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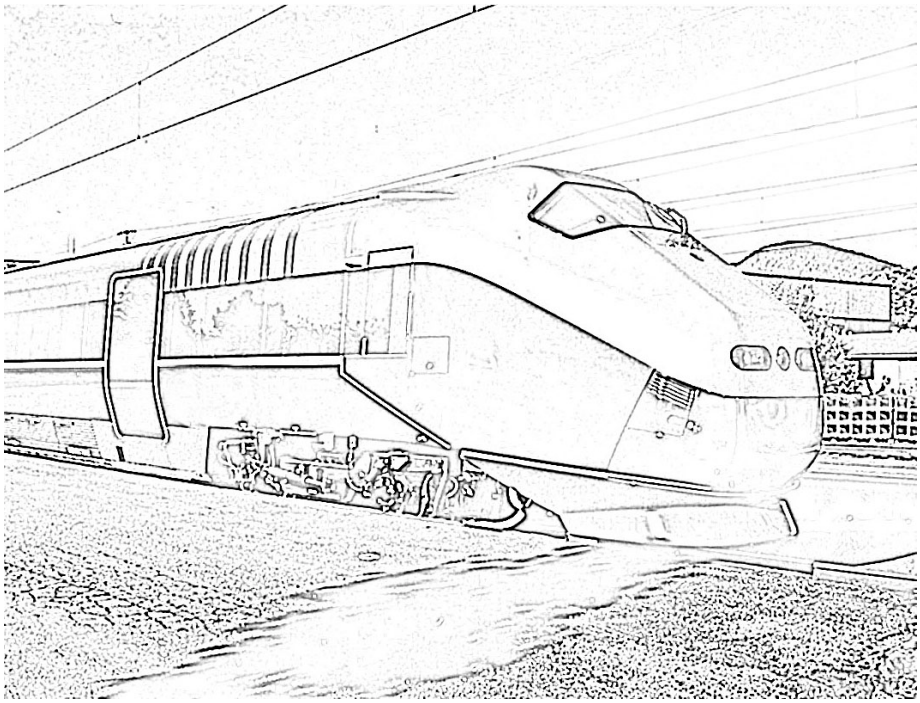
Ride comfort and motion sickness in tilting trains

Human responses to motion environments in train experiment and simulator experiments

Doctoral thesis

by

Johan Förstberg



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Johan Förstberg

Department of Vehicle Engineering
Royal Institute of Technology

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Abstract

This thesis presents a systematic study of human responses to different motions and strategies of car body tilt control regarding ride comfort, working/reading ability and motion sickness on high-speed tilting trains. Experiments with test subjects were performed in a tilting train on curved track as well as in a moving vehicle simulator. The study is multi-disciplinary, combining knowledge and methods from the fields of railway technology, human factors and vestibular science.

The main experiment in a tilting train was performed with about 75 seated test subjects, mainly students from Linköping University, making three test runs. In total, these subjects participated in about 210 individual test rides, each with a duration of about 3 hours. Additional tests on comfort disturbances with pushbutton technique have been reported in the project. The simulator experiments used a total of about 75 subjects, making some 320 test rides each of about 30 minutes duration. Test motions consisted of combinations of horizontal (lateral) acceleration and roll acceleration, together with either roll or horizontal acceleration. Rate of change of horizontal acceleration (jerk) and roll velocity were of the same order of magnitude as in a tilting train environment, but horizontal acceleration alone was about half the magnitude. Horizontal and vertical vibrations from a tilting train were added to the test motions, and train seats and interior train noise were also introduced to create a "train feeling".

Test designs and methodology have been developed during the course of the experiments. The test subjects answered questionnaires, four times per test run in the train experiment and each 5 minute in the simulator experiment. The investigated variables were: estimated average ride comfort, estimated ability to work or read, and occurrence of symptoms of motion sickness (dizziness, nausea and not feeling well). Lateral and vertical accelerations together with roll motions were monitored and recorded for later evaluation.

Results from the train experiments show that the estimated average ride comfort was about 4 on a 5-degree scale, which indicates “good”. Results also show that a reduced tilt compensation of the lateral acceleration while curving together with a reduced tilt velocity of the car body reduce the provocation of motion sickness. However, a reduction in tilt compensation may produce an increased number of comfort disturbances due to lateral acceleration in the car body. Regression analysis shows that motion doses from roll acceleration may be used to predict the incidence of motion sickness.

The simulator experiments show that the primary sources of provocation of nausea and motion sickness are the motion doses from roll and lateral acceleration in the horizontal plane. The study proposes a hypothesis and a model of provocation of motion sickness. It is shown that motion sickness has a time decay, or leakage. A model for this leakage is proposed.

The determinative types of motion for provocation of nausea and motion sickness in tilting trains are identified and future tilting train and/or simulator experiments are proposed in order to further investigate their influence.

Keywords: Tilting train, Ride comfort, Motion sickness, Simulator, Experiments.

Preface

This thesis is the final part of the research project *Comfort disturbances caused by low-frequency motions in modern trains*. The *Swedish State Railways* (*SJ*) initiated the project during the autumn of 1993 in order to conduct experiments with test subjects and to study different tilt control strategies for the *SJ* tilting train *X2000* (class *X2*) aimed at reducing the number of passengers suffering from nausea. A postgraduate research project was discussed between different partners: *SJ*, *Adtranz Sweden*, the *Swedish Transport and Communications Research Board* (KFB) and *Swedish National Road and Transport Research Institute* (VTI) together with Prof. *Evert Andersson* at the *Royal Institute of Technology* (KTH). It was agreed that Prof. Andersson would act as principal supervisor of the project. In the spring of 1994, an agreement was reached on starting the project.

A steering committee was formed with representatives from all the parties involved. The successive chairmen of the committee were *Per Leander*, *Hugo von Bahr* and *Mikael Wrang* from SJ, with *Henrik Tengstrand* from Adtranz, *Nils Edström* from KFB, *Börje Thunberg,* later *Karl-Olov Hedman,* from VTI and *Evert Andersson* from KTH as delegates. To supervise the project, a reference committee was formed with *Peter Nyström*, later *Mikael Wrang,* from SJ, *Rickard Persson* from Adtranz and *Evert Anderson* from KTH. A special scientific committee for human factor and medical (vestibular) knowledge was formed with Dr *Håkan Alm* and Dr *Lena Nilsson* from VTI, Dr *Lars Ödkvist* and Dr *Torbjörn Ledin* from the University Hospital in Linköping. Later *Torbjörn Ledin* was appointed assistant supervisor.

The project started with a report from earlier tests (1992) on comfort disturbances, but soon the work came to be focused on nausea and motion sickness. Preliminary tests were carried out with a tilting train (X2) during October 1994 and the full test series was carried out in November 1994 and June 1995. Results showed that a lower tilt compensation reduced the *incidence of motion sickness symptoms (SMSI)*. These tests were followed by tests in the VTI car driving simulator, which has a moving system with both horizontal displacement and roll motion capabilities. The ordinary car cabin was replaced with a two-seated "train" cabin. This enabled different combinations of lateral and roll motion to be individually tested with regard to provoking nausea. The experiments showed that combinations of roll and horizontal acceleration increase the nausea ratings.

The results from the present project will be useful not only when designing and operating tilting trains, but also in planning new lines that combine both high speeds and tilting. They will make it possible to reduce the requirements on large curve radii set by high speed train travel (250 – 300 km/h).

As a result of the knowledge obtained, the project has attracted interest from the *Passenger Comfort Group* at *UIC* regarding improvement of train performance by permitting higher speeds on curves. The project has also provided support for *NSB BA*, *Jernbaneverket* and *Adtranz Sweden* in planning and conducting comfort and nausea tests with the new tilting express train during autumn 1999.

Publication list

In present project the following reports have been published (cf. references):

Förstberg, J. (1994). *Comfort disturbances caused by low-frequency motions in modern trains: A project description.* VTI notat 36-94.

Förstberg, J. (1994). *Comfort disturbances caused by low-frequency motions in modern trains.* VTI notat 71-94.

Förstberg, J. (1996). *Motion-related comfort levels in trains: A study on human response to different tilt control strategies for a high speed train.* Licentiate Thesis. TRITA-FKT report 1996:41. KTH: Stockholm. (Also published as VTI Särtryck 274, 1997)

Förstberg, J. (1997). *Rörelserelaterad komfortnivå på tåg: Inflytande av olika strategier för korglutningen med avseende på åkkomfort - prov utförda på snabbtåget X2000.* TRITA-FKT report 1996:17. KTH: Stockholm. (Also published as VTI Meddelande 801, 1997). (Motion-related comfort levels in trains: Influence of different strategies for car body tilt with regard to ride comfort: Experiments on the *SJ* type *X2000* high speed train; in Swedish.)

Förstberg, J., & Ledin, T. (1996). *Discomfort caused by low-frequency motions: A literature survey of hypotheses and possible causes of motion sickness.* TRITA-FKT report 1996:39. KTH: Stockholm. (Also published as VTI Meddelande 802A).

Förstberg, J. (2000). *Influence from lateral and/or roll motion on nausea and motion sickness: Experimentss in a moving vehicle simulator.* TRITA-FKT report 2000:26. KTH: Stockholm.

Förstberg, J. (2000). *Motion-related comfort levels in tilting trains: Human responses and motion environment in a train experiments (SJ X2000).* TRITA-FKT report 2000:27. KTH: Stockholm.

Major contributions to seminars and international papers are:

Förstberg, J., Andersson, E., Ödkvist, L. M., & Ledin, T. (1996). *Influence of different compensation strategies on comfort in tilting high speed trains.* Journal of Vestibular Research, suppl. (XIXth Meeting of the Bárány Society, Sydney, Australia, August 11-14, 1996)., 6(4S), p. 57.

Förstberg, J., Andersson, E., Ödkvist, L. M., & Ledin, T. (1996). *Influence of different compensation strategies on comfort in tilting high speed trains.* NES, XXIV, pp. 325-331.

Förstberg, J., Andersson, E., & Ledin, T. (1997). *Influence of different alternatives of tilt compensation in motion-related discomfort in tilting trains.* Paper presented at the UK group meeting on human response to vibration, Nuneaton (England). (Also published as VTI Särtyck 268).

Förstberg, J., Andersson, E., & Ledin, T. (1997). *Assessing influence of tilt compensation control strategies on passenger comfort levels in a high speed train.* In proceedings of Multisensory control of posture & gait. 13th International symposium, Paris, International society for posture and gait research.

Förstberg, J., Andersson, E., & Ledin, T. (1997). *Influence of different conditions of tilt compensation on motion and motion-related discomfort in high speed trains.* In L. Palkovics (Ed.), Proceeding of the 15th IAVSD Symposium held in Budapest, Hungary, August 25-29, 1997. (Vol. Vehicle Systems Dynamics Suppl. 28 (1998), pp. 729-734). Budapest (Hungary): Swets & Zeitlinger.

Förstberg, J., Andersson, E., & Ledin, T. (1997d). *Influence of different conditions of tilt compensation on motion related discomfort in tilting trains.* In proceedings of Motion sickness: Medical and human factors: International workshop, Marbella, Spain.

This presentation has later been reviewed, revised and published in

Förstberg, J., Andersson, E., & Ledin, T. (1998). Influence of different conditions for tilt compensation on symptoms of motion sickness in tilting trains. *Brain Research Bulletin, 47*(5), pp. 525-35. (Also published as VTI Särtryck 317).

Förstberg, J., Andersson, E., & Ledin, T. (1998). *The influence of roll acceleration motion dose on travel sickness: Study on a tilting train.* Paper presented at the 33rd meeting of the UK group on human response to vibration, 16th - 18th Sept. 1998, Buxton (England). (Also published as VTI Särtryck 314).

Förstberg, J., Andersson, E., & Ledin, T. (1999). Influence of different compensation strategies on comfort in tilting high speed train. *Acta AWHO, 18*(1), pp. 18-21.

Förstberg, J. (1999). *Effects from lateral and/or roll motion on nausea on test subjects: Studies in a moving vehicle simulator.* Paper presented at the 34th UK group meeting on human responses to vibration, 22 -24 Sept. 1999, held at Ford Motor Company, Dunton, (Essex, England), Dunton (England).

Förstberg, J., Andersson, E., & Ledin, T. (1999). *Influence from lateral acceleration and roll motion on nausea: A simulator study on possible causes of nausea in tilting trains.* Paper presented at the WCCR´99, RTRI: Tokyo (Japan).

Kufver, B., & Förstberg, J. (1999). *A net dose model for development of nausea.* Paper presented at the 34th UK group meeting on human responses to vibration, held at Ford Motor Company, Dunton, Essex, England, 22-24 Sept. 1999. (Also published as VTI Särtryck 330-1999)

Thesis contribution

This thesis is believed to present original research on the following aspects:

- Experiments on ride comfort and motion sickness in *tilting trains,* thereby investigating the human response to different tilt compensation strategies, such as tilt compensation ratio, limitations in roll velocity and limitations in roll acceleration.
- Development of testing and evaluation *methodologies* for above mentioned train experiments, introducing the criterion "Symptoms of Motion Sickness Incidence" (*SMSI*).
- Presentation of a possible *regression model* for *SMSI* generated by roll motions in tilting trains.
- Experiments on ride comfort and motion sickness in a *moving vehicle simulator,* intending to imitate low frequency curving motions in tilting trains, with systematic variation of different combined horizontal (lateral) and roll (tilt) motions. Additional studies were made on the time influence during exposure and after exposure together with adaptation process to the motion conditions.
- Development of testing and evaluation *methodologies* for above mentioned simulator experiments.
- Presentation of a *net dose model* for development of nausea, based on train and simulator experiments (in co-operation with Björn Kufver).
- Presentation of possible *regression models* for development of nausea (*NR*), based on horizontal and roll motions as well as test subject's self-estimated sensitivity to motion sickness.

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I thank all the test subjects who have endured the experiments. Without them, there would have been no human responses to be evaluated. Especially, I want to thank those who had the endurance to come back the next day after becoming badly nauseated on a test run.

Finally, I am most grateful for the patience and understanding shown by my wife, *Maria,* and my sons, *Björn* and *Per*. To my sister, *Karin*, for not believing in questionnaires and wishing to travel from point A to point B as fast as possible with tilt or with no tilt, this thesis may be a step forward.

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1 Introduction

"*A hypothesis which one would like to verify is the following: Under certain conditions railways are capable of competing successfully with domestic air traffic over longer, as well as shorter, distances. These conditions ought to be looked into and stated with respect to future technological prospects for both air and railway transport*" quotation of Karsberg, SJ director of R&D dept. 1964, as quoted in Flink & Hultén (1993).

Throughout the world, railway companies are searching for ways of increasing train performance, for example in terms of speed and comfort. By introducing high speed trains, they intend to win back passengers lost to competition from other transport modes (Whitelegg, Hultén, & Flink 1993). However, most countries have a significant mileage of curved track which limits speeds and thus certain measures must be taken to shorten travel times. One alternative is to construct new railways with improved horizontal alignments, i.e. large curve radii. This method may be very expensive and it is often necessary to use additional areas of valuable land.

An alternative is to use the existing tracks and make it possible to tilt the car bodies of the train inwards during curving, consequently reducing the lateral forces and lateral accelerations experienced by the passengers. A train equipped with such a car body tilt system can travel typically 20-25% faster on existing tracks, usually without reducing ride comfort (Andersson, von Bahr, & Nilstam 1995, Wagner 1998). The overall reduction in travel time may be in the order of 10 – 20% depending on the route, number of stops, horizontal alignment, track quality, etc. However, adjusting the horizontal alignment for higher speeds by tilting trains may improve speed for conventional trains as well (Kufver 1997c).

The tilting of the car body reduces the quasi-static[1] lateral acceleration and lateral forces perceived by the passengers during curving. The suspension system must, however, cope with both higher speeds and higher centrifugal forces to be able to produce a smooth ride. The tilt control system must detect curves in time and tilt the car body according to the desired values without causing any momentary discomfort. Nevertheless, even the best designed tilt system will generate low-frequency roll motions and the combined effect of roll and lateral acceleration in the horizontal plane will create low-frequency vertical accelerations. These accelerations may cause substantial discomfort, such as drowsiness, dizziness and nausea. The symptoms are typical for motion sickness and some people are highly sensitive to this phenomenon.

Different modes of transport are accompanied by different problems with motion sickness, such as car sickness and seasickness. Train travel seems to have been accompanied by very few cases of nausea in the past. An American study shows that during the 1950s and 1960s, about 0.13 % of the passengers on a night train experienced motion sickness. Tilting trains have raised this very low level of incidence of motion sickness to a level where it cannot be neglected. Although symptoms of motion sickness in tilting trains seem to be a minor problem for most passengers, they may be a problem to those prone to nausea.

[1] Quasi-static values are the mean values of accelerations and forces on circular curves (and straight track), i.e. the mean values are defined by train speed, curve radius and cant.. No dynamic effects are involved.

Scientifically, this problem has been addressed in at least two works from Japan (Ohno 1996, Ueno et al. 1986) describing the situation in the pendulum tilting trains operating in Japan. Although neither of these works proposes a solution to this particular problem, they point out low-frequency roll motions as a probable cause. They conclude that no genuine understanding of the provocation process of motion sickness exists at present.

There are other works proposing limit values for roll velocity and roll acceleration due to disturbances in ride comfort, but these were also probably positive for reducing motion sickness (Koyanagi 1985, Sussman, Pollard, Manger, & DiSario 1994, Suzuki 1996). Förstberg (1996) have reported the incidence of motion sickness symptoms for different tilt control strategies from a Swedish horizon. At the World Congress on Railway Research (WCRR´99) in Tokyo, Cléon, Quetin, Thibedore, & Griffin (1999) reported on motion sickness research and a test with a prototype tilting TGV, where very high levels of motion sickness were encountered.

The work reported in this thesis describes methods and experiments regarding human responses to motions that are more or less typical for tilting trains.

1.1 Objectives of the research project

The purpose of this research project, "*Comfort disturbances caused by low-frequency motions in modern trains",* was to describe how ride comfort is related to dynamic motion quantities and in particular the influence of low frequency motions. After establishing standards and criteria for ride comfort and motions leading to comfort disturbances and passenger dissatisfaction, it may be possible to optimise vehicle and track geometry. The optimisation is performed under the restrictions of other criteria (such as safety) imposed on the vehicle and the track.

The research project was divided into different stages with different aims and proposed activities. The aims and activities for a later stage are naturally dependent on the results of earlier stages. The objectives of these stages are listed below, see Förstberg (1994c) and Appendix B.

Stage 1.

- Establish hypotheses of causes of comfort disturbances due to low frequency motions, mainly from literature surveys.

Stage 2.

- Establish methods of description and evaluation of these disturbances.
- Establish methods of testing different hypotheses.
- Determine the influence of different vibration and motion components (such as low frequency lateral accelerations, jerks and roll motions) for comfort disturbances.
- Establish possible criteria for evaluation of comfort disturbances caused by low frequency motions.

Stage 3.

- Check the validity of comfort criteria in a high speed train environment.

Possible stage 4. This stage (if scheduled) will be greatly influenced by earlier results and experiences. Possible actions are:

- Investigate how different parameters for track and vehicle influence the comfort disturbance.
- Suggestions of various actions for improving ride comfort in order to minimise the number of comfort disturbances and passenger dissatisfaction.

Research hypotheses

The above project stages presented 1994 have been modified into three research hypotheses:

1. What types of translational and angular motions influence ride comfort and motion sickness?
2. What differences are there between the motions of a conventional (non-tilting) train and a train equipped with a car body tilt system?
3. How do different tilt control strategies influence ride comfort, working ability, comfort disturbances and symptoms of motion sickness?

A background test was presented on comfort disturbances with push-button technique with comparison with earlier studies at SJ and BRR in (Förstberg 1994a) and presented at WCRR'94 in Paris (Förstberg 1994b).

The last issue was discussed in Förstberg (1996), slighly revised as (1997a). This issue has also been presented in the following conference proceedings (Förstberg, Andersson, & Ledin 1997a, Förstberg, Andersson, & Ledin 1997b, Förstberg, Andersson, Ödkvist, & Ledin 1996a, Förstberg, Andersson, Ödkvist, & Ledin 1996b).

The second issue was discussed in Förstberg (2000b) and has been presented at the IAVSD symposium in Budapest 1997, UK Group on Human Response to Vibration at Buxton 1998 and as a reviewed paper in Brain Research Bulletin 1998 (Förstberg, Andersson, & Ledin 1997c, Förstberg, Andersson, & Ledin 1997d, Förstberg, Andersson, & Ledin 1998a, Förstberg, Andersson, & Ledin 1998b).

The first issue have been studied in the simulator experiments, see below.

Hypothesis simulator tests

The possible hypothesis for a test in a moving simulator was not explicitly expressed in the document from 1994 (Förstberg (1994c). In the course of development of the project, it become necessary to study the influence from lateral acceleration (both in the horizontal plane as well as in the cabin floor plane) and roll motion.

The first of the above research hypothesis is changed into investigations of the influence of horizontal and roll accelerations (motions) on nausea, ride comfort, ability to work/read. Formulate, if possible, a regression model for this influence.

This influence of horizontal and roll acceleration was discussed in Förstberg (2000a) and has been presented at UK Group on Human Response to Vibration at Dunton 1999 and World Congress of Railway Research in Tokyo (WCRR´99) (Förstberg 1999, Förstberg, Andersson, & Ledin 1999a). It is presented also here in this thesis together with proposed regression models.

A net dose model for prediction of motion sickness have been presented in Kufver & Förstberg (1999) at UK Group on Human Response to Vibration at Dunton. A review of hypotheses and possible causes of motion sickness, especially for tilting trains, have been presented in (Förstberg & Ledin 1996).

1.2 This thesis

Chapter 2 presents trains with car body tilt systems, specific problems and theoretical considerations. An example on difficulties when the tilt velocity is to limit is discussed.

Chapter 3 presents the concept of comfort and discusses definition of ride comfort. Different models for measuring ride (dis-)comfort are presented.

Chapter 4 presents hypotheses and models for prediction of motion sickness together with some basic on the vestibular and posture system.

Chapter 5 presents test designs and hypothesis of the project, train and simulator experiment.

Chapter 6 presents the tilting train experiments, especially the motion evaluation since the licentiate thesis. Frequency and regression analyses are presented and discussed.

Chapter 7 is the main body of this thesis. It presents the experiments conducted in the moving base simulator. It presents and discusses the influence of horizontal (lateral) and roll motion on nausea, comfort, ability to work/read, mental ability, adaptation to motion and decay (leakage) of accumulated nausea.

Chapter 8 presents the net dose model together with some experimental data.

Chapter 9 presents regression models from the simulator experiments.

Chapter 10 is the discussion and conclusion of the thesis.

2 Trains equipped with a car body tilt system

The need for UIC to publish a report on this subject was also identified, given the remarkable range of applications and commercial susses of this technology (UIC 1998).

2.1 Introduction

The idea of tilting the car body on curves to make it possible from the aspect of comfort to increase train speed and thereby shorten journey times, is not new. It was discussed in Germany as early as 1938 (UIC 1998). Experimental trains with passive tilt or active tilt were built in France in 1957 and in Germany in 1965. Later, experimental trains or single coaches with tilt systems were built and tested in Italy, Japan, Sweden, the UK, Canada and Norway. In certain countries, such as France, Germany and the UK, development was halted, in one case when the trains were just about to enter revenue-earning traffic. In other countries, such as Italy, Japan, Spain and Sweden, the development of tilt systems has continued, and revenue-earning services started in the late 1980s or early 1990s (UIC 1998).

The tilt system may be passive or active. In a passive system, the centre of rotation is above the car body point of inertia and the suspension system allows the car body to swing out on curves.

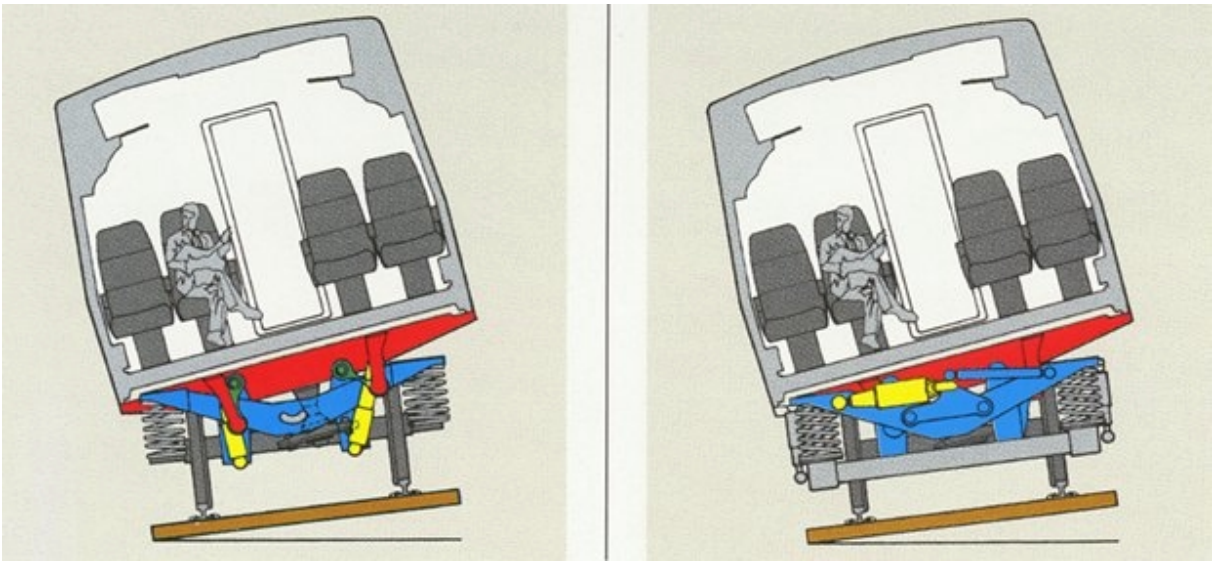


Figure 1 *Example: Fiat tilt system for RENFE "Alaris" train based on the Italian "Pendolino" concepts. The hydraulic actuator is placed above the secondary suspension and a lateral actuator is also needed to restrict the lateral motion of the car body. Source: Alaris project, Fiat[2].*

Examples of this design are the Spanish Talgo Pendular trains and certain Japanese tilting trains.

