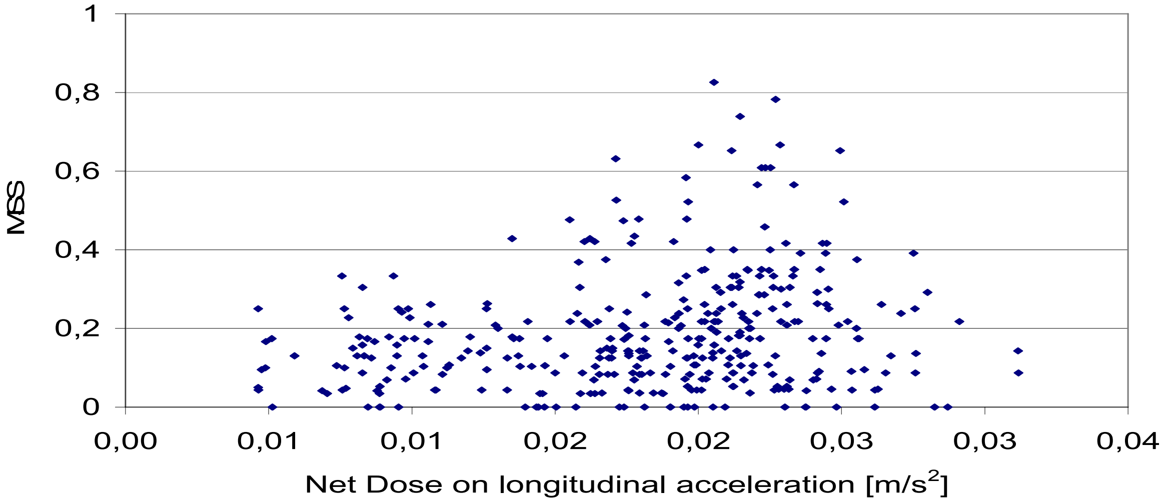


Figure D-5: ***MSS as function of ND (excl. k_{ND}) on longitudinal acceleration, Kristiansand.***

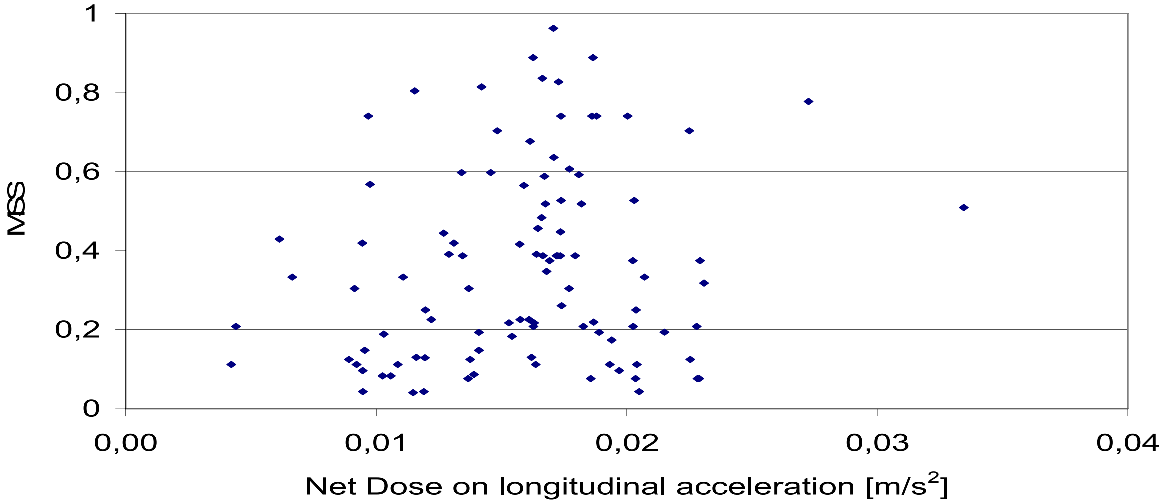


Figure D-6: ***MSS as function of ND (excl. k_{ND}) on longitudinal acceleration, Linköping.***