[2] Source: Alaris project at the web-site http://www.railway-technology.com/projects/alaris/index.html.

In an active tilt system, an actuator (pneumatic, electric or hydraulic) is used to force the car body to tilt. There are many ways of achieving this. The actuator may be placed above the secondary suspension (Figure 1) or between the primary and secondary suspensions (Figures 2 and 3). An example of controlled tilting using air suspension is given in Kirat (1996).

A thorough survey of available tilt systems in 1992 and possible running conditions is given in the FRA report: "High speed rail tilt train technology - a state of the art survey" (Boon, Hayes, Kesler, & Whitten 1992). There is a recent state of the art report on tilting train technology from UIC (1998) and a summary of available tilting trains in service (Barron de Angoiti 1998). Therefore, it is not necessary here to describe every design of tilt control. However, a number of important features are described for tilt control systems, in particular those exerting an influence on possible causes of discomfort and motion sickness.

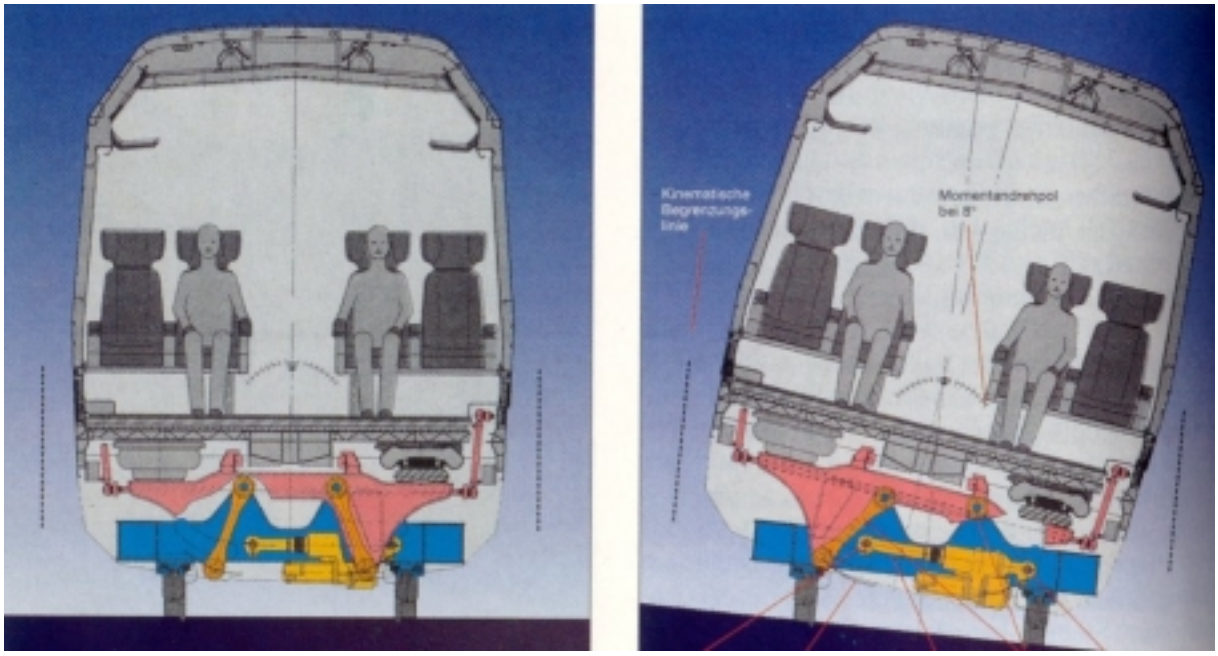


Figure 2 *Example: Adtranz tilt system for DB VT611. An electric actuator is located below the secondary suspension. Source: Adtranz Germany.*

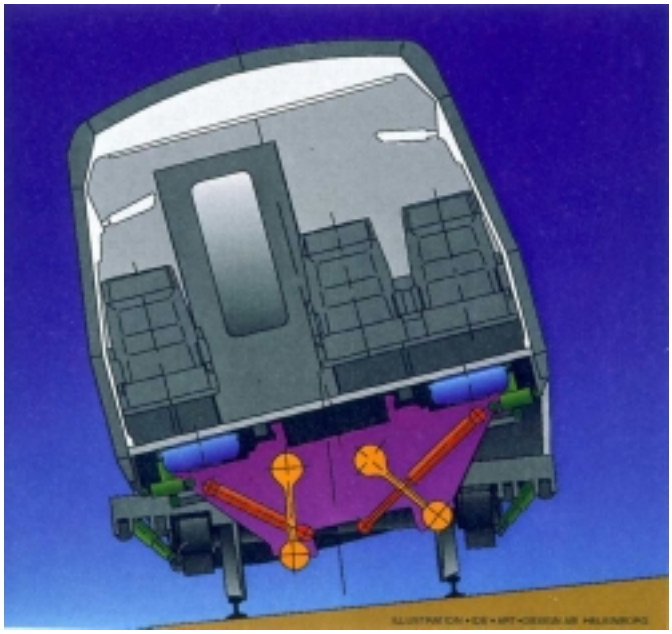


Figure 3 *Example: Adtranz Sweden tilt system for SJ X2 (X2000). Hydraulic actuators are located below the secondary suspension. Source: Adtranz Sweden.*

2.2 Requirements of a tilt control system

The tilt system has in essential to cope with the following situations, see Figure 4:

- Detection of transition curves and superelevation ramps.
- Compensation ratio for different lateral accelerations in the track plane[3] (i.e. the amount of tilt angle for a given lateral acceleration).
- Change of train speed while passing a curve.
- Dynamics due to track irregularities and the suspension system.

The first point (above) is essential for the tilt system to react in time. Two possibilities are given:

- First; detection of curves as the train moves along the track. This can be done by accelerometers mounted in the bogies with additional information from rate gyros, bogie angles, inertia system etc. Filtering of signals from sensors in order to reduce reactions on track irregularities gives time delays.
- Second; curve detection can be done from wayside beacons at or before curve entrances (Okamoto 1999) or calculation of the train position from beacons and distance travelled (Garcia, Giménez, Haberstock, Sembtner, & Dalacker 1998) or other equivalent methods.

Important design parameters are:

- Filtering of input sensor signals and the resulting time delay.
- Handling of time delays and methods to minimise them.
- Desired tilt angle for a given lateral acceleration (in the track plane); i.e. tilt compensation ratio.
- Any limitations of tilt velocity and tilt acceleration.
- Design of a control loop for tilt angle to minimise undesired dynamic behaviour and to achieve fast response.

The control loop has to be designed together with the vehicle suspension dynamics in order to minimise the interference with the tilt system. A feedback loop of the bogie tilt angle may result in that the car body rolls dynamically on the secondary suspension. For example, a state control system with estimation of non-measured states with a Kalman filter (Stribersky, Steil, Müller, & Rath 1996) or inverse dynamics (Suescun, Martín, Giménez, & Vinolas 1996) may minimise this dynamic behaviour.

[3] Measurement of lateral acceleration can be done either in the track plane or in the bogie plane.

Requirements of a tilt control system

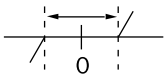
Detection of track alignment
- Problem: Late detection and filtering of signals=> time delays
- Rate gyros or other methods needed to minimise time delays
- Fixed or adaptive tilt algorithms

or

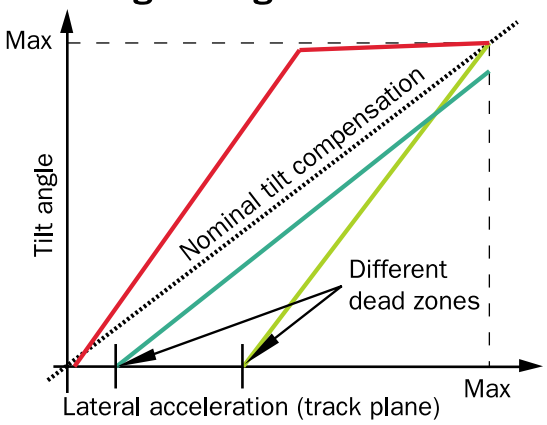
Curve geometry stored on train
- Problem: To determine the position of train
- Track-side beacons or other positional methods may be needed
- Advantages: Tilt algorithm can be optimised for each curve. No delays.

Tilt algorithm

Important aspects:
- Desired tilt angle for each lateral acceleration, (see Figure to the right)
- Tilt compensation ratio
- Limitation of tilt velocity
- Limitation of tilt acceleration
- Small or large dead zones



Alternative strategies for choosing tilt angles



Control strategy
- Feed back of actual tilt angle
- State system estimation
- Other methods

Vehicle/Track dynamics
Suspension dynamics

Perceived lateral accelerations, jerks, roll velocities, influence ride comfort/discomfort, provocation of motion sickness, etc.

Figure 4 *Possible variables and parameters in a tilt control system. A choice exists between on-train detection and stored geometry on train. There are alternative control strategies for generating tilt angles for a given lateral acceleration in the track plane. The perceived motion quantities influence comfort and provocation of motion sickness.*

2.3 Important motion quantities and definitions

Transition curves are track sections where the horizontal curve radii change and *superelevation ramps* are track sections where cant change. Normally these two sections are coincident. *Circular curves* have constant radii.

Cant (*D*) is the height difference between the two rails (outer and inner rail in a curve), normally expressed in [mm] but can also be expressed as an angle (φ_t) [rad, °].

Cant deficiency (*I*) is defined as the additional height (angle) the outer rail has to raised to achieve a lateral acceleration in car body (a_{yc}) = 0. [mm, rad, °].

Nominal acceleration in the horizontal plane during curving

In a co-ordinate system (X_H, Y_H, Z_H) parallel and perpendicular to the horizontal plane the following nominal[4] accelerations during curving can be defined:

$$a_{Y_H} = a_{yH} = \frac{v^2}{R} \quad [\mathrm{m/s^2}] \quad [2.1]$$

$$a_{Z_H} = a_{zH} = g \approx 9.81 \quad [\mathrm{m/s^2}] \quad [2.2]$$

where v is train speed [m/s] and R is curve radius [m].

Nominal acceleration in the track plane during curving

In a co-ordinate system (X_t, Y_t, Z_t) parallel and perpendicular to the track plane the following nominal accelerations during curving can be defined:

$$a_{Y_t} = a_{yt} = \frac{v^2}{R} \cdot \cos(\varphi_t) - g \cdot \sin(\varphi_t) \approx \frac{v^2}{R} - g \cdot \sin(\varphi_t) \quad [\mathrm{m/s^2}] \quad [2.3]$$

$$a_{Z_t} = a_{zt} = \frac{v^2}{R} \cdot \sin(\varphi_t) + g \cdot \cos(\varphi_t) \approx \frac{v^2}{R} \cdot \sin(\varphi_t) + g \quad [\mathrm{m/s^2}] \quad [2.4]$$

where cant angle is (φ_t) [rad], curve radius = R [m] and train speed v [m/s]

Perceived nominal lateral and vertical acceleration

In a co-ordinate system (X_c, Y_c, Z_c) parallel and perpendicular to the vehicle body (car body floor) plane, the following nominal accelerations during curving can be defined:

$$a_{Y_c} = a_{yc} = \frac{v^2}{R} \cdot \cos(\theta_c + \varphi_t) - g \cdot \sin(\theta_c + \varphi_t) \quad [\mathrm{m/s^2}] \quad [2.5]$$

$$a_{Z_c} = a_{zc} = \frac{v^2}{R} \cdot \sin(\theta_c + \varphi_t) + g \cdot \cos(\theta_c + \varphi_t) \quad [\mathrm{m/s^2}] \quad [2.6]$$

where cant angle is (φ_t) [rad], tilt angle (θ_c) [rad], curve radius = R [m] and train speed v [m/s].

Roll angle (φ) refers to the horizontal plane and *tilt angle* (θ) to the track plane.

[4] *Nominal* responses are the part of the acceleration that are caused by train speed, horizontal curve radius, cant and nominal tilt compensation. *Dynamic* responses are caused by all other inputs, e.g. track (and vehicle) irregularities, suspension characteristics, etc.

For the roll angle of the car body (φ_c):

$\varphi_c = \varphi_t + \theta_c$. [2.7]

Effective roll factor (f_r), *roll coefficient* (s): $f_r = 1 + s = \frac{a_{yc}}{a_{yt}}$ [2.8]

$f_r > 1$ if the car body rolls outwards during curving (conventional trains) and $f_r < 1$ for tilting trains.

The *tilt compensation ratio* indicates how large proportion of the lateral acceleration in the track plane is reduced and perceived by the passengers:

$k_c = 100 \cdot (1 - f_r)$, if $f_r < 1$. [%] [2.9]

See also Appendix A3 and A6 for more information and definitions.

Speed versus track geometry

Train speed and running time performance are governed by the track standards set by the track authorities in the different countries. Table 1 below gives some examples of these limits for various trains in some countries.

Table 1 Certain limits governing train speed in a number of countries.

Country	*Type of train*	*Cant D* [mm]	*Rate of change of D dD/dt* [mm/s]	*Cant deficiency I* [mm]	*Rate of change of I dI/dt* [mm/s]	*Min length of circ. curve Lc / V* [m·h/km]
Sweden[1]	Cat A	150	46	100	46	0,25
Sweden[1]	Cat B	150	56[6]	150	56	0,25
Sweden[1]	Tilting	150	70[6]	245	79	0,25
Norway[2]	Express	150	69	160	100	0
Norway[2,3]	Tilting	150	75[6]	280	140[5]	
Germany[4]	IC	160		150		
Germany[4]	Tilting	160		270		

Remark:
1) Source: (Banverket 1996), Cat A = conv. train. Cat B = conv. train with radial steering bogies.
2) Source: (Jernbaneverket 1995; Jernbaneverket 1998).
3) Draft standard.
4) Source: (Sauer, Kottenhahn et al. 1997)
5) The limit in the standard is 140 mm/s but the practical limit of tilting train is 125 mm/s.
6) The limit in the standards is set to these values but this limit is never binding, i.e. reducing the train speed.

2.4 Tilt control system

An example for a tilt control system and program called **P** is shown in Figure 5. The program calculates a new *lead* value for the tilt angle (θ_{lead}) from one or several of the following inputs (Persson 1989, Wagner 1998):

- Lateral acceleration from the leading bogie (preferably) other bogie, or/and from car body.
- Yaw rate from the curve radius.
- Roll velocity (leading bogie). This information can minimise time delays when entering a superelevation ramp.
- Difference in angle between the leading bogie and next bogie.

Restrictions on the new tilt value may be one of the following:

- Limitation of tilt velocity.
- Limitation of tilt acceleration (optional).
- Other parameters such as dead zones (optional, to minimise unnecessary tilt motion on tangent track).
- Position in train. Tilt action should be delayed according to the curve entrance of the actual car in relation to the leading car.

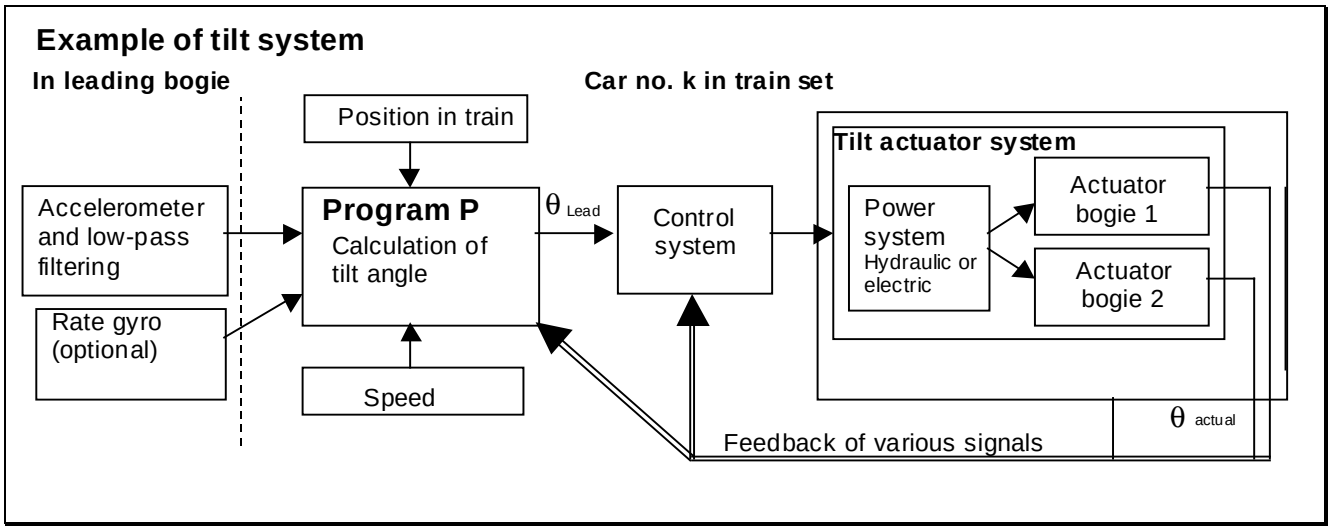


Figure 5 Example of a tilt control system P.

The control system then governs the tilt operation and tries to steer the tilt angle (tilt velocity) as close to the desired value as possible. The actuators work between the primary and secondary suspensions or between secondary suspension and car body. The actuator can normally achieve 7 – 9 ° but sway (roll) in the suspensions reduces typically this angle with 1 – 2 ° to an effective tilt angle(θ_i) of 5 – 7 °, i.e. the angle between car body floor and the track plane.

2.5 Tilt control – example of limitation of tilt velocity

An example on the effects of limitation of tilt velocity is a simulation from AEA Technology of a BR APT-train (Kent & Evans 1999). It is travelling at 200 km/h through a curve with radius R = 1200 m and with 122 m long transition curves. This transition length is the shortest which would be allowed under British design rules for a conventional train travelling at 160 km/h. This is then quite a severe test case for a tilting train running at 200 km/h. The uncompensated lateral acceleration (a_y) is about 1.6 m/s^2. Roll velocity may be important for both comfort disturbances and provocation of motion sickness.

Figure 6 displays the effects of a test case with no limitation of tilt velocity ($\dot{\theta}_c$) and two test cases with limitation of the tilt velocity to 3 °/s and 2 °/s. Total roll velocity ($\dot{\varphi}_c$) and perceived passenger lateral acceleration (a_{yc}) are shown in the figure. The total roll velocity is higher than these limitations of tilt velocity because the total roll velocity is the sum of both tilt velocity and the roll velocity caused by the rate of cant ($\dot{\varphi}_t$), and any dynamic roll motion. The limitation of

the tilt velocity to 3 °/s reduces the roll velocity slightly and the lateral acceleration is likely to be acceptable for the passenger. However, a limitation of tilt velocity to 2 °/s will give a strong reduction of the roll velocity to the cost of high levels of lateral accelerations caused by contact with bump stops in suspension system.

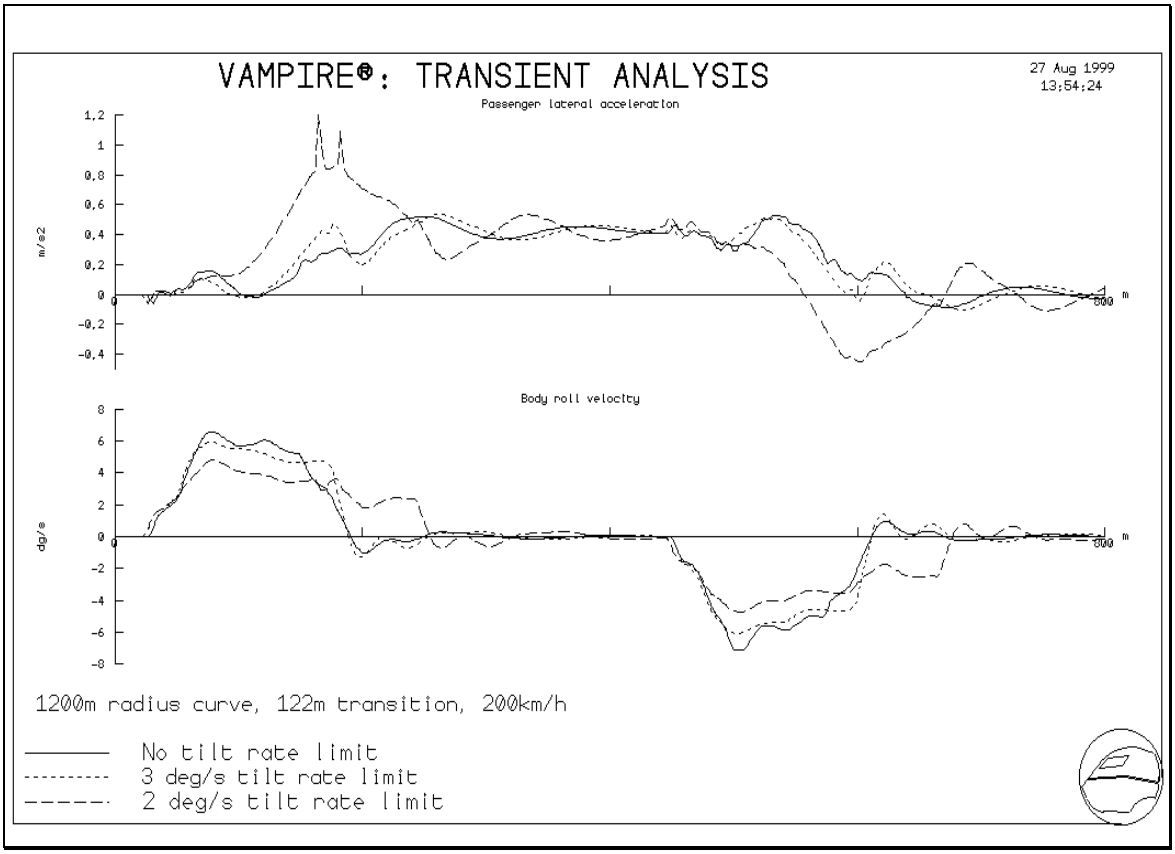


Figure 6 *Influence of limitation of tilt velocity on perceived lateral acceleration (upper part of figure) and roll velocity (lower part of the figure). (Source: Kent & Evans 1999)*

Figure 6 also displays clearly that the car body rolls dynamically on the secondary suspension. When the tilt motion starts, the inertia of the car body forces the suspension out from the equilibrium state and the suspension stores energy. In the next moment, the energy is released and the car body will have too high velocity.

Figure 6 indicates that the tilt motion, in the initial tilting phase, is compensating the lateral acceleration in the track plane with about 100% and with having very high roll velocity (6 – 7 °/s). The perceived lateral acceleration in the car body is only increasing at the end of the transition curve. The overall compensation ratio is 75% in the circular curve.

According to Kent & Evans (1999) the position of the passenger is important for the resulting lateral acceleration perceived by passengers. This is especially true with short transition curves that are generating high yaw acceleration (Kufver 1999a personal communication).

3 Ride comfort - human responses to vibration

Comfort: 1: a state of being relaxed and feeling no pain, 2: a feeling of freedom from worry or disappointment, 3: the act of consoling; giving relief in affliction (Webster's dictionary)

3.1 Comfort

"*Comfort has both psychological and physiological components, but it involves a sense of subjective well-being and the absence of discomfort, stress or pain*" (Richards 1980). However, comfort is not only defined by the absence of negative attributes. It is possible to feel a positive experience of comfort to various degrees. Comfort involves evaluation; it is felt to be good and its opposite is felt to be bad The only way to of finding whether a person is comfortable or not is ask the person in question (Richards 1980).

Comfort in transportation research is normally defined as subjective well-being, although comfort is one of the variables that may contribute to well-being, it is not a necessary part of it (Alm 1989). However, there exists many terms, such as *comfort*, *passenger comfort*, *ride quality*, *ride comfort*, *ride index,* that are not clearly defined and which have been used with varied and overlapping meanings. The sections below are an attempt to structure the terminology concerning comfort.