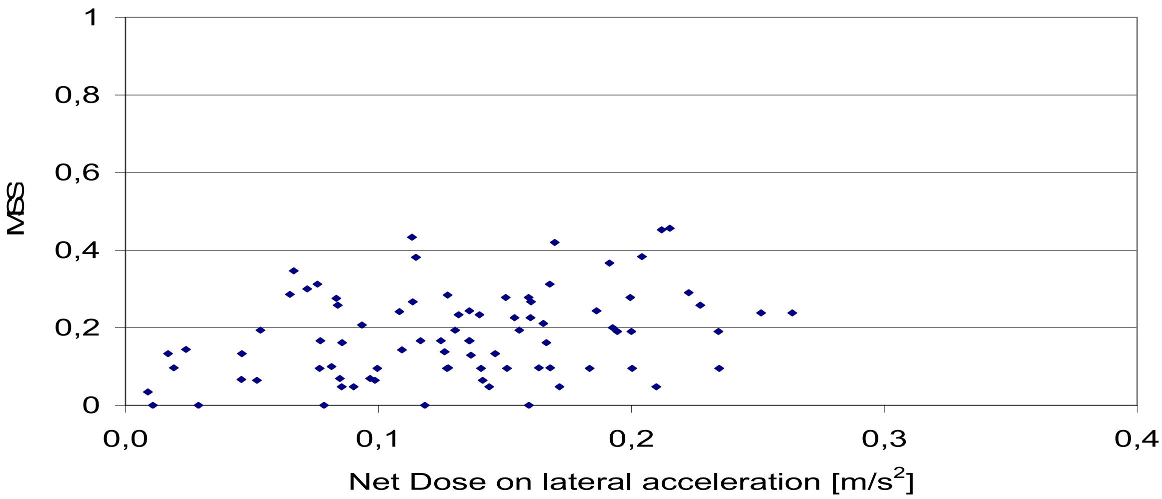


Figure D-7: ***MSS as function of ND (excl. k_{ND}) on lateral acceleration, Hamar.***

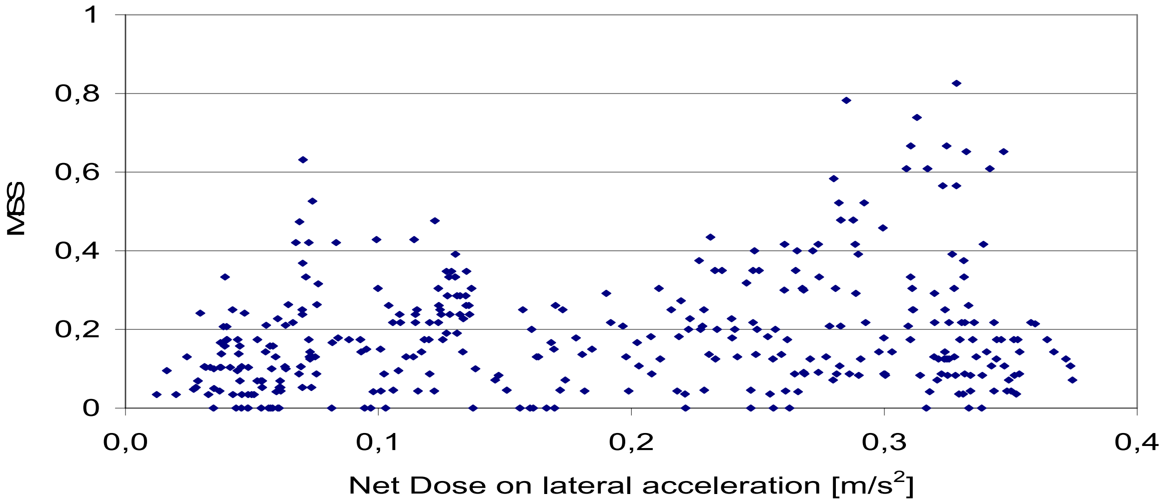


Figure D-8: ***MSS as function of ND (excl. k_{ND}) on lateral acceleration, Kristiansand.***