3.1.1 Ride quality

Ride quality is a person's reaction to a set of physical conditions in a vehicle environment, such as *dynamic, ambient* and *spatial* variables[5]. *Dynamic* variables consist of motions, measured as accelerations and changes (jerk) in accelerations in all three axes (lateral, longitudinal and vertical), angular motions about these axes (roll, pitch and yaw) and sudden motions, such as shocks and jolts. Normally, the axes are fixed to the vehicle body (ISO 1999). The *ambient* variables may include temperature, pressure, air quality and ventilation, as well as noise and high frequency vibrations, while the *spatial* variables may include workspace, leg room and other seating variables. Other *factors* may be convenience of the transport, frequency, etc. (Allaman & Tardiff 1982, Higginbotham 1982, Kottenhoff 1999, Richards 1980). However, many use the term *passenger comfort*, *ride comfort* or *average ride comfort* for ratings on a ride quality scale regarding the influence of dynamic variables. Normally, higher rating on a *ride quality* scale means better comfort, whereas higher rating on a *ride (dis-)comfort* scale means less comfort.

3.1.2 Ride comfort

In this thesis, *ride comfort,* or more precisely *ride discomfort,* will be used as the technical evaluation of dynamic quantities (motions of the vehicle). This is in accordance with CEN and in general with ISO (CEN 1996a, CEN 1999, ISO 1996b, ISO 1997, ISO 1999). This technical evaluation is based upon human reactions to these dynamic quantities. However, there is much argument concerning the appearance of these relations, e.g. differences in weighting curves, evaluation formu-

[5] *Ride quality* and *ride comfort* were defined in the opposite way in Förstberg (1996, 1997a) but this usage is in accordance with ISO (1997) and CEN (1996a, 1999).

las and statistical approach. Other denominations used for ride comfort are *passenger comfort* (Oborne 1976, Oborne 1978) and *ride quality*. (Richards, Jacobson, & Pepler 1980, Sussman & Wormley 1982).

The human evaluation of comfort, *ride quality*, involves not only motion quantities but also *human interaction variables*, see Figure 7. This agrees with the evaluation of ride comfort in Japan (Suzuki 1998). Human variables may be of a social or situational kind. Modifying human variables include age, gender, posture, alcohol, experience and mental activity (Griffin 1990). Psychological variables are important and can modify the severity of the human responses. Among these variables are expectation and suggestion, specific conditioning effects of past experiences, habituation effects of past experience, effects of concurrent activity and effects of concurrent emotional state (Guedry 1991a, Wendt 1948).

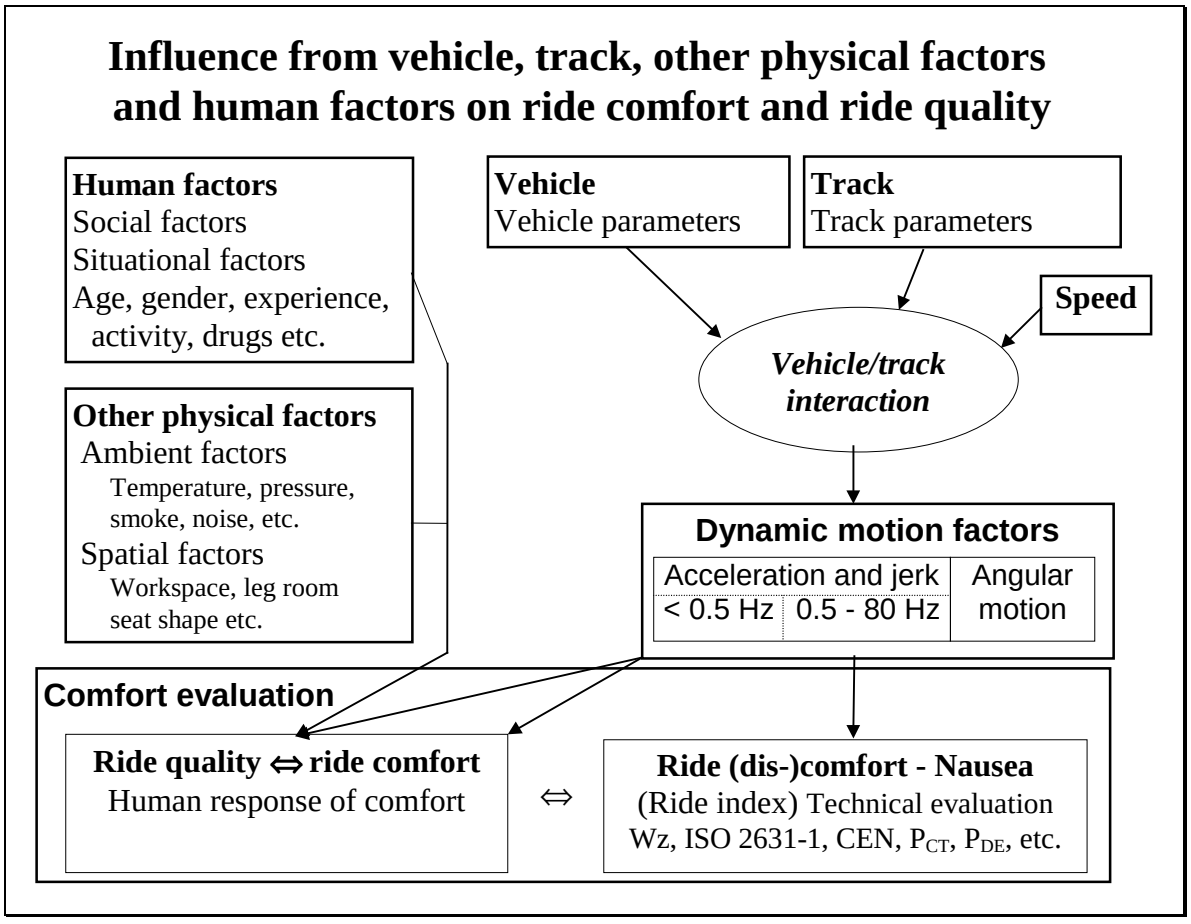


Figure 7 *Interaction in the field of ride comfort and ride quality evaluation. The human response (ride quality) involves human variables as well as dynamic motion and other physical variables, but the ride comfort response and technical evaluation of ride (dis-)comfort involves dynamic motion variables only. Modified from Förstberg (1994c, 1996).*

As mentioned before, motion quantities (physical dynamic quantities) are usually: acceleration (lateral, longitudinal and vertical) and angular motions (roll, pitch and yaw). Some of these quantities are evaluated by international standards or by company standards. Motion quantities are also influenced by the type of vehicle, suspension system, tilt system, type of track and the speed of the train. An example of analysis of vibration transfer from track to the car body is Wingren (1997). The structural flexibility of the car body can enhance the vibrations at certain frequencies and exert a negative influence on ride comfort (Carlbom 1998)

3.1.3 Ride comfort definitions

In this thesis, the following definitions and conventions apply:

Ride comfort, as human reaction to and technical evaluation of dynamic variables can be divided in different categories:

- *Average ride comfort/discomfort level (ride index)*, regarding only accelerations (longitudinal, lateral and vertical) in a frequency interval from 0.5 Hz to 80 Hz. Higher average values show a decreased level of ride comfort and increased level of discomfort. Examples for comfort/discomfort scales are: Wz (Sperling & Betzhold 1956), Ride Index, N_{MV} (CEN 1996), evaluation according to ISO 2631-1 (ISO 1997).
- *Estimated ride comfort*, The subjects rated ride comfort on a 5-point scale from 1 (*very poor ride comfort)* to 5 (*very good ride comfort*) (Förstberg 1996, 2000a, 2000b).
- *Comfort disturbances* due to motions such as high horizontal accelerations, jerks and jolts[6]:
  - The first type is a direct comfort disturbance caused by a sudden motion of the vehicle, a so-called *discrete event* (Harborough 1986b), resulting in discomfort, such as difficulties in walking, standing, reading or writing. It may have both a high and low frequency content and may be caused by passage of a turnout or some kind of irregularity in track alignment. Discrete events are also comfort disturbances caused by the combined effects of high lateral forces in circular curves and track irregularities.
  - The second type of disturbance is caused by high lateral accelerations and/or lateral jerks while negotiating transition curves (Harborough 1986b). These accelerations and jerks are results of a changing track geometry (horizontal alignment and cant) together changing tilt angle (tilting train). The resulting disturbance may also be problems with balance while standing or walking, etc. Works that have addressed the problem of balance include Abernethy, Jacobs, Plank, Stokosa, & Sussman (1980), Graaf de, Bles, & Bos (1997), Nashner (1971).

  Harborough (1986a) and CEN (1996) evaluated acceleration and roll velocities up to 2 Hz while in Sweden lateral acceleration is evaluated up 0.5 Hz and jerks up to 0.3 Hz (Andersson & Nilstam 1984).
- *Motion sickness* due to prolonged low-frequency translational (< 0.5 Hz) and/or angular motions.
  - This third type of discomfort results in dizziness, headache or nausea after a shorter or longer period of travel, i.e. motion sickness. There are different terms for this indisposition depending on the provocative environment. Typical terms are seasickness, travel sickness, airsickness, etc. Common scientific terms are *motion sickness* and *kinetosis*. This subject is addressed in Chapter 4.

Another problem is the effects of vertical vibrations (0.5 – 10 Hz) on writing and drinking for passengers. This has been described by Corbridge and Griffin (1991). It seems like 4 Hz has largest influences on spilling water while drinking and 5 – 6 Hz for writing difficulties.

[6] Jerk is the rate of change in acceleration. In a train environment, jerk is normally associated with the change of lateral acceleration on a transition curve. Jolt is a sudden motion caused by passing a turn-out or an irregularity in track alignment.

3.2 Models for ride comfort

Track geometry (alignment and cant), track irregularities, vehicle characteristics and vehicle speed generate motion quantities that are perceived by passengers. The combinations of these quantities affect the passengers' perception of ride comfort, see Figure 8.

Since the quasi-static levels or low-frequency content of lateral and vertical accelerations perceived by the passengers, as well as roll motions, are highly dependent on the track geometry and the effective roll factor[7] (f_r) of the vehicles, it is important to study both track and vehicle characteristics. For a conventional (non-tilting) vehicle, the effective roll factor (f_r) is in the range 1.2 – 1.4, generating a higher lateral acceleration in the car body than in the track plane. For a tilting train, the effective roll factor is less than unity and therefore the lateral acceleration perceived by the passengers is less than in the track plane. On the other hand, the roll motions in a tilting vehicle are greater than for a non-tilting vehicle.

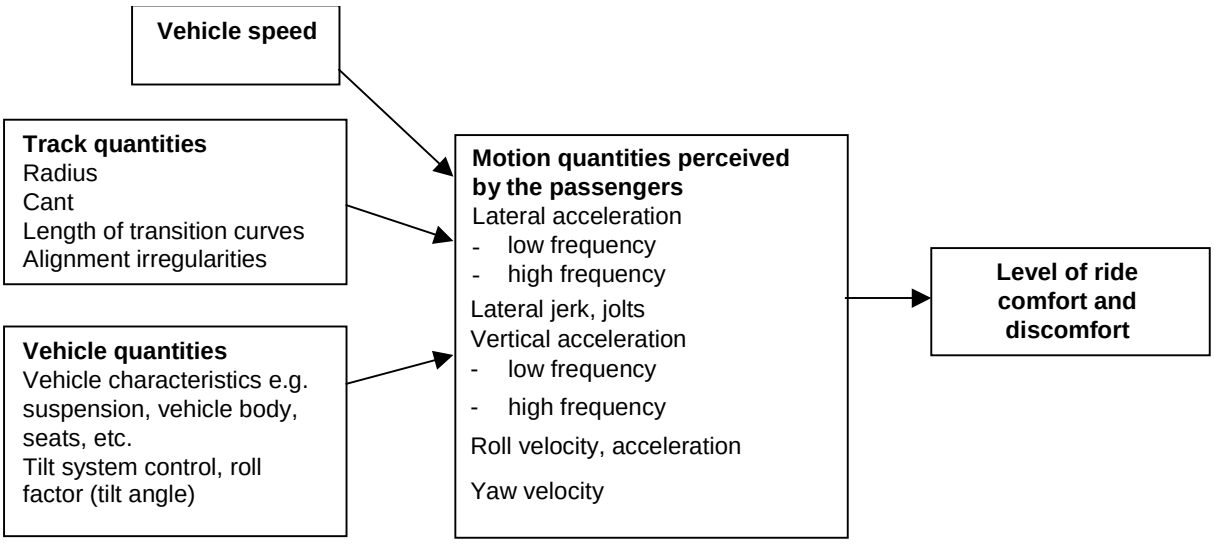


Figure 8 *Certain track and vehicle quantities and related motion quantities that have ride comfort and discomfort responses.*

3.3 Ride comfort research methodology

3.3.1 Introduction

When a test track is chosen, the track quantities radius (R), cant (D), lengths of transition curves (L_t) and circular curve (L_c) are given for each curve. These quantities together with the train speed (v) and the effective roll factor (f_r) gives the nominal (low-frequency) lateral and vertical accelerations and roll angle, and their derivatives (jerk, roll velocity), according to definitions in section 2.3. Since these track quantities are fixed, the only way to change the motion quantities is to change the train speed and change the effective roll factor (tilt compensation).
By negotiating curves at different speeds (v), the quantities I, dI/dt, and dD/dt are altered, as well as lateral acceleration in car body (a_{yc}) and jerk (da_{yc}/dt). With a tilting car the tilt compensation may be altered and therefore increase the possible variation of roll angle (φ_c) and roll velocity

[7] Effective roll factor: $f_r = a_{yc}/a_{yt}$ (= 1 + s)

($d\varphi_r/dt$). In addition, by using both conventional and tilting cars, the effective roll factor f_r may be alternated from values of 1.2 – 1.4 to values of 0.3 – 0.5.

However, by using only tilting cars, where the effective roll factor can easily be varied between different test series, physical quantities such as lateral acceleration, lateral jerk, roll angle and roll velocity can be chosen with great flexibility. At the same time, other comfort aspects, such as seats and interior standards, are held at a constant level. For example, with an effective roll factor (f_r) of 1.2 or more (tilting outwards), quite high levels of lateral acceleration may be generated at a relatively low train speed. In this case, a high level of lateral acceleration is combined with a low level of lateral jerk (a long time is spent on the transition curves) and low roll velocities. On the other hand, with $f_r \approx 0$ (100% compensation), low levels of lateral acceleration and lateral jerk are experienced but passengers will be subjected high levels of roll motion.

3.3.2 Independent variables

It is important for a multi-dimensional analysis to have physical quantities of both high and low magnitudes and that these motion quantities can be varied independently, see Table 2. However, this may sometimes be difficult to achieve in experiments.

Table 2 Examples of independent variables and possible variation.

	Low	*Medium*	*High*
Lateral acc.	x	(x)	x
Lateral jerk	x	(x)	x
Roll velocity	x	(x)	x

3.3.3 Dependent variables

Previous comfort tests have used push-button technique with two different methods of judging ride discomfort (Andersson & Nilstam 1984, Wichser and Boesch 1982; Harborough 1986; Förstberg 1994; Kufver 1997a; ERRI 1998). The push-buttons have been pushed by the subjects:

- whenever the subject felt dissatisfied with the level of comfort, or
- in accordance with a scale (five or six grades) where the test subject registers a judgement whenever the test manager gives a sign.

In the first method, the subject presses a push-button whenever the lateral (sideways) ride is considered uncomfortable compared to the subjects normal standard of comfort. The button can be pressed as long as the uncomfortable ride (continuous lateral shaking or prolonged lateral forces) is endured (Chappel 1986) or pressed twice if the ride is very uncomfortable (Förstberg 1994).

The second method uses a multi-grade scale from very comfortable to very uncomfortable. Here, the test subjects press a corresponding button or tick an appropriate response alternative. The comfort evaluation zones can be announced in beforehand by light and sound signals (ERRI 1998) or after the passage of the test zone. Normally, curves are not announced to the passengers, so the test design should reflect this.

It is obvious that these two methods will not give the same answers. The number of test subjects who pressed the button (dissatisfied) is probably not proportional to the mean value of discomfort. One clear disadvantage of the first method is the threshold level. Below a certain limit, no one will press the button and above another limit, all subjects will press the button. Hopefully, it

is the zone between these two limits that is the interesting and will be studied in the test (for further analysis of this aspect, see Kufver 1997). The disadvantage of the second method is the announcement of the evaluation zones. In normal railway operation, sharp curves, turnouts and other possibly uncomfortable sections of the track are not announced to the passengers. A combination of these two methods has yet not been tested in experiments, as far as known.

3.4 Ride comfort evaluation in railway applications

Research regarding passenger comfort, ride quality or ride comfort in railways has attracted many analytical works and has been carried out since the 1930 – 40s (Helberg & Sperling 1941, Schramm 1937, Sperling & Betzhold 1956).

Also railway companies and organisations such as UIC, former ORE and now ERRI have been carried out comfort research. Under ERRI Questions B153 and later B207, much investigations and research was undertaken for a better understanding of comfort evaluation both on tangent lines and on curves (ERRI 1989, ERRI 1993, ERRI 1998, ORE 1986, ORE 1987, ORE 1989a, ORE 1989b, ORE 1990). CEN published a draft standard based on the research of ORE/ERRI (CEN 1996a, CEN 1999)and there been some publications from the members of committee (CEN 1996a, Cléon 1986, Cléon & Lauriks 1996). Although ISO is responsible for comfort evaluation for all kinds of motion environment, not only railway vehicles, a number of specific ISO standards for railway applications have recently been published (ISO 1996a, ISO 1996b, ISO 1997, ISO 1999).

Independently from ORE and ERRI, The British Railways and Swedish Railways have undertaken research on comfort responses, in particular comfort disturbances on curves (Andersson & Nilstam 1984, Andersson et al. 1995, Chappel 1986, Harborough 1986a, Harborough 1986b). The Japanese have done extensive work on comfort and nausea for both very high speed trains and tilting trains (Koyanagi 1985, Ohno 1996, Suzuki 1996, Suzuki, Shiroto, Tanka, Tezuka, & Nakagawa 1999, Ueno et al. 1986, Urabe, Koyama, & Iwase 1966). Concerning motion sickness a fair understanding of the problem is still needed (Ohno 1996). Otherwise, motion sickness research has been carried out in the area of sea, air and space travel (AGARD 1991, Crampton 1990, Griffin 1990, Griffin 1991, Nieuwenhuijsen 1970). A standard for prediction of vomiting incidence (VI) from vertical acceleration has been accepted as the *motion sickness dose value* ($MSDV_z$) by ISO (1997).

The Americans have manly been working on the wider range of comfort issues but also on possible comfort problems in very high speed guided transport systems such as MAGLEV (Higginbotham 1982, Pepler, Sussman, & Richards 1980, Richards et al. 1980, Sussman & Wormley 1982, Sussman et al. 1994).

Safety aspects of vibration have been investigated by Griffin (1986).

A thorough investigation of methods and results for ride comfort and comfort disturbances is done in Kufver (1997a). The main interest from Kufver is vehicle reactions caused by horizontal track alignment. The main aspect, in this report, is to focus on possibilities of optimisation of the car body tilt system. It might be possible to optimise a given train on a given track (or a given track for a given train) but in order to achieve the best results the optimisation has to combine these aspects.

Table 3 shows different comfort standards applicable for different conditions on railway environments. Average comfort is measured over at least four test periods of 5 minutes each (CEN 1996). Typical time periods needed for comfort disturbances is 2 - 5 s (Harborough 1986). The time necessary to develop motion sickness (nausea) is at least 10-20 min under realistic circumstances (Förstberg 1996).

Table 3 Some international standards for evaluation of ride comfort.

	Non-tilting trains	*Tilting trains*
Average comfort	N_{MV}, N_{VA}, N_{VD}, ISO 2631, *Wz*, Ride Index.	Same as non-tilting trains
Comfort disturbances		
Straight track	P_{DE} *(discrete events)*	Same as non-tilting trains
Transition curve	P_{CT} *(curve transition)*	Same as non-tilting trains
Circular curve	P_{DE} *(discrete events)*	Same as non-tilting trains
Motion sickness (vertical)	$MSDV_Z$, (No standard available for lateral acceleration)	$MSDV_Z$, (No standard available for lateral or roll acceleration)

3.4.1 Average ride comfort/discomfort

In the past, comfort has been calculated for the dominating frequencies and the maximum amplitude for these frequencies has been multiplied with corresponding frequency weighting factors (ISO, Wz) (Förstberg 1994a, Helberg & Sperling 1941, ISO 1975, ISO 1985, ISO 1997, Kufver 1997a, Sperling & Betzhold 1956).

Modern equipment has made it possible to filter the acceleration with a weighting curve and then calculate an r.m.s.-value over a period of time (e.g. 1 min) or track length (e.g. 1 km).

$$Wz = 4.42 \cdot \left[1/T \int_0^T (a_{Bf}(t))^2 dt \right]^{0.15} \qquad [3.1]$$

where $a_{Bf}(t)$ is frequency weighted acceleration with the $B(f)$ filter, measured in [m/s^2].

$$ISO = \left[1/T \int_0^T (a_w(t))^2 dt \right]^{0.5} \qquad [3.2]$$

where a_w is acceleration (longitudinal, lateral or vertical), weighted with an appropriate filter w_x according to ISO-standard 2631-1 (ISO 1997), measured in [m/s^2].

The time T is either a fixed time or the time for passage over a certain distance of track (e.g. km, half a mile, etc.).

The accelerations are lateral and vertical (sometimes longitudinal) measured at the floor of the car body (Wz) and at the human body interfaces, such as seat, back rest (*ISO*). The Wz- or *ISO*-methods give figures corresponding to average ride comfort over a certain time T.

Variations and the fluctuation of the accelerations levels have been addressed in ERRI question B153. These variations have been taken into account for correctly describing the ride comfort as estimated by standing or seated passengers (ERRI 1989, ERRI 1993). Therefore the time interval

for r.m.s.-calculations has been changed from the time T to small adjacent intervals of 5 s up to a total time of 5 min. At least four blocks of five minutes duration has to be completed. A statistical analysis of the collected 240 r.m.s.-values[8], has when to be performed. The 95th percentile is selected for further calculation of comfort (CEN 1996a, Cléon 1986, Cléon & Lauriks 1996, ERRI 1989, ERRI 1993). In addition, the measurements can be made at the surfaces of interaction between the human body and the chair.

Examples for seated passengers, simplified method (MV) and full method (VA).

$$N_{MV} = 6 \cdot \sqrt{(a_{XP95}^{W_d})^2 + (a_{YP95}^{W_d})^2 + (a_{ZP95}^{W_b})^2} \qquad [3.3]$$

$$N_{VA} = 2 \cdot \sqrt{(a_{YA95}^{W_d})^2 + (a_{ZA95}^{W_b})^2} + 4 \cdot (a_{ZP95}^{W_b}) + 4 \cdot (a_{XD95}^{W_c}) \qquad [3.4]$$

where:

N	Ride comfort value (N < 1 very comfortable to N > 5 very uncomfortable)	
a	Acceleration, r.m.s – value over 5s,	[m/s^2]
w_b	Weighting filter for vertical accelerations, (ISO 2631-1 suggest w_k instead)	
w_c	Weighting filter for longitudinal accelerations (backrest seat)	
w_d	weighting filter for lateral accelerations	
X, Y, Z	Direction of measurement (longitudinal, lateral and vertical, respectively)	
P, A, D	Position of measurement (floor, seat interface, backrest interface, respectively)	
95	95th - percentile of sampled 5 s r.m.s. – values under 5 min duration of constant and representative condition. At least four 5 min units shall be evaluated.	

The proposed ISO standards 10056 and ISO 2631-4 incorporate this statistical evaluation technique as an alternative method (ISO 1996b, ISO 1999). See also Appendix D for weighting curves and definitions.

Comfort disturbances

Comfort disturbances on straight track and on circular curves (P_{DE}) may partly have the same causes (discrete events). The difference between them is that on a circular curve there is an additional quasi-static level of lateral acceleration in the car body, caused by the curvature, cant, possible car body tilt and speed. Either the mean lateral acceleration by itself, perceived by the passengers, is enough for causing the discomfort or a combination of the mean level and any fluctuating lateral acceleration may cause the discomfort. This fluctuation, caused by irregularities, turnouts etc., can be measured as peak to peak value, see Appendix D and Figure D-2.

On the transition curves, the mechanism is quite different. Here, a change of nominal lateral acceleration is planned. This change will cause jerk and roll motion. Both the jerk and roll motion may cause discomfort. Dynamic effects from suspension and tilt system may effect and enhance or diminish this discomfort (P_{CT}), see Appendix D and Figure D-1.

British Rail Research (BRR) has conducted several tests concerning comfort disturbances on *curves transitions* and on *discrete events* (Harborough 1986). Similar tests have been performed with other railway companies (SJ, SBB) (Andersson & Nilstam 1984, Förstberg 1994a, Wichser & Boesch 1982). These tests have been made with push-button technique. Each time the test subjects are encountering at disturbance experienced as "not comfortable, they pushes the button.

[8] 4 blocks with 5 min measurements: 4 blocks · 5min · 60 seconds = 1200 s. Each r.m.s.-value is taken over a time period of 5 s => 1200 / 5 = 240 values.