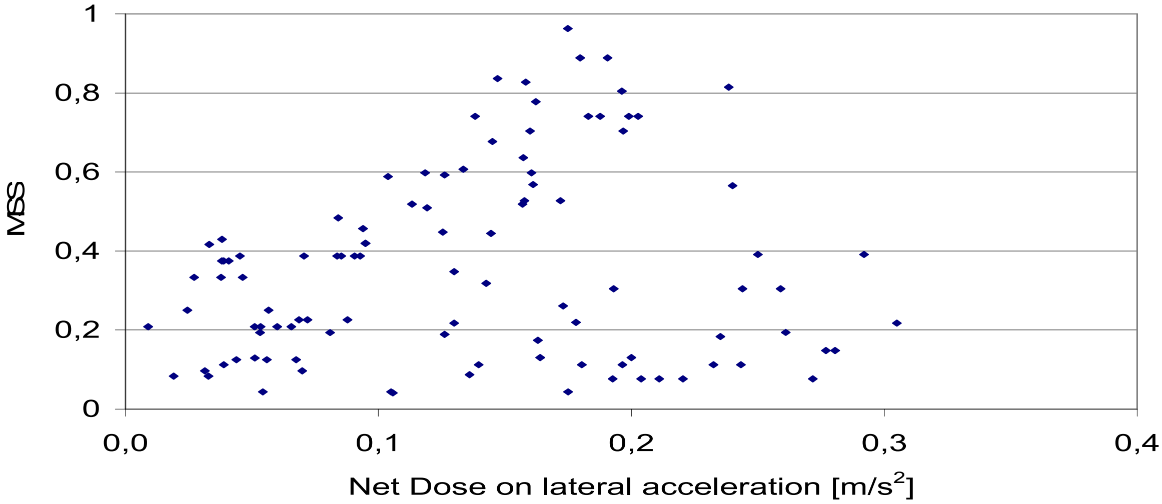


Figure D-9: ***MSS as function of ND (excl. k_{ND}) on lateral acceleration, Linköping.***

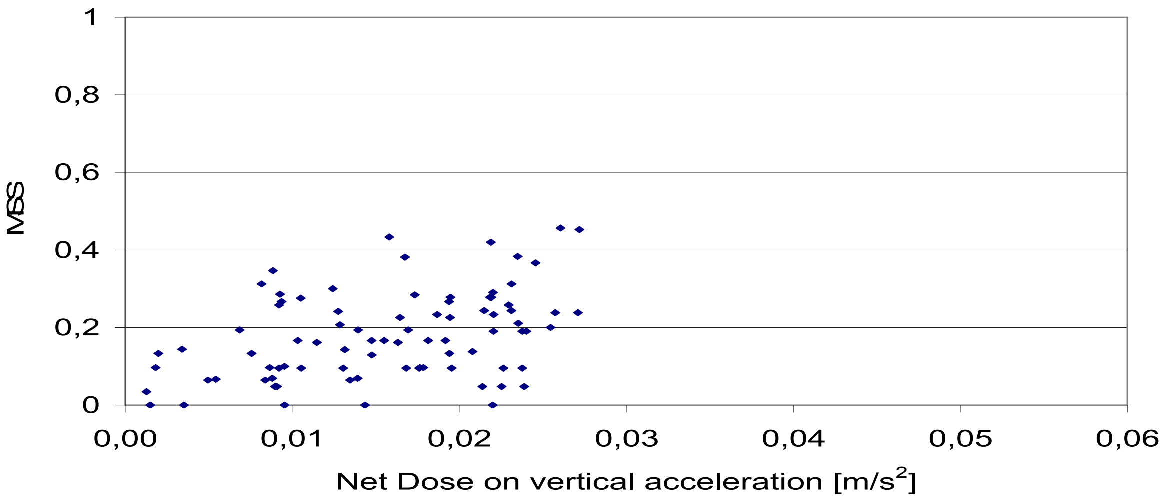


Figure D-10: ***MSS as function of ND (excl. k_{ND}) on vertical acceleration, Hamar.***

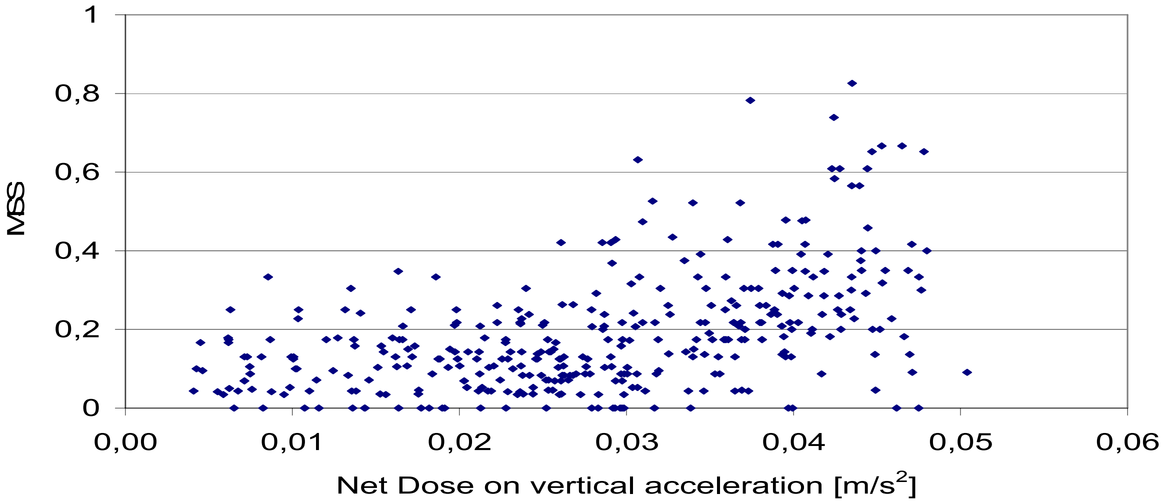


Figure D-11: ***MSS as function of ND (excl. k_{ND}) on vertical acceleration, Kristiansand.***

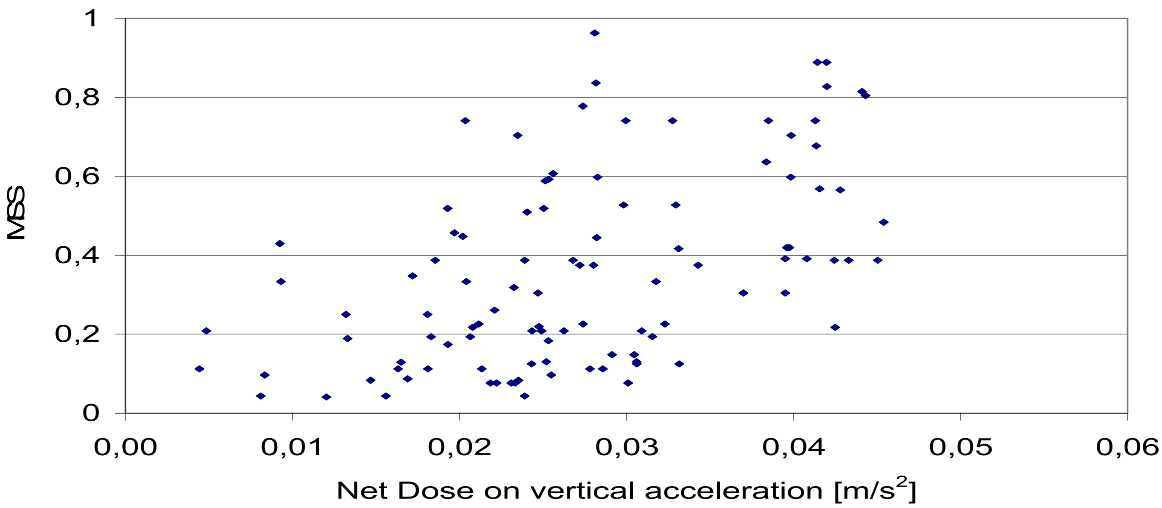


Figure D-12: ***MSS as function of ND (excl. k_{ND}) on vertical acceleration, Linköping.***