The recommendations from the Swedish experiments were (Andersson & Nilstam 1984):

	Limit values:	
Mean lateral acceleration (over 1 s)	0.9 - 1.0	[m/s^2]
Lateral jerk (low pass filtered 0.3 Hz)	0.4	[m/s^3]
Compensation in tilting system	65 - 70	[%]
Long-wave irregularities in horizontal alignment should be minimised.		

From the BRR test, regression models for prediction passenger dissatisfaction (P_{CT} and P_{DE}) were proposed (Harborough 1986). Example for calculation of P_{CT}:

$$P_{CT} = \text{Max}(A \cdot \ddot{y} + B \cdot \dddot{y} - C;0) + D \cdot \dot{\varphi}^E \qquad [\%] \qquad [3.5]$$

where $\ddot{y}$ is the absolute maximum lateral acceleration on the transition curve and the next 1.6 s [%g] and $\dddot{y}$ is the absolute maximal jerk measured over one second [%g/s] and $\dot{\varphi}$ is the absolute maximum roll velocity in car body[° /s], see also definition of the above quantities in Appendix D:

The constants are:	A	B	C	D	E
Standing	2.80	2.03	11.1	0.185	2.283
Seated	0.88	0.95	5.9	0.120	1.626

ERRI committee B207

The objective of ERRI committee B207 was to test the proposed CEN standard (CEN 1996a, CEN 1999) including P_{CT} and P_{DE} or suggest new formulas for calculation of ride comfort and discomfort in transition curves and circular curves. However, this objective was not reached (ERRI 1998). Therefore, it is necessary to identify the parameters influencing ride comfort and suggest relevant hypotheses for evaluation. The evaluation should be easy to perform and the parameters should be physically relevant, see Table 4.

There are still many effects and aspects on ride comfort and discomfort that need to be investigated (Kufver 1997a, Kuhlthau, Richards, & Jacobson 1980, Oborne 1976).

Table 4 *Motion quantities probably influencing ride comfort in different kinds of track element. Lateral and vertical acceleration are measured in car body.*

	Non-tilting trains	*Tilting trains*
Average comfort	Lateral acceleration Vertical acceleration Longitudinal acceleration Accelerations in seats	Same as for non-tilting trains
Comfort disturbances		
Straight track	Lateral acc (peak - peak)	Same as for non-tilting trains
Transition curve	Lateral acc (max, peak – peak) Jerk Roll velocity? Yaw velocity?	Same as for non-tilting trains Time delays in tilting system
Circular curve	Lateral acc (mean, peak – peak)	Same as for non-tilting trains
Discrete events	Lateral acc. (mean, peak – peak)	Same as for non-tilting trains
Motion sickness	Lateral acc. (<0.5 Hz) Vertical acc. (<0.5 Hz)	Lateral acc. (<0.5 Hz), Horizontal acc (< 0.5 Hz) Vertical acc. (<0.5 Hz) Roll acc. & velocity (Yaw acc. & velocity) Time delays in tilt system

4 Hypotheses of motion sickness

Motion sickness: The state of being dizzy or nauseated because of travelling in a moving vehicle (Websters dictionary)

Hippocrates (5th century BC) declared *that sailing on the sea shows that motion disorders the body*. In other words, he was aware that seasickness is caused by motion. Periodically, this knowledge was then forgotten, as quoted from (Reason 1974).

4.1 Motion sickness in vehicles and vessels

Motion sickness can be evoked in many different types of environments, both with and without motion; but what they have in common is that there is a sensation of motion, sensed through the vestibular system, the eyes or the body (Benson 1988, Förstberg & Ledin 1996, Griffin 1990, Money 1970, Ohno 1996, Reason 1974, Reason 1978). A list of different environments, activities or devices that can provoke motion sickness is shown in Table 5.

Table 5 Examples of environments, activities or devices that can cause motion sickness, according to Griffin (1990).

Boats	Camel rides
Ships	Elephant rides
Submarines	
Hydrofoils	Simulators
Hovercraft	
Swimming	Fairground rides
Aeroplanes	Cinerama
Helicopters	Inverting/distortion spectacles
Spacecraft	Microfiche readers
Cars	Rotation about an off-vertical axis
Buses	Coriolis stimulation
Trains	Low-frequency linear oscillation
Tanks	

Transportation of people has always been associated with occurrence of motion sickness in sensitive individuals. There are large differences in the percentages of people experiencing nausea or motion sickness when comparing different modes of transport, see Table 6. Note that the values in Table 6 are given in different contexts and are shown here for a brief estimation of the variation in motion sickness severity. Different values cannot simply be compared with each other.

Table 6 *Findings from different reports concerning symptoms of motion sickness fro different modes of transport. Note that sources differ in definition of categories and subjects. The values are given in different contexts and cannot simply be compared. They are shown here for a brief estimation of the variation in motion sickness severity.*

	Not feeling well	*Nausea*	*Motion sick[(i)]*	*Motion sickness experience[(ii)]*
Cars			3-4%[(1)]	36%[(2)]
Buses:				
(Britain)	23 - 28%[(2)]	10%[(2)]	1-2%[(2)]	
(Sweden)				28%[(10)]
Aircraft		< 1% [(3)]	mean <0.5%, max <8%[(1)]	9%[(2)]
Boats		21%[(4)]	7%[(4)]	26%[(2)]
	30%[(5)]		mean 7%, max 40%[(5)]	
Trains:				
Trains (USA)			0.13%[(1. 8)]	
Trains (Britain)				4%[(2)]
Trains (Sweden)				7%[(9)]
TGV Duplex	4%[(3)]	2%[(3)]		
JNR type 165		4%[(7)]	0[(7)]	
Tilting trains:				
JNR type 381		26%[(6)]	2%[(6)]	
X2000 sensitive subjects	13%[(7)]	9%[(7)]	0%[(7)]	
X2000 modified, sensitive subjects	8%[(7)]	6%[(7)]	0%[(7)]	
TGV prototype tilting train			up to 10%[(10)]	

Sources: (1) Money (1970), (2) Turner (1993, 1999a, 1999b), (3) Bromberger (1996a, 1996b), (4) Lawther and Griffin (1988b), (5) Lawther and Griffin (1988a), (6) Ueno et al (1986), (7) Förstberg (1996), (8) Kaplan (1964), (9) Kottenhoff (1994), (10) Cleón et al (1999), Gautier (1999)

Remarks: i The definition varies between different authors. In most cases, motion sick is defined as vomiting.
ii A motion sickness experience sometime in life in this type of vehicle/vessel.
TGV: Train à Grande Vitesse. French high speed train. TGV Duplex: two level high speed train
JNR: Japanese National Railways. Now named Japan Railways Group (JR)

4.2 A conceptual model of motion sickness

Figure 9 shows a model of variables possibly involved in provoking and modifying sensitivity to motion sickness. Provoking variables are mainly low-frequency linear and angular motions, which are sensed and registered by the vestibular system, vision and the proprioceptive[9] system. The signals are transmitted to the central nervous system (CNS), where they are interpreted as an awareness of motion.

Modifying variables are human and psychological variables, for instance, age, gender, expectation and suggestion (Griffin 1991, Guedry 1991b).

The posture (vestibular) systems are important for the information gained and evaluated by the Central Nerve System (CNS) in order to cope and handle different motion environments and visual backgrounds.

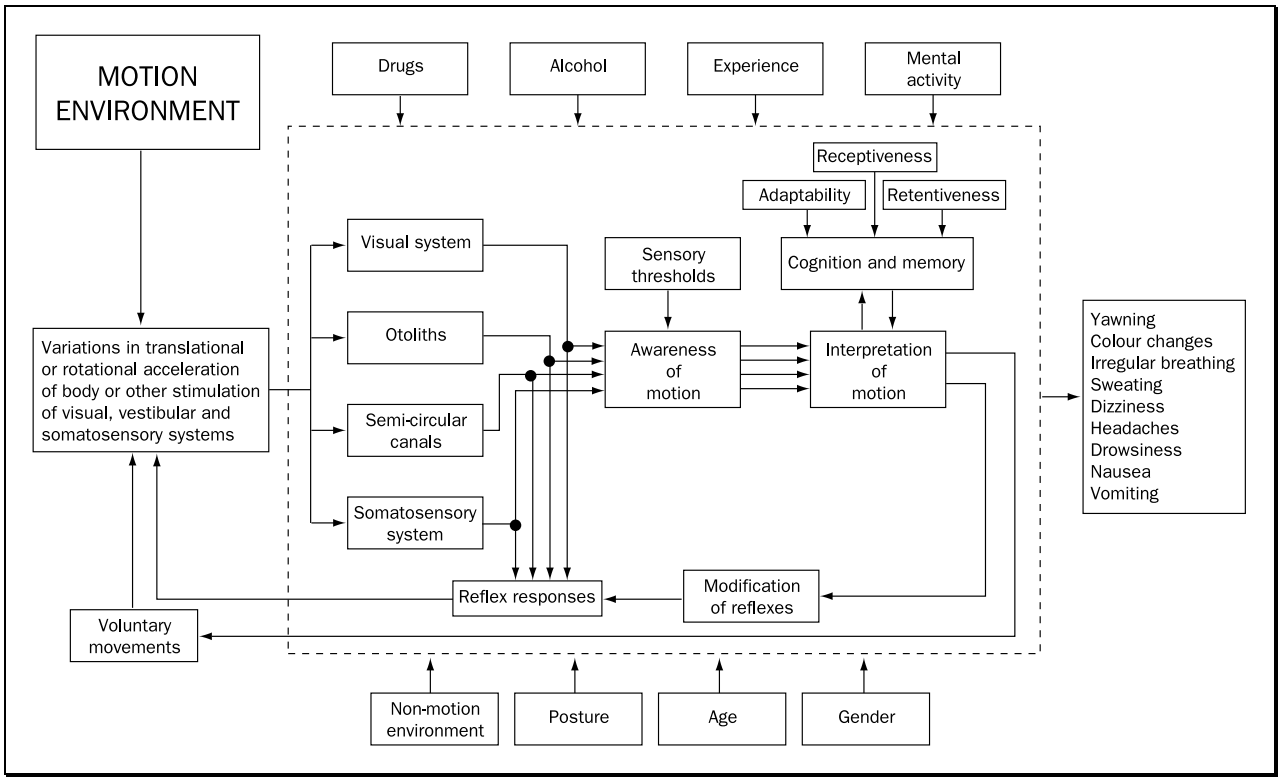


Figure 9 *A conceptual model of variables possibly causing motion sickness. From Griffin (1990).*

[9] The proprioceptive system is sometimes called the somatosensory (from the body) system or muscle sense. Proprioceptive information is superficial and consists of deep sensations from special sensory units located in the skin, muscles, tendons and joints. These sensory units record pressure, tension and muscular contraction caused by gravity and inertia (Henriksson et al. 1972, Henriksson 1974).

4.3 The posture system

Humans have the capability to control the posture and movements in relation to the surroundings. This is done by the postural information (about the posture) from:

1. *Sensory information* concerning linear and angular accelerations from the non-auditory (vestibular) part of the inner ear.
2. *Visual information* from the eyes.
3. *Proprioceptive information* from muscles and joints.

The messages from all these sensory organs are integrated by a cell network in the cerebello-brainstem area. This central processing unit supplies complete information on position and movement to the individual. Ordinarily, this integration is performed at a subconscious level. However, when a person encounters unusual or difficult circumstances, this process and the interpretation of posture information becomes a conscious phenomenon.

When we move, new postural information from the vestibular, visual, and proprioceptive systems is continuously gathered and evaluated. The posture system uses a form of feed-back from the motor output to register new signals from the sensory systems, see Figure 10.

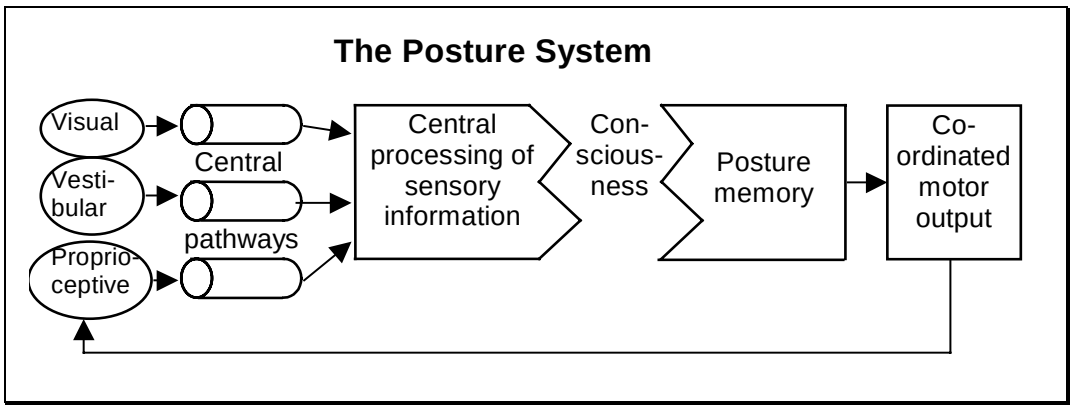


Figure 10 *The visual, vestibular and proprioceptive systems provide postural information for central integration. A disturbance of any system at any level may cause imbalance and dizziness. Modified from Henriksson et al. (1972) and Henriksson (1974).*

The three sensory systems normally create an overflow of postural information (redundant information). If one of the systems has reduced capacity or none at all, we can usually maintain our balance, but only the proprioceptive system can provide enough information for a human to maintain an upright position by himself.

The vestibular system

The vestibular system consists of the peripheral and central vestibular system.

The functions of the vestibular system are (Henriksson 1974, Henriksson et al. 1972):

- To inform the CNS about any linear or angular acceleration or deceleration.
- To aid visual orientation by eye muscle control, the so-called vestibulo-ocular reflex (VOR).
- To control skeletal muscular tonus for maintenance of adequate posture.

The *peripheral vestibular system* consists of the *otolithic organs* and the *semicircular canals*. They are found in the inner ear together with the *auditory* part (the *cochlea*). The *otolithic* organs (two in each inner ear) are sensitive to static and dynamic linear accelerations of normal head movements. The organs act as seismic instruments sensing accelerations with a layer of heavy crystals (*otoliths*) on top of the sensory cells.

The *semicircular canals* (three in each inner ear) are sensitive to dynamic angular accelerations about all three axes. The *semicircular canals* are filled with a fluid, which starts to rotate relatively to the skull, because of its inertia, when the head is under angular acceleration. The sensing organ, *cupula*, acts like a door, which by its opening angle measures the flow in the semicircular canals. Because of this construction, the response is proportional to the angular velocity at all normal frequencies of head movements. The semicircular canals cannot detect a continued rotation after about 60 s (time constant about 15 s).

The practical upper frequency limit of the posture system, including impulses from the vestibular system in co-operation with CNS handling and reactions to muscles, can be estimated to be in the range of 5 - 10 Hz (Förstberg & Ledin 1996, Mayne 1974).

Co-operation between the vestibular organs

Information from both the *semicircular canals* and the *otolithic organs* is required in order to enable the body to uphold spatial information. Together with visual impressions and information from the proprioceptive system, a comprehensive picture of the position of the body and its movements is obtained. There is normally an agreement in the information from all these organs. The interaction between signals from the two different kinds of receptors of the vestibular organs has an everyday functional value. The function and contribution of this interaction to the origin of motion sickness is an important area of research (Guedry 1991a, Guedry 1991b).

The optimal estimator for spatial orientation

In two papers, Borah, Young, & Curry (1979, 1989) have presented an optimal estimator model for human spatial orientation. The model takes into account vision, vestibular and proprioceptive information and assumes that the processing of the spatial information of the CNS can be modelled as an optimal Kalman filter.

The model represents a naive human subject - such as a passenger - who has no advance knowledge of the stimulus to be received or of the characteristics of the vehicle. This model provides a reasonable understanding of spatial orientation and has the following properties (according to Borah et al. 1989):

- Fairly accurate perception of forward acceleration in the presence of confirming visual clues.
- Fairly accurate perception of roll and pitch orientation changes as long as sensory information is consistent.

This model, based on modern control theory, together with a model for the car body tilt system may be suitable to develop for an understanding of the spatial reference for the passengers in the train.

4.4 Hypotheses

4.4.1 Sensory conflict model

Motion sickness is a common but inconvenient, unwelcome and unpleasant side-product of travelling, motions or moving visual fields. Some people are highly susceptible but others hardly noticed any kind of symptoms. The most common hypothesis for explanation of motion sickness is the *sensory conflict hypothesis*. It can also be called *neural mismatch* or *sensory rearrangement* (Benson 1988, Reason 1978, Reason & Brand 1975). The *sensory conflict hypothesis* postulates, cf. Figure 11:

> *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 CNS* (Benson 1988).

The central idea of this explanation model is a comparator, which compares *sensed* motions and accelerations with those that the body *expects* to feel. If these signals are not in accordance, the comparator sends out a so-called *mismatch signal*. Normally, we use this mismatch signal in order to correct our motion or position rapidly. However, if this mismatch signal is strong and continuous (e.g. we are on a boat moving up and down by the waves, while the body still expects to be on the ground) two things will happen:

1. The mismatch signal will change the internal model for expected signals (as we adapt to the floating boat).
2. The mismatch signal will provoke a number of neural and hormonal signals that together will form the motion sickness syndrome (Benson 1988).

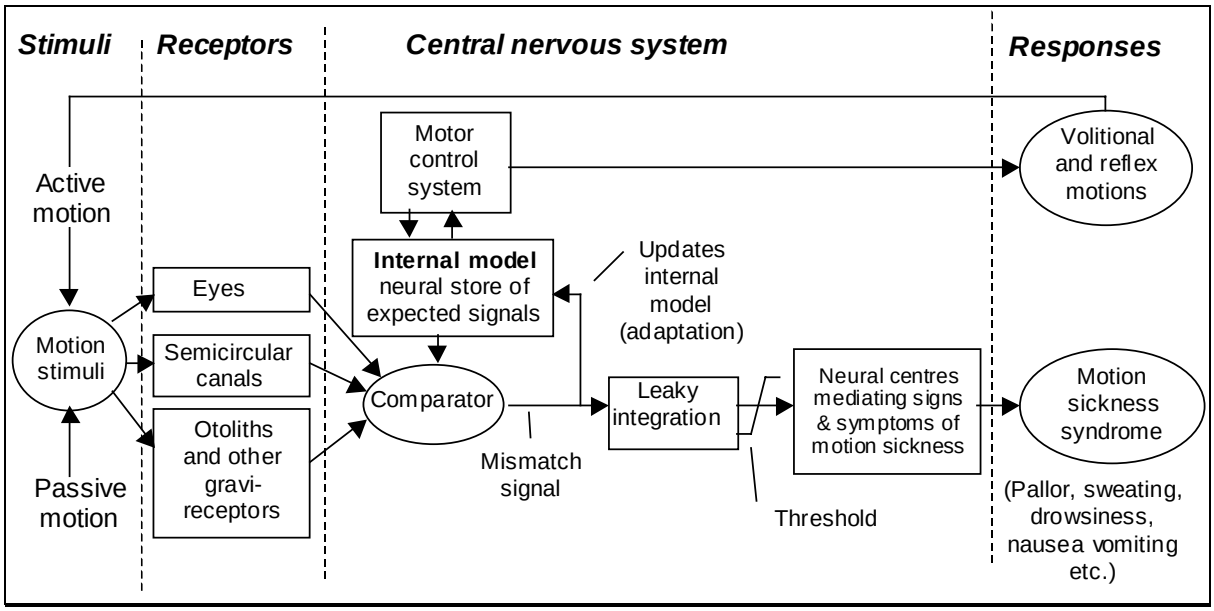


Figure 11 *Diagrammatic representation of the model of motion control, motion detection and motion sickness according to the sensory conflict hypothesis. Modified from Benson (1988).*

Recent research has advocated that the driving conflict is the difference between the *sensed* and *subjective* direction and amplitude of vertical g-vector. Bles, Bos, de Graaf, Groen, & Wertheim (1998) formulate this as:

> *All situations which provoke motion sickness are characterised by a condition in which the sensed vertical as determined on the basis of integrated information from the eyes, the vestibular system and the nonvestibular proprioceptors is at variance with the subjective vertical as expected from previous experience* (Bles et al 1998)

4.4.2 The evolutionary hypothesis

A hypothesis that may explain why motion sickness is characterised with dizziness, nausea and finally vomiting, is the so-called evolutionary hypothesis. According to Treisman (1977) the body maintains three spatial reference systems originating from the eyes, vestibular organs and proprioceptive system. These are continuously evaluated, compared and calibrated with one another.

> *The trigger for motion sickness consists not of the movement but from the occurrence of repeated challenges to predetermine the relations of the head-eye or head-body or both systems. This suggestion is similar to that of the sensory conflict hypothesis but differs in that the trigger seems to lie not in the conflict between the present pattern of input and past experience, but in the occurrence of a situation where two closely coupled spatial reference systems must both be consulted continuously and in parallel in order to perform a motor task (which may be the control of eye position) where irregular or unpredictable perturbations are introduced into the previously established correlation between the two systems* (Treisman 1977)

Under evolutionary pressure, every species must develop means of protecting itself from ingesting toxins. Treisman's second suggestion is that this delicate and continuously working system is an ideal warning system for early central effects of neurotoxins. Unfortunately, this system responds to certain types of motions. Money puts it quite directly by saying: *Motion sickness is possibly the purest and simplest poison response available for study, because it can be produced for study without the complicating presence of a poison.* All the signs and symptoms of motion sickness are aimed at lowering the effect of that poison, from yawning, pallor, salivation, drowsiness to the extreme reaction of emptying the stomach (Money 1991).

All these hypotheses are qualitative as they seekto explain why a situation can generate motion sickness but not to what extent. Models for prediction, of what degree adults will become nauseated or vomiting from motions, are few. Both McCauleys et al's model from 1976 and Lawther and Griffins model from 1987 restrains to only vertical acceleration (Griffin 1990, Lawther & Griffin 1987, Lawther & Griffin 1988b, McCauley, Royal, & Wylie 1976). Golding with different co-authors[10] have undertaken quite a lot of experiments regarding the nauseogenic potential of horizontal accelerations and compared with vertical accelerations. Angular motions and especially cross-coupled angular motions can be very nauseogenic. It is probably the fastest way to generate nausea in subjects (Griffin 1991, Guedry, Jr Benson, & Moore 1982, Guedry, Norman, Turnipseed, & Rupert 1990, Howarth 1999, Izu, Yanagihara, Yoneda, Hattori, & Koo 1996, McCauley et al. 1976, Wertheim, Bos, & Bles 1998). The visual field has a great impact on the provocation level of the motion. A reference to a horizontal line may be essential to reduce nausea (Rolnick & Bles 1989).

[10] (Golding, Finch, & Stott 1997, Golding & Kerguelen 1992, Golding & Markey 1996, Golding, Markey, & Stott 1995, Golding, Müller, & Gresty 1999)

4.4.3 Stott's rules

In an attempt to provide simplifying principles containing many characteristics of motion stimuli that provoke sickness, Stott (1986) suggested some general rules. These rules define some basic observations of the brain evaluation of match/mismatch situations, because in most cases in normal life, the visual scene is stable and gravity does not change in direction or intensity:

1. *Visual - vestibular interaction*: Angular motion of the head in one direction must result in angular motion of the external visual scene to the same extent in the opposite direction. A similar relationship exists for linear motion.

2. *Semicircular canal - otolith interaction*: Rotation of the head, other than in the horizontal plane, must be accompanied by an appropriate angular change in the direction of linear acceleration due to gravity.

3. *Utricle - saccule*[11] *interaction*: Any sustained linear acceleration is due to gravity, has an intensity of 1 g (9.81 m/s^2) and defines *downwards*.

For vehicles that normally have roll motions when negotiating a curve (aeroplanes, tilting trains, proposed magnetic levitation vehicles etc.) where the passengers normally have few visual clues for accompanying the roll motion, the first rule probably applies. For instance, if the passenger does not sense the roll motion and finds that the expected horizontal plane is not horizontal when looking outside the vehicle, a sensory mismatch may occur, provoking motion sickness symptoms. The opposite is a rider on a motorcycle, who has strong visual clues when making a roll motion while taking a curve.

Hypothesis based on control theory

Oman (1982, 1990) made a model based on control theory for the sensory conflict hypothesis. This model may be able to predict motion sickness but it explains in more *qualitative* terms the conflict with control theory. See Figure 12 and also explanations in Appendix C.