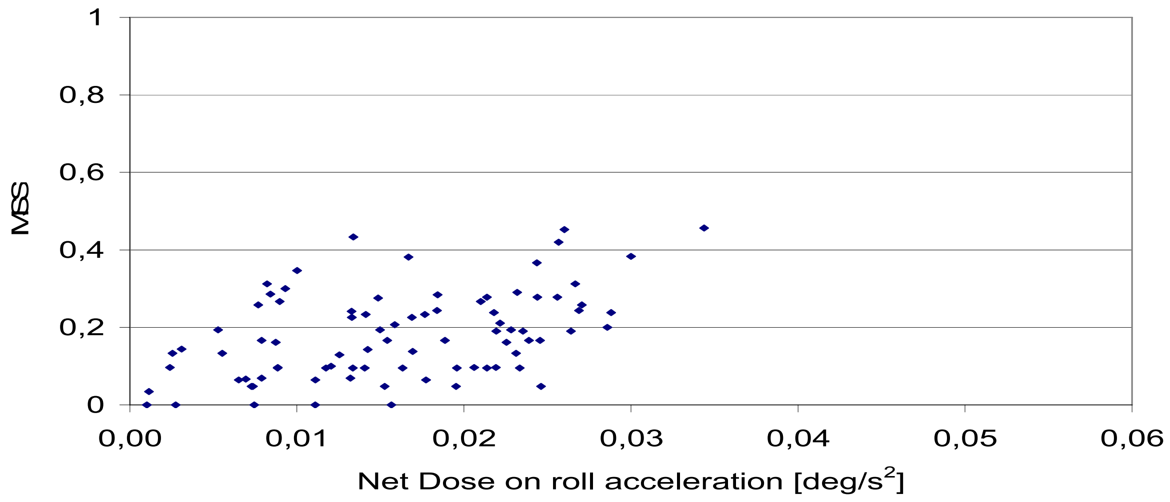


Figure D-13: ***MSS as function of ND (excl. k_{ND}) on roll acceleration, Hamar.***

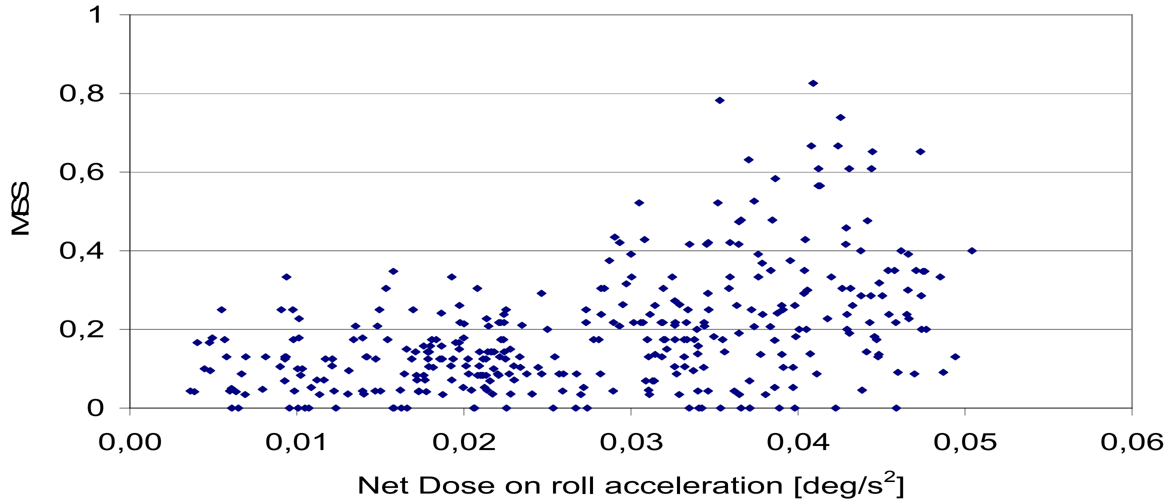


Figure D-14: ***MSS as function of ND (excl. k_{ND}) on roll acceleration, Kristiansand.***