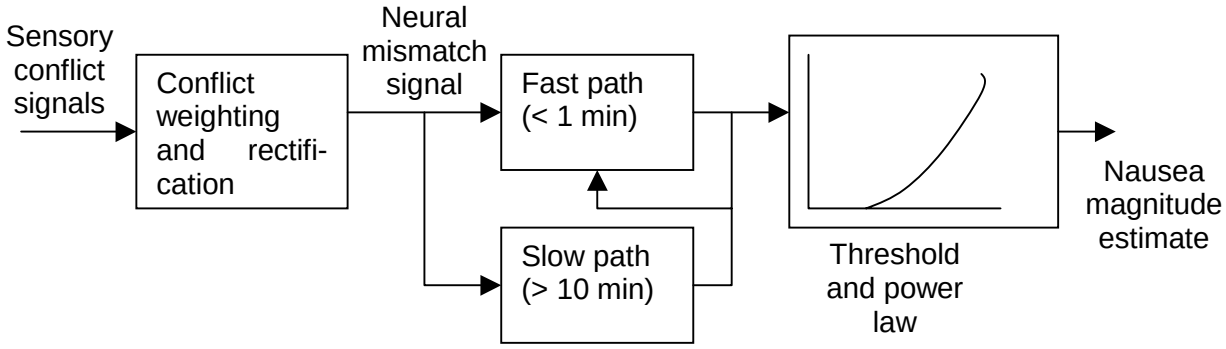


Figure 12 Oman model of nausea estimation

[11] Utricle and saccule are the names of the two otolith organs in each inner ear. The saccule measures mostly accelerations in the head's vertical axis (z) and the utricle in the head's horizontal (x, y) plane.

4.5 Models for prediction of motion sickness

An review of *quantitative* models for prediction of motion sickness and nausea shows that the model from McCauley et al (1976) and Lawther and Griffin's *motion dose model* (1987) are the most commons ones. McCauley's model is complicated and has been replaced by the concept of motion dose. The motion dose model is now an international standard for prediction of vertical accelerations (ISO 1997).

For a fixed *frequency and amplitude* the motion sickness incidence[12] (*MSI*) will increase according to:

$MSI = k \cdot \Phi(\log t)$ McCauley et al's model

where $\Phi(z)$ is the standardised normal distribution function

$MSI = k \cdot \sqrt{t}$ Lawther and Griffin's model[13]

where k is motion dependent variable and t is time. A short description of these models appears in appendix C.

Motion dose model

Motion sickness dose value ($MSDV_Z$) is the international standard for prediction of vomiting (*VI*) and illness (*IR*) for an unadapted population of adult males and females, see the box below. It is based on vertical low-frequency accelerations below 0.5 Hz. Therefore, this model is best suited for predicting motion sickness where the dominating provocations are vertical accelerations.

Motion Sickness Dose Value $MSDV_Z$ (according to ISO 2631-1:1997):

$$MSDV_z = \left[\int_0^T a_{wf}^2(t)dt \right]^{0.5} \quad [\mathrm{m/s^{1.5}}],$$

where $a_{wf}(t)$ is frequency-weighted acceleration by the w_f filter. Integration time T is between 20 min and 6 hours.

Percentage of persons who may vomit = $K_m \cdot MSDV_Z$ [%] where K_m = 1/3 for a mixed population of unadapted male and female adults.

Illness Rating (IR): (according to Griffin 1990)
0 = *I felt all right*, 1 = *I felt slightly unwell*, 2 = *I felt quite ill*, 3 = *I felt absolutely dreadful*.

IR = 1/50 * $MSDV_Z$.

[12] Vomiting incidence (*VI*) 0 – 100%.
[13] 20 min < t < 6 h, *MSI* < 70%

4.6 Symptoms of motion sickness

The most common symptoms of motion sickness are: yawning, perspiration, pallor, awareness of the stomach, headache, fatigue, dizziness and finally, if the motion is sufficiently provocative, retching or vomiting (Graybiel et al 1968, Money 1970, Money 1991, Lawther and Griffin 1989, Griffin 1990).

4.6.1 Measuring motion sickness

Graybiel et al (1968) suggested a classification scheme to investigate the severity of motion sickness. They assigned different symptom of motion sickness points from 1 to 16 depending of a certain symptom had on the severity of motions sickness. The points are accumulated to a total sum and the sum is then used to classify the degree of motion sickness severity, see Table 7 and Table 8.

Table 7 Diagnostic categorisation of different levels of the severity motion sickness, as defined by Graybiel et al. (1968).

Category	*Additional qualifying symptoms 1 point*	*Minimal 2 points*	*Minor 4 points*	*Major 8 points*	*Pathognomonic 16 points*
Nausea syndrome	Epigastric awareness	Epigastric discomfort	Nausea I	Nausea II, III	Vomiting or retching
Skin colour	Flushing	Pallor I	Pallor II	Pallor III	-
Cold sweating	-	I	II	III	-
Increased salivation	-	I	II	III	-
Drowsiness	-	I	II	III	-
Pain	Headache	-	-	-	-
Central nervous system	Dizziness: Eyes closed ≥ II, Eyes open III	-	-	-	-

Remarks: I = slight, II = moderate and III = severe or marked

Points accumulated from Table 7 above are used in Table 8 below to determine the relevant degree of motion sickness severity.

Table 8 Levels of severity of motion sickness as defined by Graybiel et al. (1968).

Points	*Level of severity*	*Sickness Category*
1 - 2	Slight Malaise	M I
3 - 4	Moderate Malaise B	M IIB
5 - 7	Moderate Malaise A	M IIA
8 - 15	Severe Malaise	M III
≥ 16	Frank sickness	S

Another interesting scale is *Illness Ratings* (*IR*), especially useful for field test surveys (Griffin 1990, Lawther & Griffin 1986, Lawther & Griffin 1987, Turner 1993). Table 9 shows both the original illness ratings, here called IR_{OLD} and the used modified scaled IR_{MOD}. The change was caused by both by wording in Swedish and the suggestion to achieve a more sensitive rating scale.

Table 9 Illness rating scales. Lawther and Griffins original scales (IR_{ORG}) and the used IR scale (IR_{MOD})

IR_{ORG}	*Well-being*	IR_{MOD}	*Well-being*
0	I felt all right	0	I feel all right
1	I felt slightly unwell	1	I do not feel quite well
2	I felt quite ill	2	I feel rather unwell
3	I felt absolutely dreadful	3	I feel bad (miserable)
-	-	4	I feel very bad (miserable)*

Remark: * IR_{MOD} = 4 was used in the train experiments but not used in the simulator experiments.

The scale, used in the train tests reported here, were first based on *Illness Ratings*. Initially the Graybiel et al's scale modified according to Turner (1993) was tried. This scale was used with different weights for different severe symptoms (yawing/light sleepiness, headache, cold sweat/pallor, increased salivation, drowsiness, dizziness, nausea). However, this did not work out very well.

Symptoms of motion sickness

Evaluation of the train test was mainly based on the symptoms of motion sickness (*SMS)*, defined as the symptoms *dizziness* and/or *nausea* and/or that the subjects *did not feel well*. The *SMSI*[14] scale is well suited for measuring low levels of illness, considering every single symptom. As a complement to *SMS* the IR_{MOD} scale was used.

However, in the simulator experiment, it was possible that every subject in a test group could have an SMS, making comparisons between different conditions difficult. Therefore, it was decided to substitute the *SMSI* scale with a scale based on rating the degree of nausea.

Nausea rating scales

Scales for rating nausea is common, since this one of the most characteristic symptoms of motion sickness. For low ratings other symptoms are used such as stomach awareness, uneasy feeling in head etc. The difficulties, with these all scales, are to find scales with equidistant intervals between the grades. Table 10 shows different used scales from different authors.

The choice was the one used by Golding et al (1997) SR_{G2} and this scale was then slightly modified, see Table 11. As complement the IR_{MOD} scale (Table 9) was used for the possibilities to make comparison between the simulator and the train tests.

[14] Symptoms of motions sickness incidence = the percentage of a group of subjects having *SMS*.

Table 10 Comparison of different scales for measuring motion sickness or nausea. For enhanced comparison, all scales start at zero.

	Grades *Used by different authors*			
Symptoms ratings	SR_{GK} (Golding & Kerguelen 1992), IR_L (Lobb 1999)	SR_{G2} *(Golding et al. 1997, Golding et al. 1999)*	N_{GM} *(Guignard & McCauley 1982)*	*MISC* (Wertheim, Wientjets, Bles, & Bos 1995)
0	No symptoms	No symptoms	No symptoms	No problems
1	Any symptoms, however slight	Initial symptoms, but no nausea		Stuffy or uneasy feeling in the head
2	Mild symptoms, e.g. stomach awareness but no nausea	Mild Nausea		or
3	Mild nausea	Moderate Nausea stop motion)		Stomach discomfort
4	Mild to moderate nausea		Severe nausea	or
5	Moderate nausea but can continue		Vomiting (emesis)	Nauseated
6	Moderate nausea and want to stop			or
7				Very nauseated
8				or
9				Retching
10				Vomiting

Remark: SR = Symptom Rating, N = Mean Nausea, MISC = Misery Scale.
Subscripts indicate authors and users of the scales.

Table 11 Used grades for nausea ratings in the simulator test (Förstberg 1999, Förstberg 2000a).

Nausea rating (NR_F)	*Grades*	*Remarks*
0	No symptoms	
1	Mild symptoms, but no nausea	
2	Mild Nausea	
3	Moderate Nausea	Subjects were told to stop here
4	Strong Nausea	Many subjects continued to here
5	(Vomiting)	

4.7 Far from a fair understanding

Kennedy and Frank (1986) point out the fact that we are far from a correct understanding of the phenomenon of motion sickness. They indicate the need of joining the different hypotheses into a uniform one. Their opinion is that a clue to the explanation of the phenomenon of motion sickness is to be able to understand the influence of varied motion stimuli on the receptor level. They believe motion sickness is a result of decorrelated sensory canals. This decorrelation could arise when the motion signals are not in phase with what the body is expecting, or because of the way the body is constructed to register and interpret motion.

Suggested reading on motion sickness is AGARD (1991), Benson (1988), Griffin (1990), Oman (1990) and Yardley (1992).

5 Test designs and hypotheses

Ride comfort, comfort disturbances from jerk and sudden motions, and motion sickness are functions of parameters dependent on human parameters as well as the motion environment inside the train. Visual impressions and audio noises add further influence to the complex situation for both the passengers and the test subjects.

Comfort - discomfort and symptoms of motion sickness are responses from subjects exposed to the conditions of the experiments. Their responses may be modified by human and physical variables. Therefore, a fairly large group of subjects is needed to minimise the influence from random variables and to make it possible to achieve statistical significance when evaluating comfort and motion sickness.

Three experiments with subjects were performed on the tilting high speed train (*X2000*) during 1994 - 95 (Förstberg 1996). Additional a comfort disturbance test on *X2000* during 1992 is reported here. The experimental hypotheses and test design for the train experiments are described in Chapter 5.1. The experiments are described in Chapter 6. The experimental hypotheses and test designs for the addition studies a moving simulator (*VTI car driving simulator*) are described in Chapter 5.2 and the experiments in Chapter 7.

5.1 Hypotheses of the train experiments

The first assumption is that low-frequency (< 0.5 Hz) motion quantities caused by track alignment, cant and cant deficiency and addition tilt motions influence nausea, motion sickness and comfort disturbances, whereas dynamic motion variables influence the average ride comfort, ability to read and work. In principle, the lower the principal frequency for the motion the more it changes the focus from ride comfort towards motion sickness and comfort disturbances. The second assumption is that both the horizontal and vertical alignment as well as track irregularities influence these motion quantities. The third assumption is that different tilt control strategies influence these motion quantities.

For example, the provocation of motion sickness can be assumed to be a function of the prolonged exposure of vertical and lateral accelerations either alone or combined with angular velocity or accelerations with frequencies probably less than 0.5 Hz. Systematic differences in dynamic motion patterns between the different cars in the train may occur and influence differences in nausea. Different railway lines with differences in number of curves per length, typical curve geometry, track quality, train speed etc. probably exert large effects on motion discomfort and nausea. Major influences also originate from the subjects' sensitivity to motion sickness, and physical and physiological variables such as well-being, tiredness, occupation (working/reading/talking) etc.

For provoking motion sickness in trains, at least the following hypotheses are possible:

- Excessive angular motions in car body tilt systems, leading to large roll angle velocities and roll angle accelerations, provoke nausea and motion sickness.
- Excessive vertical and/or lateral accelerations through the combined effects of the tilt system (if existing, cf. below) and track variables provoke nausea and motion sickness.
- The suspension system of the vehicle, including damping, may cause some frequencies to be almost non-damped and amplifies motions in these frequencies in a sensitive frequency range.
- Unfavourable interaction between translational and angular motions influence the provocation of motion sickness.

For trains equipped with car body tilt system, additional motion-related discomfort may be caused by:

- Long-wave lateral track alignment irregularities and transition curves. Higher train speeds will increase the amplitudes as well as frequencies of the motions due to these track characteristics.
- The tilt system itself (angular motions due to the tilt system), and possibly vertical and lateral motions caused by the angular motions.

Improvement in comfort and motion sickness can probably be achieved through:

- Improved control strategies or control parameters for the tilt system.
- Better track alignment and longer transition curves.
- An improved suspension system.

Of these possible improvements, the first seems the easiest way of improving ride comfort and reducing motion-related discomfort.

Research hypothesis

The following research hypothesis is used in the train experiments:

- Different tilt control strategies influence nausea and symptoms of motion sickness among the test subjects.

This hypothesis is not possible to test statistically. To be able to test a hypothesis, it must be formulated as a *null* hypothesis (H_0), i.e. an hypothesis of *no effect*. It is put forward with the expressed purpose of being rejected. If it is rejected, the *alternative* hypothesis (H_1) is then supported (Siegel & Castellan 1988).

The following null hypotheses (H_0) are used in the tilting train experiments:

- Different tilt control strategies do not influence the incidence of symptoms of motion sickness (*SMSI*)[15] among the subjects.
- Different tilt control strategies do not influence the rated ride comfort or frequency of comfort disturbances among the subjects.
- Different tilt control strategies do not influence the ability to work/read among the subjects.

[15] See Section 4.6.1 and 6.2.7 for a definition of *SMSI*.

Comfort disturbance test

The objective of the comfort disturbance test with subjects equipped with push-buttons were investigate the influence of track alignments long wave irregularities, transition curves had on comfort disturbances for seated and standing passengers. Additionally, ride comfort and nausea were recorded by the subjects.

5.2 Hypotheses of the simulator experiments

The simulator tests were based on the results from the train tests, where it was not possible to separate lateral acceleration in the horizontal plane from roll (tilt) motion. The main purpose was to study the influence of lateral accelerations (both in horizontal plane as well in the cabin) and roll motions, both individually and combined, on comfort and motion sickness (part I). The second purpose was to study the influence from limited roll velocity, roll acceleration and smoothed ends or corners both in lateral acceleration and in roll motion (part II).

The influence from other variables should be minimised, the tests used a cabin with no visual reference from the outside and with high damping of external noise. Typical train noise and vibrations were added to create a "train-like" impression from the vibrations and with actual train seats.

The lateral acceleration selected had “train-like” time dependence with a linear increase in horizontal acceleration as on a transition curve and constant horizontal acceleration as on a circular curve. During the test ride, the subjects answered different questionnaires at certain time points but otherwise they were instructed to read and work as they would do during normal train ride.

The severity of motion sickness was tested by asking the subjects how they felt (illness rating) and how severe their nausea was (nausea rating). This method of questioning implies a change from the train tests, where the subjects did not rate their severity of nausea, only their illness. A special test, the p-deletion test (p-test), was tried to determine the mental activity of the subjects. Additionally, there were questions on comfort, working/reading ability, etc.

Research hypotheses

The used hypotheses, in the simulator tests part I, were that one or several of the following motions were able to provoke different levels of nausea or influence ride comfort or discomfort differently:

- Lateral acceleration in the cabin perceived by the subjects
- Horizontal (lateral) acceleration
- Roll motion (velocity or acceleration)
- Combined influence from lateral (horizontal and/or cabin) and roll motion

The second part of the tests, part II, used horizontal motion and roll motion fixed in magnitude but with varied designs. The used test conditions were with limited roll velocity, limited roll acceleration and condition where both the horizontal and roll motion had smoothed ends or corners. Additionally a condition with no added vibrations.

The following null hypotheses (H_0) are used in the simulator experiments:

- The condition in Part I with varied amplitudes of horizontal acceleration and roll motions do not influence nausea rating (*NR*), illness ratings (*IR*), estimated ride comfort, discomfort, ability to work/read and mental activity measured with the p-deletion test

- The condition in part II (varied roll velocity, roll acceleration etc.) do not influence nausea ratings (*NR*).

5.3 Test designs

Several considerations have to be taken, when choosing test design. The first is to use the test subjects only once (*randomised design*) or use them several times (*within-subjects design, repeated measurement*) (Campbell & Stanley 1966, Keppel 1991). The advantage of a within-subjects design is the control of subject variability – that is, the individual differences. In the ideal case, all variation will reflect the different test conditions. The within-subjects design is therefore much more sensitive than complete *randomised design* using the subjects only once. However, one assumption for this is that the subjects will remain *constant* during the whole test procedure, i.e. respond the same way for the same kind of input. This can be checked by balancing the design (see section 5.3.2). The within-subjects design has been used in train tests (Förstberg 1996) and in the simulator tests. However, in the simulator test, complementary subjects have been used to get a subset with randomised design.

With the within-subjects design, there are several disadvantages. First, there is a *practice effect*, that may be controlled by *balancing* the order of appearance of the conditions. Second, there may also be *differential carry over effects*, which means that different conditions will influence the next condition differently. Third, there may be subjects that do not want to come back and thus the balanced design is not fulfilled. Finally, there may also be some *statistical* problems and a problem of *generalizability of results* (Keppel 1991).

5.3.1 Choice of test designs

The choice of the design of the experiment is to minimise the systematic and stochastic errors that might disturb the interpretation of results. It is not only a question of choosing the independent and dependent test variables but also minimising interference with human variables and other modifying variables. The independent variables of interest are the motion variables listed in Table 12.

Table 12 Independent variables of interest and their possible variation.

Independent variable	*Range*
Horizontal acceleration	low, medium, high
Lateral acceleration (cabin)	low, medium, high
Roll velocity	low, high
Roll acceleration	low, high

However, it is not always possible to vary these parameters easily and independently. It is clearly possible to vary the horizontal and/or lateral acceleration (cabin), both in the tilting train and simulator experiments.

Train experiments

Especially for the train experiments the following applies. The possible parameters of variation in the tilt control system are: degree of tilt compensation ratio, tilt velocity, and maybe tilt acceleration. Other independent variables that might influence the responses are: train speed, positions of the subjects, track geometry and track irregularities on different track sections. Some of these variables are easy to vary, but some others are not.

However, also other variables (physical or human) might influence the human responses. There may be some systematic differences for the motion patterns in each of the individual cars in the test train. For example, the leading and the rear end car may differ from the intermediate cars in the train. Human variables, which may influence the experiment, are: gender, age, sensitivity to motion sickness, former experience of symptoms of motion sickness, occupation during the ride and the status of well-being.

The responses (dependent variables), in this case are related to ride (dis-)comfort and nausea, may also influence and modify the human variables with time. See Figure 13 for a schematic graph of the relations between these different variables.

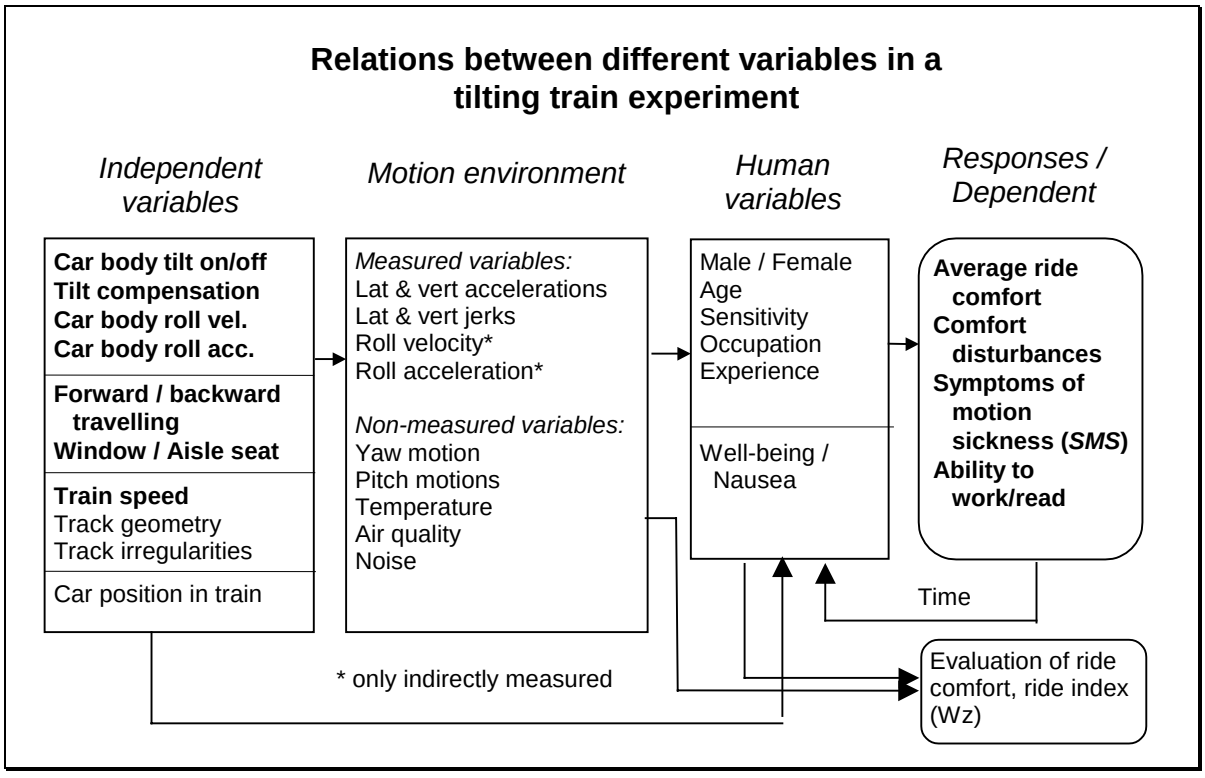


Figure 13 *Dependencies from different variables in tilting train experiment regarding responses of ride (dis-)comfort, nausea and symptoms of motion sickness, showing the independent variables, other influencing variables, motion environment and responses. Independent and dependent variables used in the experiments, are marked with bold typeface.*

The method used, in the train tests, was to sample ratings from the subjects through questionnaires completed four times per test run. The physical parameters (vertical and lateral accelerations, tilt angle, train speed etc.) of the train ride were recorded for future analysis of possible relations between train motions and ride comfort, ability to read/write, symptoms of motion sickness (*SMS*).

In the simulator tests, the response variables were collected per 5 min (nausea), per 10 min (P-test) and per 15 min (comfort and work/read ability.

It is possible to reduce the influence the human and other modifying variables and increase the statistical significance by increasing the group size, under the assumption that these variables are randomly distributed. A complementary way is to use groups of subjects, which are matched in the most dominating modifying variables. In this experiment, these are: age, gender and sensitivity to motion sickness.

5.3.2 Test design (train tests)

Another way of enhancing the significance of the experiment, is to use all groups in more than one of the conditions, i.e. a within subjects design. A so-called Latin Square[16] design ensures that influence from non-controlled variables and that carry-over effects from one condition to another are minimised (Campbell and Stanley 1966). For construction of a Latin square, e.g. see Thompson & Martinsson (1994).

In June (1995) Experiment, three groups were exposed to three conditions simultaneously during three test runs using a *balanced design*, according to the Latin Square principle in Table 13, see also Section 6.2.6.

Table 13 Balanced design of Latin Square type. A, F and G are different tilt conditions.

Test group	*Day 1 Test run 1*	*Day 2 Test run 2*	*Day 3 Test run 3*
Group 1, car 1	A	F	G
Group 2, car 2	G	A	F
Group 3, car 4	F	G	A

The size of the test groups was chosen to at least 20 subjects in these experiments, in order to achieve enough statistical power in the different tests under assumptions of certain standard deviation of the response variables (Keppel 1991).

5.3.3 Test design (simulator experiment)

Part I

The test design in part I had seven test conditions. They were chosen with increasing roll motion and increasing lateral acceleration along two axes, se Figure 14. The test conditions are numbered 1 - 7 as in the figure, see also section 7.2.5. The test condition 1 represents a condition that has no roll motion and 100 % of a defined lateral motion in the horizontal plane. Condition 7 have a 75% roll motion and no lateral motion and condition4 have 100 % motion in both lateral (horizontal) and roll. Thus, in the latter case, the perceived lateral acceleration for the subjects is zero (nominal) creating a condition with a compensation ratio of 100%.
The comparisons possible in this design is three-folded:

- Along the abscissa (Figure 14) with the same lateral acceleration (horizontal) with increasing roll motion.

[16] A Latin square is characterised by that only once in a row and once in a column a certain symbol is used (see also Appendix A). Both rows and columns can be permuted. Table 13 shows the used Latin square of order 7, where the columns have been randomly permuted. The permutation is used to prevent order effects, for example, that condition 2 always follows condition 1.

- Along the ordinate with the same roll motion but increasing horizontal motion.
- Condition with same compensation ratios, i.e. condition 3 with 5 and 4 with 7.

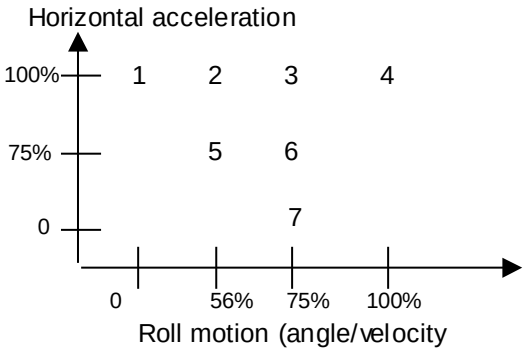


Figure 14 Test design of simulator experiment. 1 – 7 are different test conditions

Part II

Tests in part II were divided in two test series IIA and IIB with four test conditions and two conditions, respectively. Latin square of order 4 (see Table 15) was used for Part IIA. Subjects were randomly selected between the tests parts (Part IIA and Part IIB). Condition 3 used as a reference condition in part IIA and Part IIB and by that linking the test parts together.

Balanced design

The designs used in this test, had both random assignments of subjects and a repeated design, i.e. subjects taking part in one, some or in all conditions. The experiments were divided in two parts; Part I and Part II. Part I had seven conditions as in Figure 14. Part IIA had 4 conditions and Part IIB had 2 conditions.

Repeated measurements Part I and Part II

Two designs were used, one for seven conditions with a Latin square of order seven and one for four conditions with a Latin square of order four (Table 14 and Table 15). There also should be about same number of subjects in each group of seven and group of four.

Subjects only participating in four turns, they were randomly distributed into two groups: one with the conditions no. 1, 2, 3 and 4 and another with the conditions no. 3, 5, 6 and 7. They were tested according to a Latin Square of order 4, see Table 15. The condition 3 was used as a common link between these groups.

Table 14 *Latin square for seven conditions (A to F), i.e. seven turns and seven groups, with randomly permuted columns. The table shows the planned conditions for each turn.*

	Number of the test run (turn)						
Group	1	2	3	4	5	6	7
1	1	4	2	5	7	6	3
2	2	5	3	6	1	7	4
3	3	6	4	7	2	1	5
4	4	7	5	1	3	2	6
5	5	1	6	2	4	3	7
6	6	2	7	3	5	4	1
7	7	3	1	4	6	5	2

Table 15 *Example of a Latin Square of order 4.*

	Number of the test run (turn)			
Group	1	2	3	4
1	1	4	2	3
2	2	1	3	4
3	3	2	4	1
4	4	3	1	2

Random design

Test subjects, only taking part in one turn, were randomly distributed among the test conditions, as far as it was possible, but a tight schedule made this difficult.

6 Tests with tilting trains

Two different tests with tilting trains have been performed, the first concerning mainly comfort disturbances measured with push buttons during 1992 (before the actual project started but reported within the project) and the second concerning comfort and motion sickness measured by questionnaires during tests in Nov. 1994 and June 1995.

6.1 Test for comfort disturbances caused by low-frequency motions

This test has been reported in Förstberg (1994b, 1994a).

6.1.1 Objective

The objective of this test was to evaluate comfort disturbances caused by the track, especially low-wave horizontal track irregularities. It was an attempt to investigate limit values for mean lateral acceleration, mean rate of change of lateral acceleration (jerk) and roll angle velocity for comfort disturbances The tests were made on SJ tilting train (*X2000*) during 1992. This objective is similar to the earlier comfort test with the experimental tilting train X15, Andersson & Nilstam. (1984), see also Appendix D.4.

6.1.2 Methods

These tests were conducted in a similar way as the earlier tests, i.e. four test groups with five subjects in each group and two groups per day in different cars in the train. Measured signals were comfort disturbance markings from push-buttons, lateral and vertical acceleration on the floor, tilt angle from the tilt system control computer, roll angle velocity from a gyroscope and train speed.

The instruction to the test subjects was: *Press once whenever you feel strong shakings, jolts etc., which according to your standard are passing beyond the limit of good comfort. Press twice in rapid succession when you feel very strong discomfort.*

The test subjects were told to sit down or to stand during each test run, which lasted 20 - 45 minutes, see below.

Test sections

The test sections were on the main line between Stockholm and Göteborg.

Test section	Distance	Journey time	Maximum speed
Järna - Katrineholm	85 km	30 - 35 min	180 km/h
Katrineholm - Hallsberg	65 km	25 - 30 min	180 - 200 km/h
Hallsberg - Skövde	113 km	40 - 45 min	200 km/h

The test section Hallsberg - Skövde was tested twice in order to be able to see the consistency of the test subjects and to acquire more measurement data to attain better statistical significance.

These test sections were also recorded with a Mauzin track measurement car, thus obtaining track irregularity data for the possibility to make a comparison between track data and comfort disturbances.

6.1.3 Evaluation

The evaluation did not distinguish between the two cases "discrete events" and "transition curves", contrary of the test and analyses done by BRR (Harborough 1986b). It was suggested that the passengers are not aware of the cause of a specific motion, just that the motions are causing discomfort. Any suggested limit values should be imposed on the low frequency accelerations in the car body and this could later be translated to some limit values for track irregularities.

The second difference is that the BRR regression analysis had used several motion quantities at the same time, whereas SJ have suggested limits for these qualities one by one.

Still, to test some of the ideas behind the BRR approach, the peak-to-peak lateral car body acceleration ($\ddot{y}_{p\text{-}p}$) was selected as a variable (besides lateral jerk) for explaining disturbances.

Suggestions were also made to analyse the whole set of measurement data, even those parts with no recorded discomfort markings. This is contrary of the earlier evaluations. Therefore, a time window of a fixed length (2.56 s) was selected and this time window was moved sequentially along the time histories of the recorded signals. Within each time window, the recorded channels were evaluated. To reduce the influence of the mean low-frequency lateral acceleration, a 0.2 Hz high pass filter was used on the lateral accelerations. Different low-pass filters were tested and chosen to 1.5 and 0.6 Hz for lateral acceleration and to 0.6 and 0.3 Hz for lateral jerk. Filters were of type 4-pole Butterworth.

Evaluation variables

The probability of a comfort disturbance P_{disc} is defined as number of push-button markings divided by the number of test subjects, divided by 2 (2 markings were allowed) times 100.

$$P_{disc}(x) = \frac{N_{pushbutton\,marking}}{N_{subjects} \cdot 2} \cdot 100 \quad [\%] \qquad [6.2]$$

Regression

Regression analysis was performed for each motion quantity, one by one. Exponential regression lines show they fit very close to the data points up to 30 - 40 % comfort disturbances but above that the difference between estimated and actual disturbances is growing strongly. The probability of comfort disturbance is limited to 100 %, whereas the exponential regression line is not. One way to overcome this difficulty is to use logit regression. The logit regression is defined as:

$$P(x) = \frac{e^{a+b\cdot x}}{1 + e^{a+b\cdot x}} \qquad [6.1]$$

The logit regression is used for the latter part of the evaluations.

6.1.4 Results comfort disturbances

An example of result is shown in Figure 15. It shows a high agreement between the regression (logit) line and measured probability of comfort disturbances.

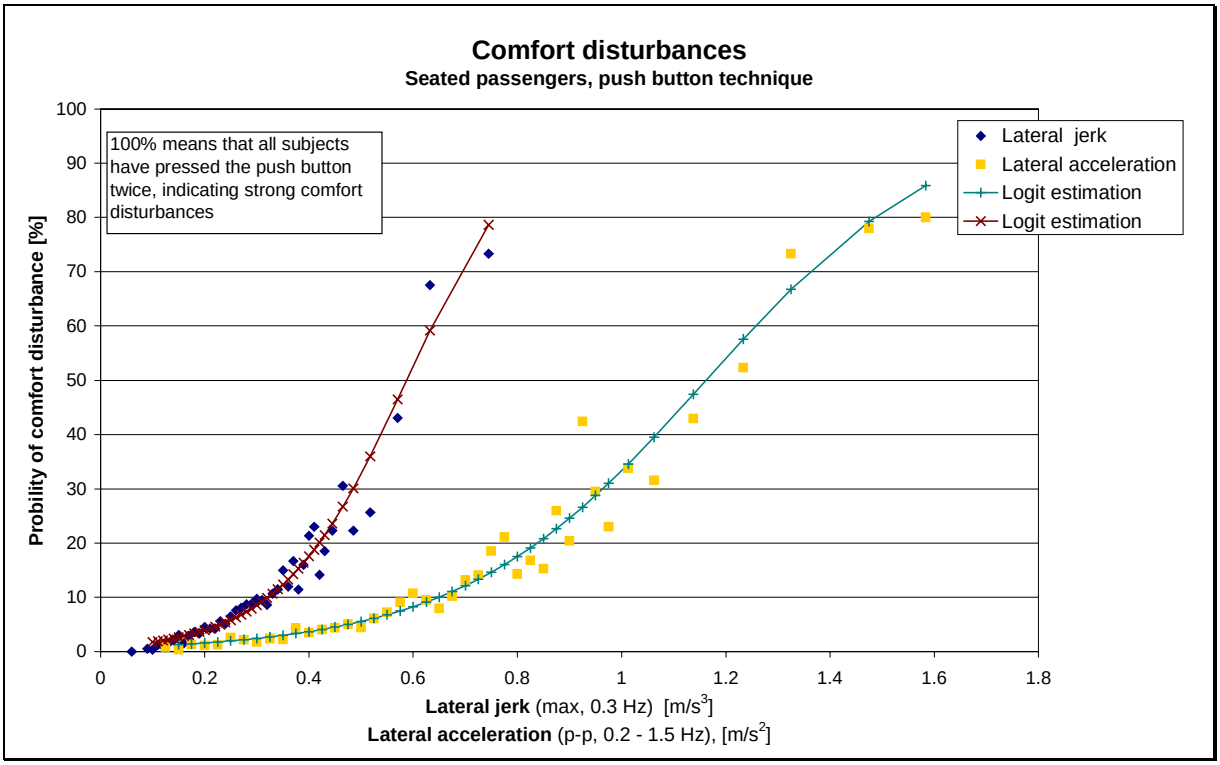


Figure 15 *Probability of a seated passenger feeling a comfort disturbance caused by a strong lateral jerk or lateral acceleration. Lines corresponding to the logit regression model are drawn to show this relation. The lateral acceleration ($\ddot{y}_{p\text{-}p}$) (squares, line to the right) was expressed as a peak-to-peak value in a time window of 2.56 s and filtered by a band pass filtered 0.2 - 1.5 Hz. The lateral jerk (diamonds, line to the left) was low pass filtered at 0.3 Hz.*

Table 16 shows the limits where there is a 20% probability of the passengers to experience comfort disturbances. The Table 16 is also displaying the regression coefficients A and B in the logit regression model shown in Figure 15.

The differences in 20% probability values between standing subjects and seated subjects are not large. This is contrary to earlier tests (*X15*, *BRR*), where seated subjects are reported to accept much higher magnitudes of lateral acceleration and jerk before they reported same level of comfort disturbance. A possible explanation is the average ride comfort, in the present test, was better than in the previous tests. Therefore, the seated subjects notify the jerks and jolts more easily and are more therefore more disturbed. It emphasises the fact that passengers ear expecting higher comfort levels in modern trains.

Table 16 Motion quantities yielding 20% discomfort probability and the regression coefficients A and B for the regression model ($e^{A+Bx} / (1+e^{A+Bx})$).

Physical quantities	*Standing passengers*			*Seated passengers*		
Lateral acceleration, [m/s^2]	20% discomfort	A	B	20% discomfort	A	B
p-p, BP 0.2-1.5 Hz	0.75	-4.95	4.75	0.84	-4.97	4.28
p-p, BP 0.2 - 0.6 Hz	0.42	-4.72	7.94	0.52	-4.13	5.34
Jerk, [m/s^3]						
Max v., BP 0.2 - 0.6 Hz	1.14	-5.09	3.25	1.18	5.39	3.40
Max v., LP 0.3 Hz	0.37	-5.43	10.94	0.42	-4.85	8.26

(p-p = peak-to-peak value, max = maximum value, 0.2 - 1.5 Hz filtered by a band pass filter.)

6.1.5 Summary

Both the peak-to-peak value of lateral acceleration and the low-pass filtered lateral jerk can be used as indicators of comfort disturbances. The choice of measurement method is a matter of convenience or equipment. At the same magnitude of lateral acceleration or lateral jerk, the seated subject (or passenger) are experiencing fewer comfort disturbances.

Further research is needed to transfer these limits into a standard for long-wave alignment irregularities and transition curves. Such a transfer needs to take also the dynamics of the vehicle into account. A transfer model from track to car body vibrations is possible according to Wingren (1997). A later evaluation of *BRR* and *SJ* experiments is done by Weisser (1999) where he refines the above models.

6.2 Tilting train test for comfort and motion sickness

This tilting train test are reported in Förstberg (1996, 2000b) and in various conference papers (Förstberg 1997b, Förstberg et al. 1997b, Förstberg et al. 1997c, Förstberg et al. 1998a, Förstberg et al. 1998b, Förstberg, Andersson, & Ledin 1999b).

6.2.1 Objectives

The objectives of tests were:

- To survey the human response regarding *ride comfort* and *comfort disturbances*, *symptoms of motion sickness* (*SMS*) and *ability to work/read* for some alternative strategies of controlling the car body tilt system.
- To describe the low frequency motion environment for a train with tilt system under these alternative tilt conditions.
- To investigate the influence of motion quantities on the *incidence of symptoms of motion sickness* (*SMSI*) and, if possible, find a suitable model.

The field tests were conducted with subjects in a train equipped with a tilt system (*SJ X2000*). The main test was conducted in June 1995 with pre-test during 1994. Tests were run in co-operation with *SJ* and *Adtranz Sweden*.

6.2.2 Test subjects

The main train experiment was conducted in June 1995 using about 70 test subjects and about half of them were females. Mean age was about 25 years. Some of subjects were chosen for high subjective sensitivity to motion sickness. Sensitivity for motion sickness is declining slowly with age over 20 years of age (Förstberg 1996). The selection of subjects was therefore focused on sensitive students to get a test group that might be somewhat more sensitive than a normal adult population. However, the most sensitive subjects might not want to participate in these kind of tests. Mean self-rated sensitivity for motion sickness[17] for the subjects was 3.6 for females and 2.6 for males. They were mostly students from Linköping University (LiU) within ages of 20 to 30 years, but also included some employees of the Swedish National Road and Transport Research Institute (VTI) and University Hospital in Linköping (UH).

The test subjects were instructed to try to read or work during the test ride. They were also instructed to ride either forwards or backwards during all test runs, which meant that they had to change seats and direction before the return trip. They were able to see each other and in some cases able to talk to each other. No one became so nauseated, that vomiting occurred. Otherwise, influences between subjects were minimised since subjects were occupying different rows in most cases. About three-quarters of the subjects occupied a window seat.

In earlier experiments (November 1994), females had reported two to three times more symptoms of motion sickness than males (Förstberg 1996). Therefore, almost identical numbers of women and men were used in all test conditions and groups, see Table 17.

[17] Sensitivity to motion sickness, rated on a scale from 1 (no sensitivity) to 7 (very high sensitivity).

Table 17 Data for subjects in the test groups (valid for the first test run, June 1995).

	Test group 1	*Test group 2*	*Test group 3*	*Total*
Number of test subjects	22	30	20	72[i]
Percentage female [%]	45	50	45	47
Mean age [years]	24	25	25	25
Mean sensitivity, female	4.2	3.6	3.0	3.6
Mean sensitivity, male	2.7	2.6	2.5	2.6
Mean sensitivity	3.3	3.1	2.7	3.1

Remark: i 72 subjects were evaluated on the first test run, however there were subjects on the train. Sensitivity, rated on a scale from 1 (no sensitivity) to 7 (very high sensitivity)

The distribution of self-rated sensitivity to motion sickness of the test subjects is shown in Table 18.

Table 18 Percentage of the male and female subjects' self-rated sensitivity to motion sickness.

Rated sensitivity:	*1*	*2*	*3*	*4*	*5*	*6*	*7*
Percentage male [%]	27	21	34	13	5	0	0
Percentage female [%]	8	30	12	25	20	5	0

6.2.3 Test train and measured motions

The test train used in this experiment was SJ tilting train *X2000*, consisting of a power car and five passenger cars. The test subjects were seated in cars no. 1 (test group 1), no. 2 (test group 2) and no. 4 (test group 3). They were submitted to three different tilt control strategies. Measurement equipment (amplifiers, recorders, etc.) was located in the bistro car, see Figure 16. Accelerometers and other sensors in the cars no 1, 2 and 4, see measurement section below.

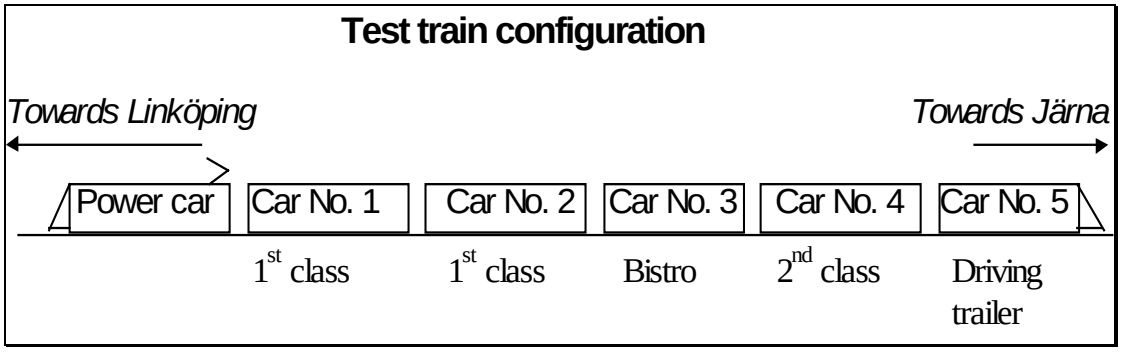
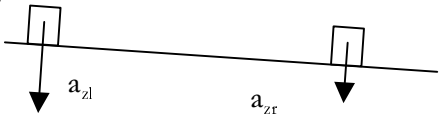


Figure 16 Test train configuration. Test subjects were seated in cars 1, 2 and 4.

Measurements

The following motion quantities were recorded during the test runs, see Table 19. Roll acceleration was measured as the difference in vertical acceleration (a_z) [m/s^2] between the left (l) and the right (r) position in the car divided by the lateral distance d [m]. Vertical acceleration was measured perpendicular to the car body floor.

$$\ddot{\varphi}_c = (a_{zl} - a_{zr})/d \qquad [\mathrm{rad/s^2}] \qquad [6.1]$$



Probably due to some misalignment between the accelerometers, it was not possible to integrate roll acceleration to roll velocity with sufficient accuracy.

Table 19 Measured motions quantities and positions during the test runs.

Signals	*Car*	*Position in car body*	*Units*
Lateral acc.	1, 2 & 4	floor, middle	[m/s^2]
Vertical acc.	1, 2 & 4	floor, middle, left	[m/s^2]
Vertical acc.	1, 2 & 4	floor, middle, right	[m/s^2]
Lateral acc.	4	floor, over bogie	[m/s^2]
Tilting angle (between bolsters)	4		[rad, °]
Train speed			[km/h]
Km - position			

Tilt system

A car body tilt system is designed to reduce the centrifugal forces (lateral acceleration) experienced by the passengers, by tilting the car body inwards on curves. The design is intended to enhance ride comfort and has small effects on safety of the train. On curves, a tilting train may travel at speeds typically 25 - 30% faster than a normal non-tilting train, if no other comfort or safety limits are violated (Andersson & Nilstam 1984, Andersson et al. 1995). A schematic sketch of the present bogie with parts of the tilt system is shown in Figure 17.

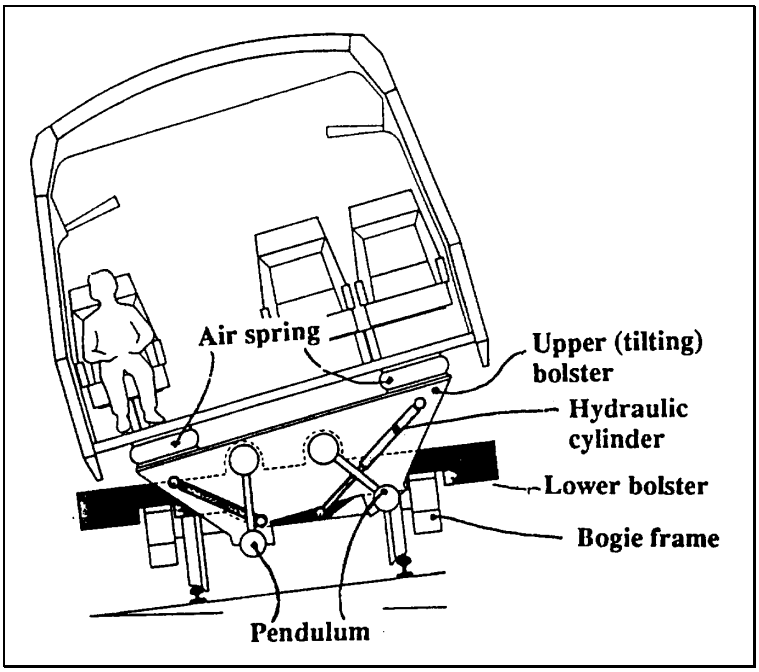


Figure 17 Tilt system in the X2000. Hydraulic cylinders tilt the upper bolster in respect to the lower bolster. Maximum angle between the two bolsters is about 8°. Because of the flexibility in the suspension system, the angle between car body and the track planes is at the most about 6.5°. Source: Andersson et al (1995).

6.2.4 Track characteristics and test parts

The test runs were conducted on a track with a large number of curves between Järna (about 47 km south-west of Stockholm) and Linköping (about 225 km south of Stockholm), see Figure 18. The test track is about 180 km, with permitted speeds within the range of 180 - 200 km/h for about 85% of the length of the track. Curve radii varied mostly within the range of 1000 - 1250 m. A section between Linköping and Norrköping has some curves with radii of 440 - 800 m, with speed limited to 125 - 145 km/h. For evaluation purposes, the test line Linköping – Järna - Linköping was divided into four parts at the stations of Katrineholm, Järna and Katrineholm. The stations of Norrköping and Katrineholm were passed at low speed due to the alignment and turnouts at the stations.

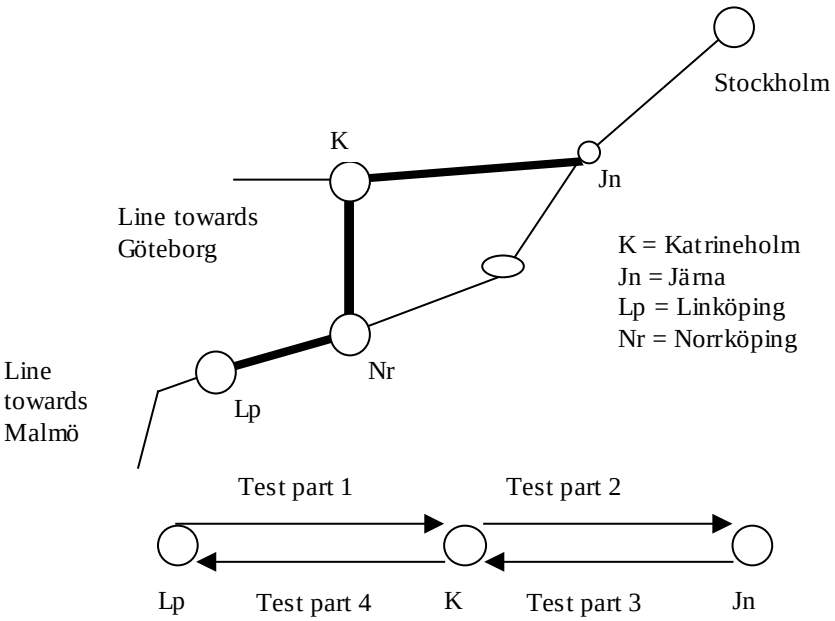


Figure 18 Test track and surrounding lines.

6.2.5 Tested compensation strategies

Three different tilt compensation strategies were tested in June 1995, see Table 20. They were called A, F and G because earlier (Nov. 1995), four different tilt conditions (A, B, C, D) had been tested with a generally positive outcome for low tilt compensations. The independent parameters for the tilt system were: ratio of tilt compensation, limitations of tilt velocity and tilt acceleration.

The intention of limitation of tilt velocity was to reduce unnecessary tilt motions caused mainly by track irregularities. The tilt motion necessary to tilt the car body in time determined the lower limit of tilt velocity. The intention of the limitation of tilt acceleration was to reduce the motion dose of roll acceleration. A too strong limitation of tilt acceleration would, however, cause an unstable tilt control system as well as undesirable long time delay. Limitations of tilt acceleration can lead to higher tilt velocity, if tilt motion starts at the beginning of the transition curve and the tilt control is programmed to minimise the time delay. However, if the tilt motion can start before the transition curve than there is no need for a higher tilt velocity.

Table 20 Variation of parameters used in the tilt system during the experiment (June 1995).

Tilt conditions*	Speed [%]	Tilt comp [%]	Max. tilt velocity [°/s]	Max. tilt acceleration [°/s^2]	Typical max. lateral acceleration in car body[ii] [m/s^2]
A	Cat S	70	4	no limit[iii]	0.6
F	Cat S	55	4	4	0.8
G	Cat S	55	2.3	no limit	0.8

Remarks: * Tilt conditions A-D were tested in earlier experiments. Tilt condition E was planned but never realised. B had 40% tilt compensation, C had 0% tilt compensation but Cat B speed (+10%), C1 had 0% tilt compensation and Cat S speed, D 70% tilt compensation and tilt velocity limitation to 2.0 [°/s].

i Cat S has approx. + 25% higher curving speed than normal non-tilting trains, Cat A

ii Typical maximum values.

iii The tilt acceleration was not limited by the tilt control system. Due to inertia of the car body and stiffness of the suspension and dampers, the maximum car body angular acceleration was estimated to be 10 - 15 °/s^2.