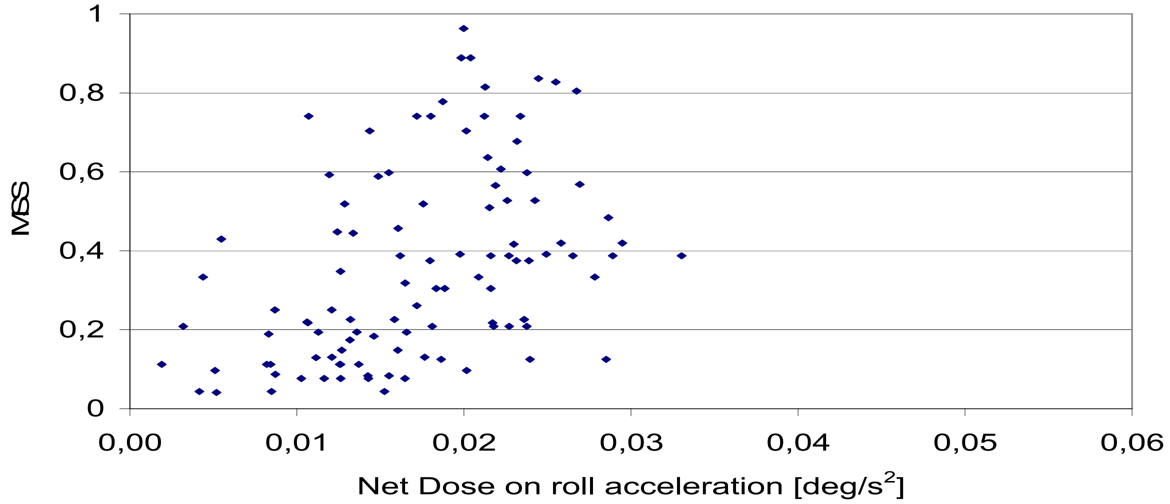


Figure D-15: ***MSS as function of ND (excl. k_{ND}) on roll acceleration, Linköping.***

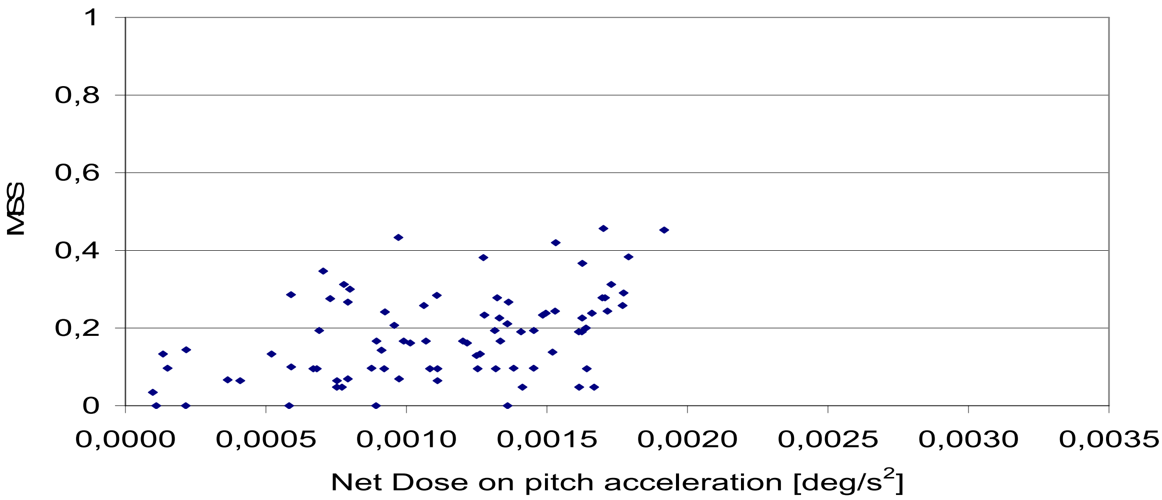


Figure D-16: MSS as function of ND (excl. k_{ND}) on pitch acceleration, Hamar.

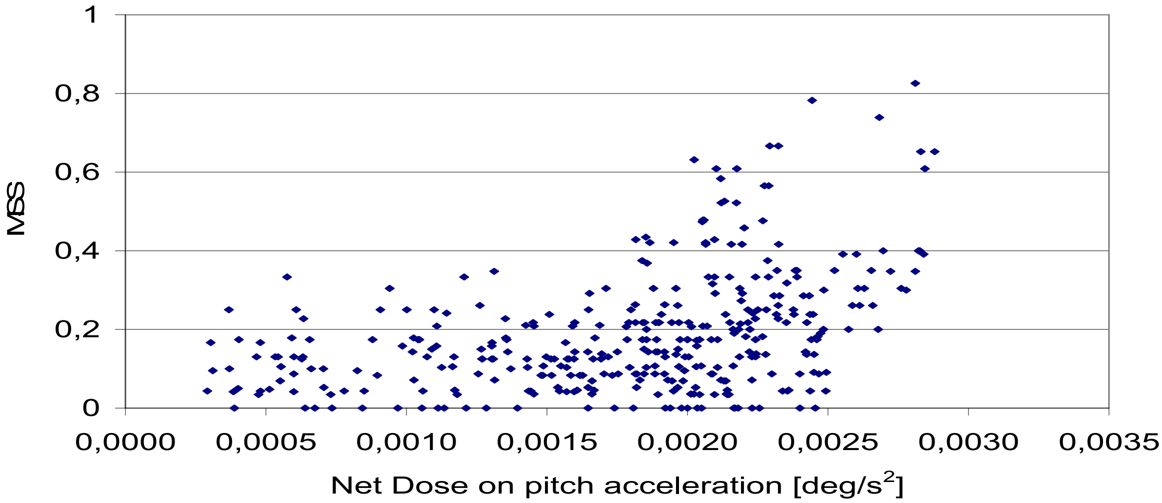


Figure D-17: MSS as function of ND (excl. k_{ND}) on pitch acceleration, Kristiansand.