6.2.6 Test design

The test design used in June 1995, of the type Latin square, is shown in Table 21. This design was selected to minimise differences in age, gender and sensitivity in the different test groups, and to minimise influence of the different cars and its position in the train. Each group was tested over a period of three days with different tilt conditions to minimise bias because of differences in sensitivity etc.

Table 21 Test design of the experiment. Tilt control strategies A, F and G are shifted around in systematic way.

		Day 1	*Day 2*	*Day 3*
Test group 1	Car No. 1	A	F	G
Test group 2	Car No. 2	G	A	F
Test group 3	Car No. 4	F	G	A

The size of the test groups was chosen to about 20 subjects in all the experiments, in order to achieve enough statistical power[18] in the different tests according to assumed variation of responses (Keppel 1991).

6.2.7 Evaluation

Before the test ride, the subjects answered a questionnaire[19] concerning age, gender, rated subjective sensitivity to motion sickness, and well being. Each test ride lasted about 3 hours (Linköping – Järna and return). After each test part (i.e. at passing the station of Katrineholm, on the arrival to Järna, at passing Katrineholm and just before arrival to Linköping), the subjects answered questionnaires concerning their activity, estimated ride comfort, if they had any comfort disturbances, estimated ability to work/read, and if they had any motion sickness symptoms such as drowsiness, pallor, salivation, fatigue, sleepiness, dizziness and nausea. They also scored their well

[18] Statistical power indicates the possibilities to have a significant result of a test. With more test subjects, the power grows.

[19] The questionnaires are displayed in the previous report (Förstberg 1996) and in Appendix E.

being (IR_{MOD})[20] on a five-degree scale, both at the beginning of the journey and after each test part. This scale is based on the four grades scale *Illness rating* (IR_{ORG}) presented by Lawther & Griffin (1987). The IR_{MOD} is called *IR* through out this thesis.

Incidence of motion sickness symptoms (*SMSI*)

The definition of a subject having a *symptom of motion sickness* (*SMS)* is if this subject (feeling well at the start of the test run) has one of the following symptoms: *dizziness*, *nausea* or reported something else than *I feel alright*. With other words; *SMS* = 0 if *dizziness* + *nausea*[21] + *IR* = 0 else *SMS* = 1, if *IR*(at start) = 0. If *IR*(at start) ≥ 1, then the subject is omitted from further evaluation.

Symptoms of motion sickness incidence (*SMSI*) is the percentage of subjects having a *SMS*. It is evaluated over all test parts where the subject had participated in a specific tilt condition *X*.

$$SMSI_X = \frac{\sum_{parts,subjects} SMS \cdot \delta(s)}{\sum_{parts,subjects} \delta(s)} \quad [-],\ [6.2]$$

where $\delta(s) = 1$ if subject s took part in tilt condition X else $\delta(s) = 0$

Evaluation of motion dose

In the evaluation of possible motion sickness provocation due the motion environment of the train, the concept of motion dose[22] (*md*) (Griffin, 1990; Lawther & Griffin, 1987) has been used.

$$md = MSDV = \left[\int_0^T a_{wf}^2 dt\right]^{0.5} \quad [m/s^{1.5}, rad/s^{1.5}],\ [6.3]$$

where a_{wf} is originally vertical acceleration but here extended to vertical, lateral and roll accelerations. The acceleration signal is filtered with weighting curve w_f.

The weighting curve (w_f) defined in ISO 2631-1 (ISO, 1997) for calculating motion dose has been slightly modified and replaced with a band-pass (BP) filter 0.08 - 0.35 Hz, see Figure 19. The BP-filter is multiplied with the factor 1. 12 in order to have the gain = 1.0 at 0.17 Hz. The reason for this is that the digital filtering in the time domain was easier with this filter than the original w_f-filter. The difference is small and lies within the error tolerance marginal of the filter (ISO, 1997), see Figure 19. This filter has been used for all calculations on motion dose from time histories of vertical, lateral and roll accelerations, since no alternative filter exists for lateral or roll accelerations. However, some other BP filters have been tested, such as decreasing the high-frequency pass band to 0.04 Hz and increasing the low-pass filter pass band to 0.5 and 1.0 Hz.

[20] The used illness rating (IR_{MOD}) grades were: *I feel alright*, *I do not feel quite well*, *I feel rather unwell*, *I feel bad*, *I feel very bad.*
[21] *Dizziness* = 1 if subjects is feeling dizziness else = 0. The same is valid for *nausea*. *IR* = 0 for subjects *feeling all right* else IR > 0.
[22] Motion dose (*md*) or Motion Sickness Dose Value (*MSDV*).

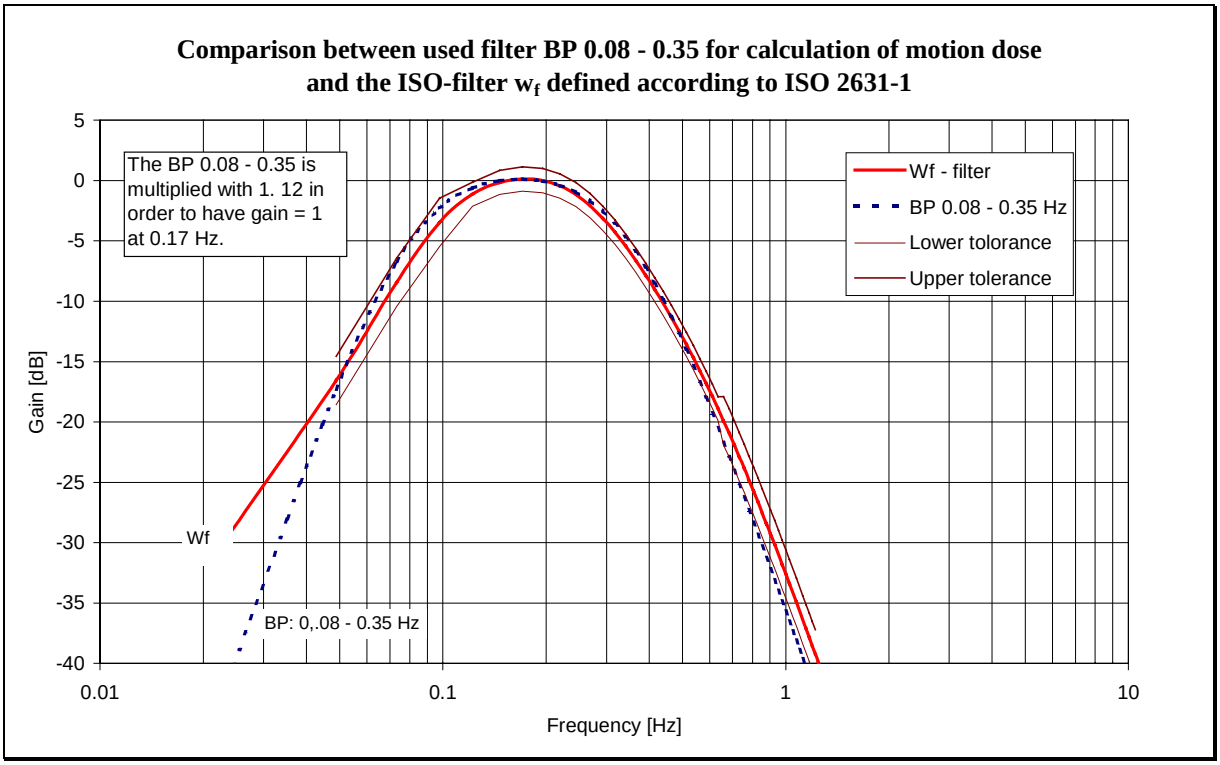


Figure 19 *Comparison between ISO 2631 weighting filter w_f (ISO, 1997) and the used BP filter 0.08 - 0.35 Hz.*

Motion doses were calculated form time histories, in the following way. Each successive time record[23] of the measurement signals (a_y, a_z, $\ddot{\varphi}_c$) was filtered with the above defined BP filter and an r.m.s. – value was calculated. These r.m.s. – values were later stored in a new time history record, each individual r.m.s. - value was squared and then integrated. The square root of the integrated value for the last entered time history was then considered as an estimated value of the corresponding motion dose (*md*, *MSDV*) for the measured signal.

$$MSDV = \left[5.12 \cdot \sum_{N} a_{BP,rms,5}^{2} \right]^{0,5} \qquad [\mathrm{m/s^{1.5}}, \mathrm{rad/s^{1.5}}], \ [6.4]$$

where $a_{BP,\mathrm{rms},5}$ is the 5.12 s long BP filtered acceleration signal (lat, vert or roll) and N is the number of 5.12 s time records for the test run or test part.

Motion doses calculated from PSD-spectra by multiply the spectra with a weighting filter (BP or w_f), and calculate an r.m.s. – value over range of 0 – 5 Hz.

Motion doses with leakage
(see chapter 8)
Instead of a summation of the 5.12 s r.m.s – values over the whole test section the accumulated motion dose was allowed to leak out according to the recursive rule:

$$MSDV(t_{N+1}) = MSDV(t_N) \cdot e^{-c_L \cdot \Delta t} + \Delta MSDV(t_{N+1}) \qquad [\mathrm{m/s^2}, \mathrm{rad/s^2}], \qquad [6.5]$$

$$\Delta MSDV(t_{n+1}) = a_{BP,\mathrm{r.m.s.},5}(t_{N+1})$$

where $1/c_L$ = time constant and Δt is the time step ($t_{N+1} - t_N$).

[23] Time record of 1024 samples with 200 Hz sampling frequency gives 5.12 s

Used time constants in the evaluation have been about 10.8, 21.6, 43 and 86 min, corresponding to half value times of 7.5, 15, 30 and 60 min, respectively.

Ride (dis)comfort – Wz ride index

Ride (dis)comfort has been evaluated as Wz (Sperling & Betzhold 1956) calculated per km and displayed as average value per test part. For a definition of Wz, see Appendix D.

Guidance on Wz numbers for accelerations in passenger cars:

Ride index *Wz*	
1	just noticeable
2	clearly noticeable
2.5	more pronounced but not unpleasant
3	strong, irregular, but still tolerable
3.25	very irregular
3.5	extremely irregular, unpleasant, annoying; prolonged exposure intolerable
4	extremely unpleasant; prolonged exposure harmful

Ride comfort and estimated ability to read/write

Subjects estimated their average ride comfort and ability to work/read on a five degree scale from very bad (1) to very good (5). The subjects also estimated their comfort disturbances on a yes/no scale on the following quantities: strong lateral accelerations (side forces), lateral shakings, vertical shakings and uneven tilt motion.

Frequency analysis (PSD – spectra)

Power spectral density (PSD) spectra have been calculated, from an approximate 5 min of time history. The acceleration signals were first low pass filtered at 5 Hz and then resampled from 200 Hz to 25 Hz. The frequency analysis used a Hanning window and a 1024 point transform, resulting in a frequency spacing of 12.5/512 = 0.0244 Hz.

The time histories were taken from a part of the test track between Katrineholm and Norrköping, where the allowed speed was 180 km/h and the train could maintain this speed, see Figure 20. The part chosen is "densely" curved with minimum curve radius about 1000 m.

PSD-spectra from the return trip on the first day, were omitted because the train was braking and therefore vibrating with other frequencies and magnitudes.

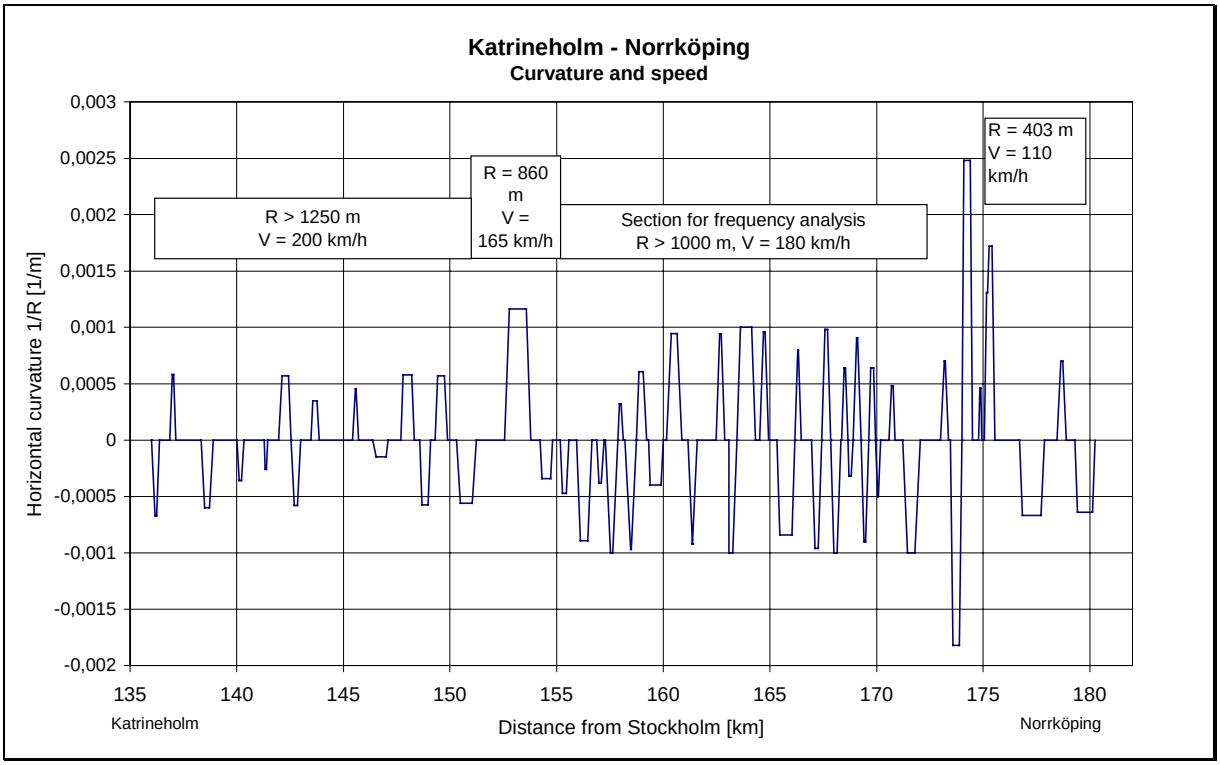


Figure 20 *Track description Katrineholm – Norrköping. Permitted speeds are indicated in the figure.*

6.3 Results comfort and motion sickness

6.3.1 Ride comfort and rated working/reading ability

The tested subjects reported that the ride comfort (ride quality) was good (on average 4.1 - 4.2 on a five-degree scale) and about the same level of comfort disturbances in all tilt conditions. They also rated their ability to read and work as about 4.1 - 4.2 for these conditions, see Table 22. The differences are small and non-significant.

Table 22 Comparison of estimated ride comfort (quality), percentage of subjects complaining of comfort disturbances due to low-frequency lateral accelerations and estimated working / reading ability.

	Estimated ride comfort mean (SD)	*Comfort disturbances from lateral accelerations [%]*	*Estimated working / reading ability*[i] *mean (SD)*
Tilt condition A	4.08 (±0,20)	58	4.05 ((±0,23)
Tilt condition F	4.22 (±0.32)	54	4.12 (±0,22
Tilt condition G	4.19 (±0.27)	54	4.19 (±0,23)

Remark: i On a five-degree scale from very bad (1) to very good (5).
ii *SD,* Standard deviation is calculated of mean values from the 24 groups (3 days x 4 parts x 2 genders).
No statistically significant differences between tilt conditions A, F and G were found.

6.3.2 Other comfort disturbances

In the questionnaires, the subjects could also register their complaints on the ride quality. Most complaints were on vibrations (56%), seat 38% and high air pressure while passing tunnels (26%).

6.3.3 Symptoms of motion sickness

In the experiment, the two tested tilt conditions with 55% tilt compensation (F and G) showed a lower incidence of symptoms of motion sickness (*SMSI*) than in condition A with 70% tilt compensation. The reduction of *SMSI* was 25 - 40% compared with condition A, see Table 23. The only statistical significant difference at 5% level was the difference between tilt condition A and condition G.

Table 23 Percentage of subjects with symptoms of motion sickness incidence (SMSI).

Tilt condition	*SMSI [%]*	*Confidence interval Approx. 95 %*	*Relative percentage to A*
A	14.5	10.5 - 18.4	-
F	10.7	7.1 - 14.3	74%
G	8.5	5.3 - 11.6	58%

Remark: A χ^2 - analysis shows that the differences between the number of test subjects experiencing *SMS* in tilt conditions A, F and G is significant on the 10 % level ($\chi^2 = 4.94$, df = 2, $p \leq 0.08$) but the difference between A and G is significant on the 5 % level ($\chi^2 = 4.73$, df = 1, $p \leq 0.029$).
No subject was vomiting during the test runs.

6.3.4 Differences in gender and seating direction

Differences in the reported symptoms of motion sickness and discomfort among gender are shown in Figure 21. Females were found to score about two to three times as high as the males did on *SMSI,* or about 12 percentage units higher.

Females also show a large variation in *SMSI* with the direction of travel. They scored significantly less *SMSI* when riding backwards, see Table 24. For men, there was very little difference. Being seated at a window or not, may affect women travelling forwards. This may indicate that the vision field (able to look steadily at the horizon) has an influence on motion sickness, especially for females (Magnusson & Örnhagen 1994).

Table 24 *SMS and SMSI for travelling forwards or backwards for male and female subjects sitting at a window seat or not, summarised over the tilt conditions A, F and G, and all test parts.*

	Window seat				*Non window seat*			
	Male forw.	*Male backw.*	*Female forw.*	*Female backw.*	*Male forw.*	*Male backw.*	*Female forw.*	*Female backw.*
SMSI	6%	7%	20%	10%	0%	0%	38%	11%
χ^2	0.06		4.77		-		10.3	
p	n.s.		0.029		-		0.001	

Remark: i Only about 25% of the subjects occupied a non-window seat.
forw. = forwards, backw. = backwards, n.s. = not significant

Correlation between self-rated sensitivity and symptoms

The subjects rated their sensitivity to motion sickness before the test runs on a seven-grade scale from 1 (none) to 7 (very large). Figure 22 shows the percentage of subjects with a certain estimated sensitivity experiencing *SMS*. For the regression line for men and women together, the coefficient of determination is high (r^2 = 0.95). About 48% of male subjects estimated their sensitivity to 1 or 2 and 47% to 3 or 4. For females, 38% of them estimated their sensitivity to 1 or 2, 37% as 3 or 4 and 25% as 5 or 6, cf. Table 18.

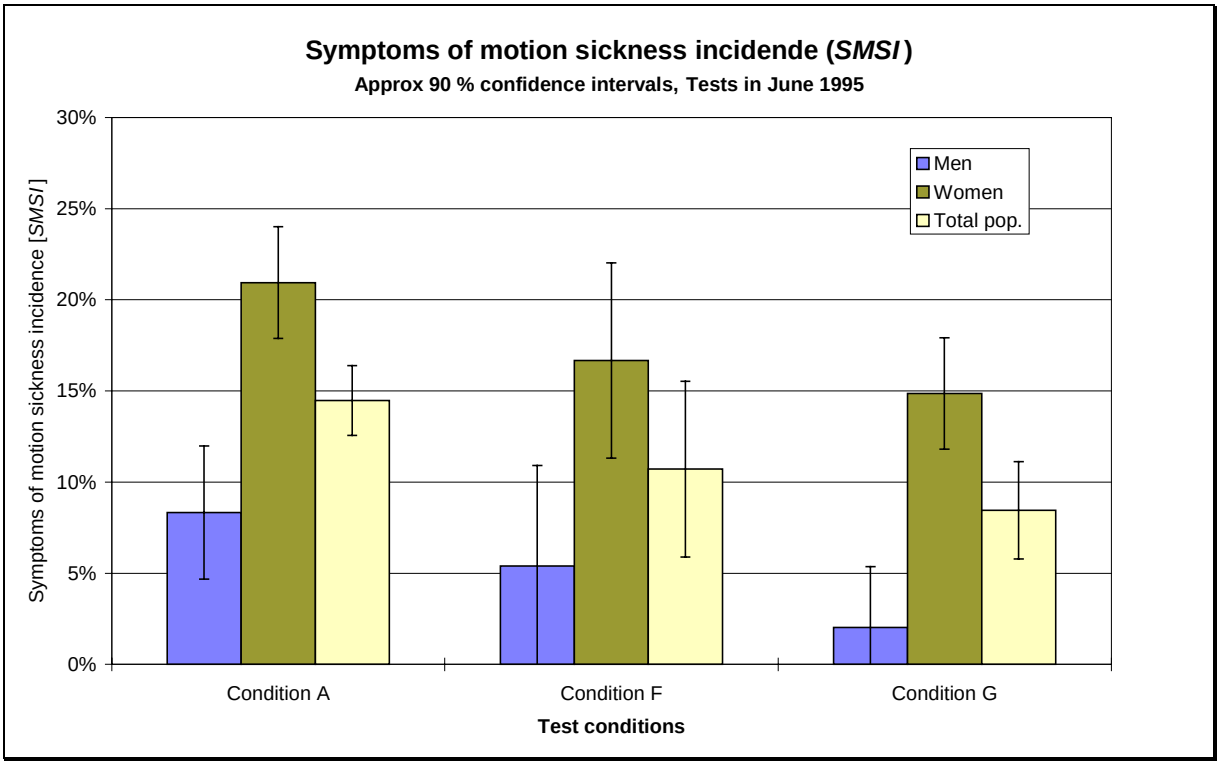


Figure 21 *Differences in SMSI for men, women and the total group of test subjects for the different tilt conditions. Values are averaged over all test parts.*

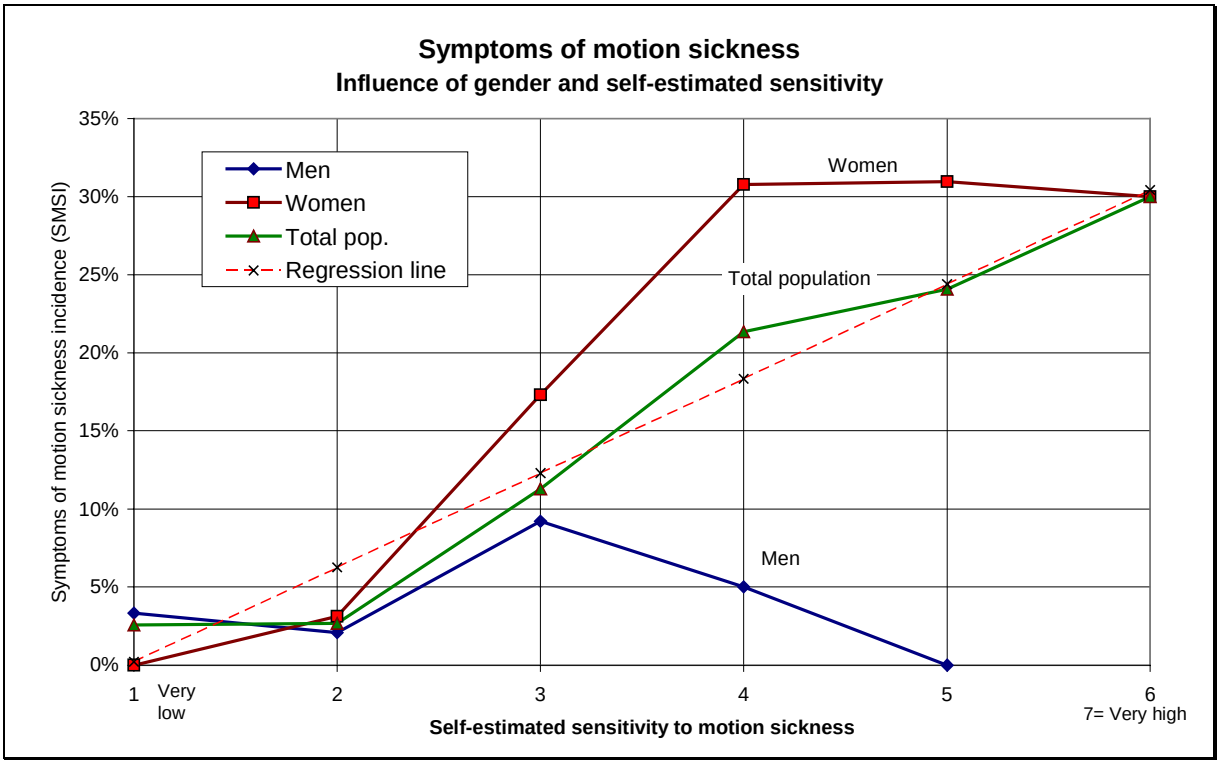


Figure 22 *Percentages (SMSI) of the subjects experiencing an SMS as a function of self-rated sensitivity. 5 % of the male subjects rated their sensitivity as 5. 25 % of the female subjects rated their sensitivity as 5 or 6.*

6.3.5 Time dependence

Analysing the time pattern of *SMSI*, the incidence of motion sickness was highest at the first and last inquiries during the three-hour ride, see Figure 23. According to the motion dose hypothesis of Lawther and Griffin (1987), the *SMSI* would increase during the course of the ride. This is indeed true when regarding the vomiting incidence (*VI*), which can only increase, e.g. during a ship journey in heavy weather. However, when considering a fluctuating motion environment and *SMSI*, it may not be true. Here the process of leakage of motion dose is probably involved (Kufver & Förstberg 1999), see also chapter 8. The *SMSI* patterns with respect to time during the test run were significantly different from a pattern with the same (mean over all test parts) *SMSI* for each test part ($\chi^2 = 10.98$, df = 3, $p \leq 0.012$). The difference between the test parts Linköping – Katrineholm (Lp – K, K - Lp) and Katrineholm – Järna (K – Jn, Jn - K) was maybe caused by a more severe motion environment generated from differences in both track geometry standards and actual track irregularities.