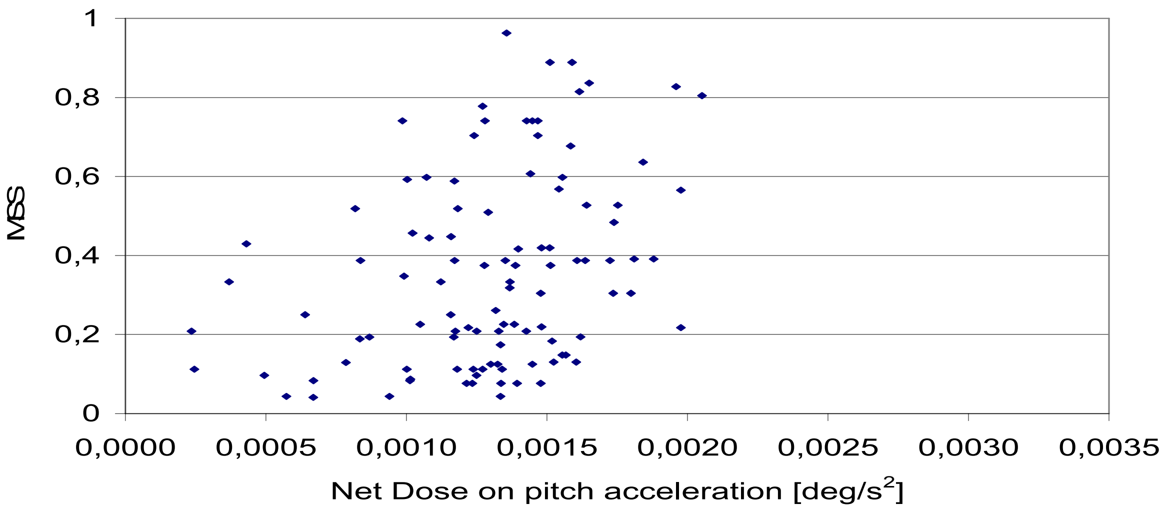


Figure D-18: MSS as function of ND (excl. k_{ND}) on pitch acceleration, Linköping.

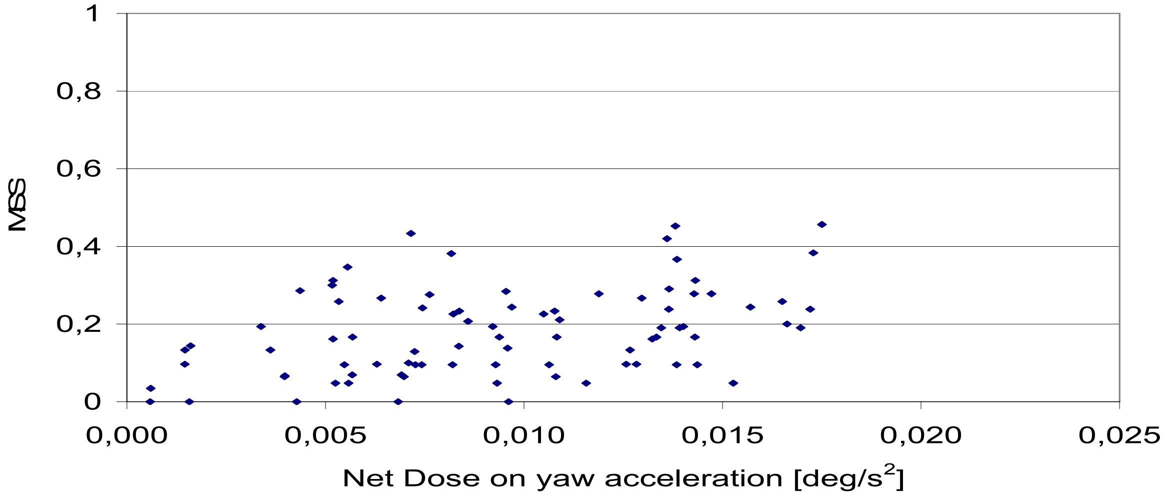


Figure D-19: ***MSS as function of ND (excl. k_{ND}) on yaw acceleration, Hamar.***

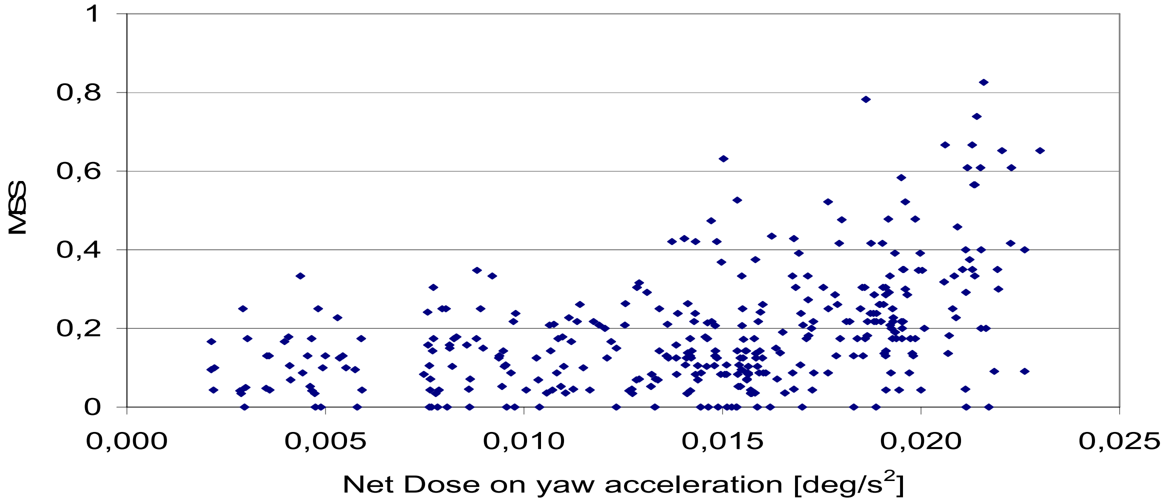


Figure D-20: ***MSS as function of ND (excl. k_{ND}) on yaw acceleration, Kristiansand.***

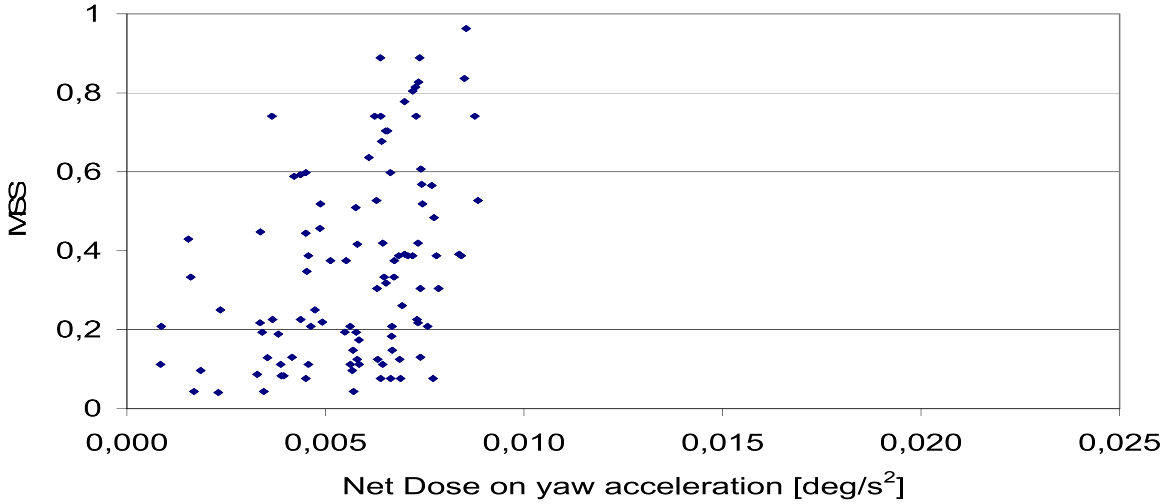


Figure D-21: ***MSS as function of ND (excl. k_{ND}) on yaw acceleration, Linköping.***