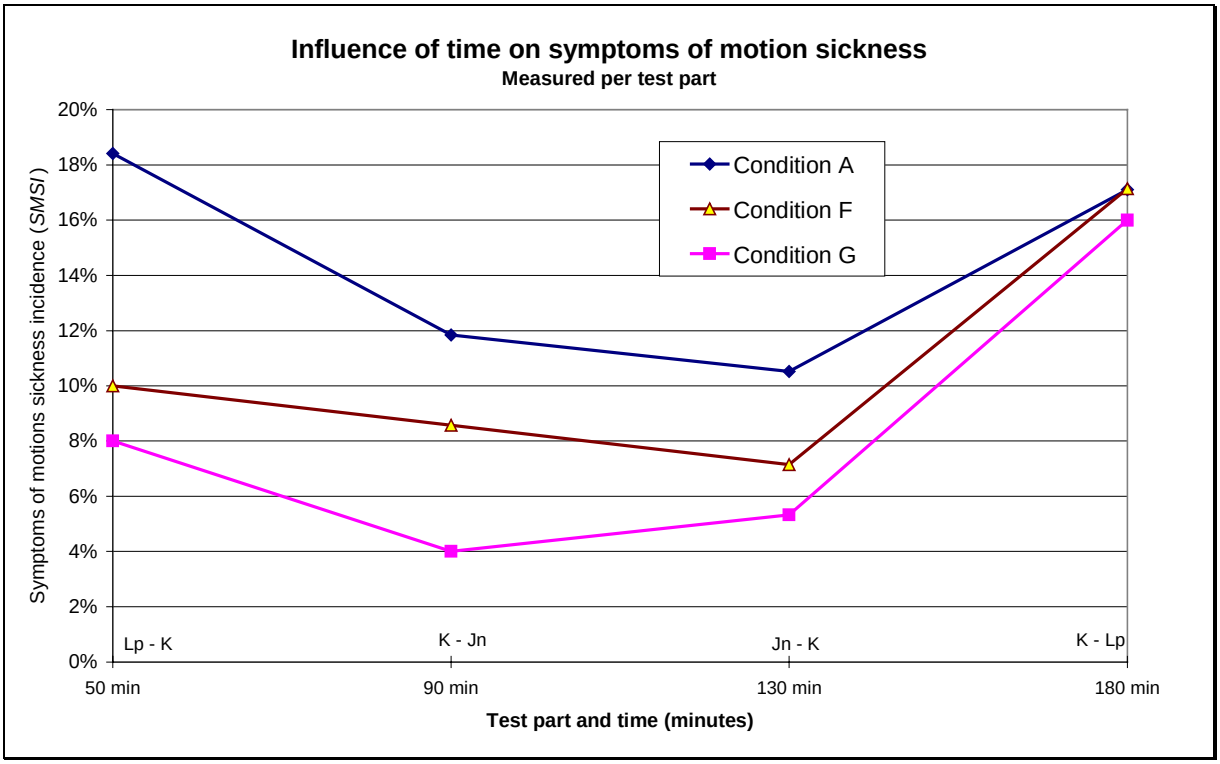


Figure 23 *Symptoms of motion sickness incidence (SMSI) measured for the different test parts. Travelling time is indicated. The test parts Lp – K and K - Lp may be more "severe" than the other test parts K – Jn and Jn - K.*

6.3.6 Motion environment

The motion environment has been divided into two parts, first as average comfort measured as Wz and secondly as motion doses for a possible correlation with *SMSI*.

Wz ride index

Average Wz for lateral accelerations is about 1.95 and average Wz for vertical accelerations is about 2.05. This corresponds to *clearly noticeable* but still good ride comfort and that corresponds well with estimated ride comfort (quality) - values of 4 (*good*) of from the subjects. The average Wz per test part show more variation over the different test parts (< 0.25) than for the different tilt conditions (< 0.09).

Motion doses

In evaluating the motion environment in terms of motion doses, vertical, lateral and roll acceleration time histories, along with the weighting filter BP 0.08 – 0.35 Hz (approx. the ISO- filter w_f) have been used.

Figure 24 shows the motion doses per test part from lateral accelerations (a_{y_o}) and vertical accelerations (a_{z_o}), both measured on the floor in the car bodies. The motion doses for vertical accelerations are also displayed as accumulated doses over the whole test run. Vertical motion doses ($MSDV_Z$) show that the differences in magnitudes between the tilt conditions A, F and G are very small. This suggest that the differences in motion dose from vertical accelerations is likely not responsible for the differences in actual *SMSI* for tested tilt conditions as shown in Figure 23.

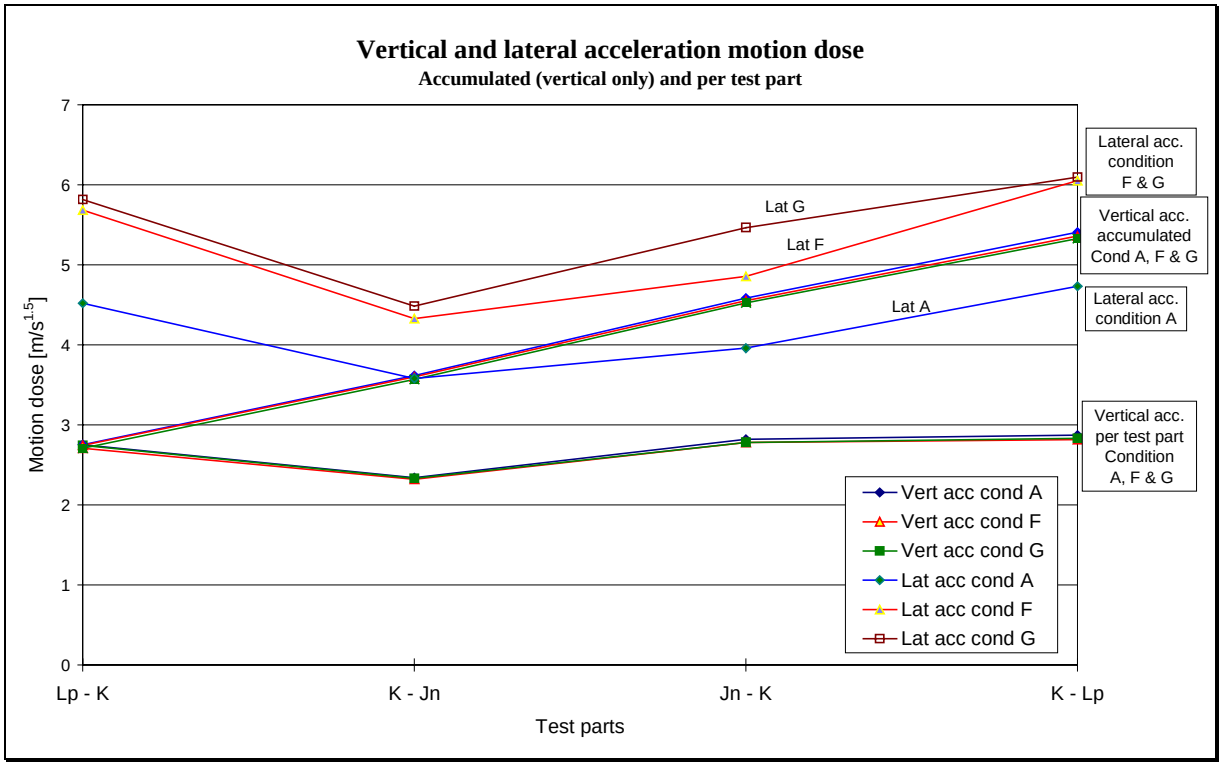


Figure 24 *Motion doses from vertical accelerations accumulated over whole test run, together with lateral and vertical motion doses per test part.*

The lateral motion doses ($MSDV_{Y_o}$) show difference between the tilt conditions and indicates that test parts 1 and 4 are more severe. However, tilt condition A shows the lowest motion dose values and condition F and G the highest. This corresponds well to the observation that condition A has a higher tilt compensation level of the lateral acceleration than the other two conditions and therefore show less lateral motion doses but contradicts Table 23 and Figure 23.

Figure 25 shows the roll acceleration motion doses ($MSDV_{RA}$)[24], where tilt condition A now displays higher motion dose values than the other two. The roll acceleration motion doses for test parts 1 and 4 are showing higher values than the other two test parts (2 and 3), as similar to the lateral acceleration motion doses. This pattern is similar to the *SMSI* pattern as in Figure 23. This indicates that the roll acceleration motion dose is probably one of the prime causes of motion sickness, at least in present case.

[24] The incidences for roll acceleration should be lower cases *ra* but for clarity the upper case *RA* is used.

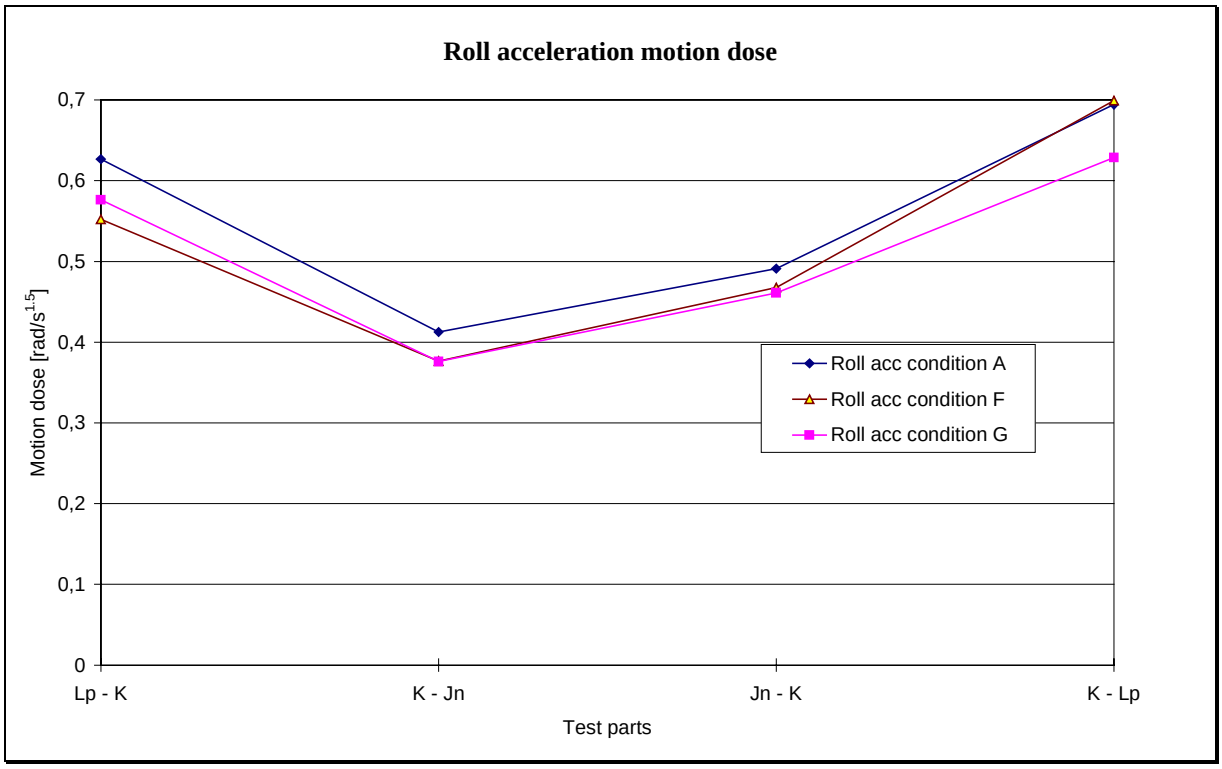


Figure 25 Motion dose from roll accelerations shown per test part.

6.3.7 Regression and frequency analysis

Regression analysis

To analyse the influence of vertical, lateral and roll accelerations on *SMSI*, regression analysis was performed. This analysis shows that the lateral and vertical accelerations do not significantly contribute to the explanation of *SMSI*.

However, a linear regression model $SMSI = \alpha + \beta \cdot MSDV_{RA}$ suggests an influence of roll acceleration motion dose on *SMSI* for the total population with a statistical significance of $F(1, 34) = 25.24$, $p < 0.001$, see Figure 26. The corresponding regression analysis for female and male subjects shows that females have a greater sensitivity than the total population, and males less sensitivity, but for males, the coefficient of determination[25] r^2 is rather weak.

[25] The coefficient of determination shows the goodness of fit between the regression of line and the samples ($r^2 = 1$ for complete fit and $r^2 = 0$ for no linear association).

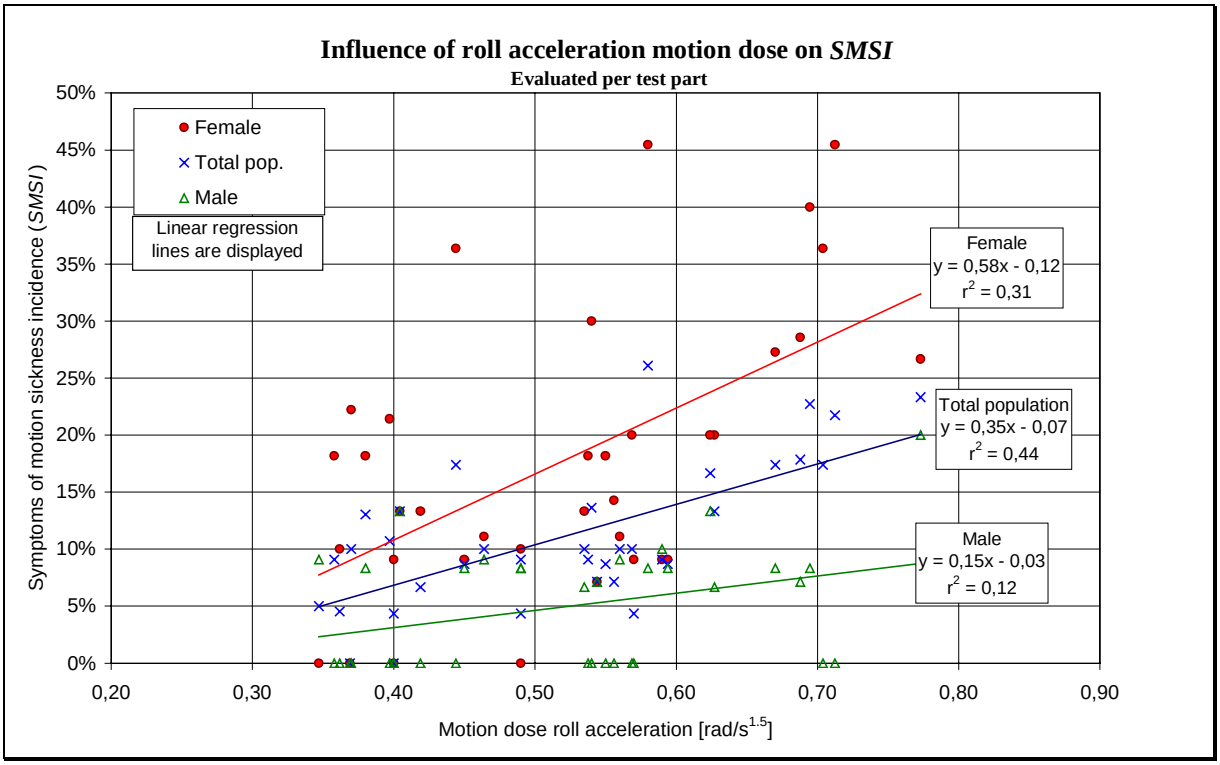


Figure 26 *Regression models for SMSI for female, male and the total population based on roll acceleration motion doses.*

Frequency analysis (PSD-spectra)

Frequency analysis was done on a part (~15 km ≈ 5 min travel) of the test track between Katrineholm and Norrköping, see Figure 20. Figure 27 shows PSD-spectra for roll acceleration for the different tested tilt conditions. These show that tilt condition A has 50 – 80% higher magnitude than tilt conditions F and G in the most interesting range for 0.08 - 0.2 Hz and 30 - 40% higher for 0.2 - 0.5 Hz. More interesting, a non-tilt condition C shows magnitudes for below 1 Hz that are about 1/10 of the magnitude of condition A. This data was obtained during tests in Nov. 1994 with train speeds according to category B[26]. Corresponding train speed was about 145 km/h in contrast to 180 km/h for the tilting trains at this section.

Figure 28 shows a corresponding frequency analysis for lateral acceleration in the car body. Here the tilt condition A has about the half the magnitudes up to 0.1 Hz, reflecting the lower quasi-static accelerations on circular curves than the other two conditions.

For vertical accelerations, there are almost no differences between the three tilt conditions (not shown here).

[26] Category B is allowed to negotiate curves with a_{yt} = 1,0 m/s² (I = 155 mm), about 10% higher speed on curves than ordinary Category A trains.

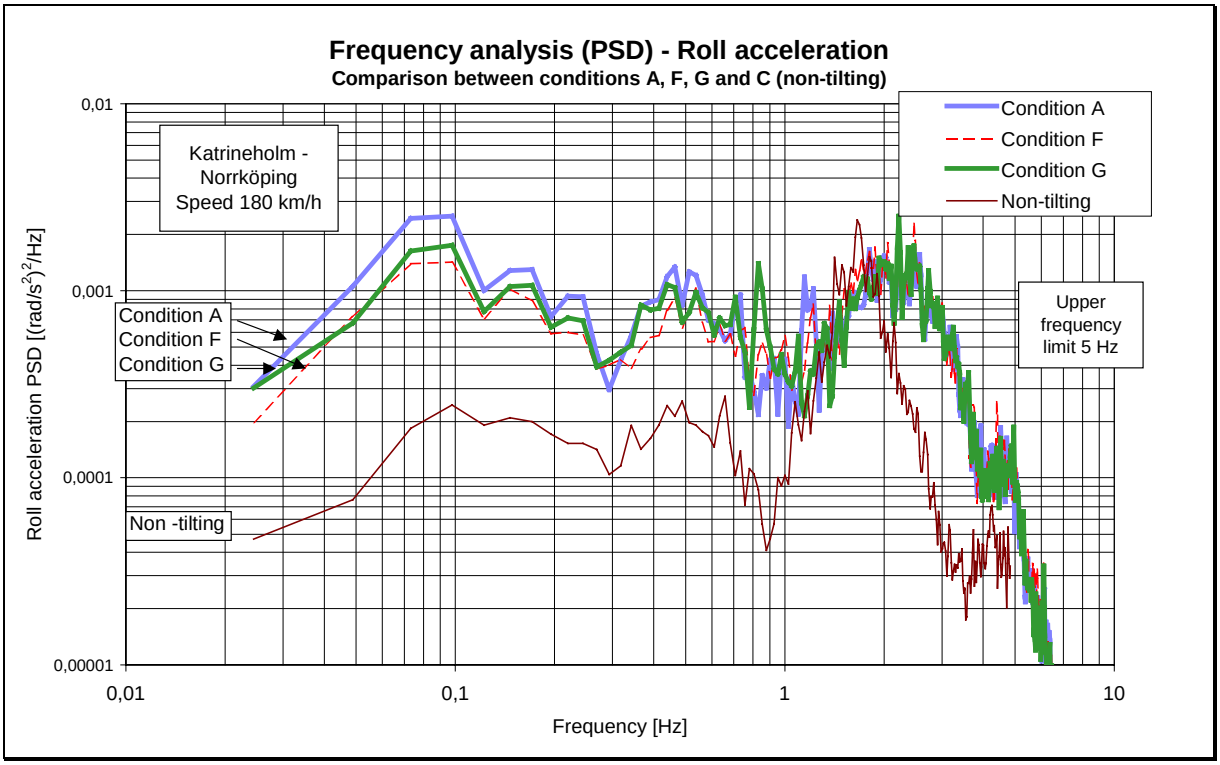


Figure 27 *PSD-spectra for roll acceleration for the different tilt conditions A, F, G and a non-tilting condition C with lower speed.*

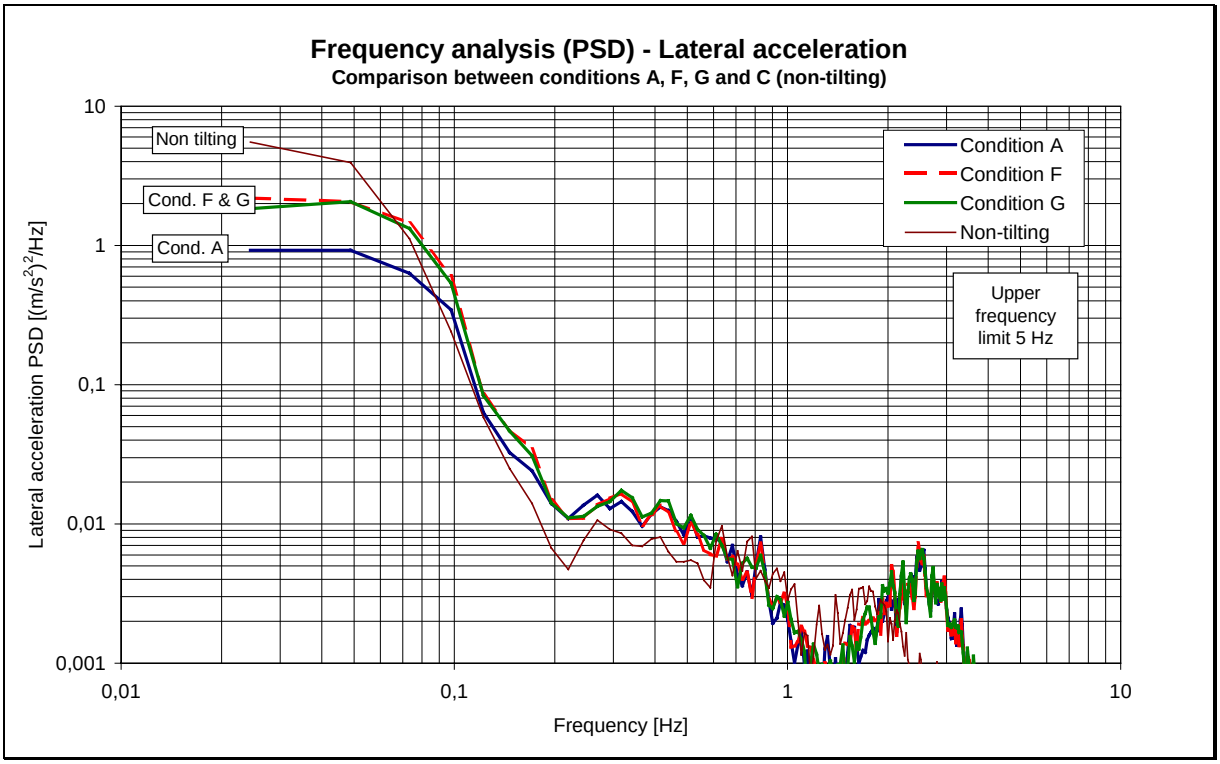


Figure 28 *PSD-spectra for lateral acceleration for the different tilt conditions A, F, G and a non-tilting condition C with lower speed.*

Tilt motion enhances the magnitudes for roll accelerations at very low frequencies but instead reduces the corresponding magnitudes for lateral accelerations.

Motion doses from PSD-spectra

The interesting point is to calculate r.m.s.-values of the PSD-spectra using the weighting function w_f. These r.m.s. – values are evaluated from a frequency analysis from about 5 min time histories and not the whole test run (about 40 min). Table 25 shows these r.m.s.-values and their relative order compared to tilt condition A. The relative difference in *SMSI* between tilt conditions A, F and G is greater than the difference in the corresponding r.m.s. - values.

Table 25 R.m.s. - values for vertical, lateral and roll acceleration calculated from PSD-spectra using the weighting filter w_f.

	R.m.s. – values, w_f-weighted, calculated from PSD-spectra			*Relative to tilt condition A*	
	Cond. A	Cond. F	Cond. G	Cond. F	Cond. G
Vert acc. [m/s^2]	0,079	0,077	0,077	98%	98%
Lat acc. [m/s^2]	0,145	0,191	0,198	132%	137%
Roll acc. [rad/s^2]	0,0180	0,0163	0,0151	91%	84%
SMSI	-	-	-	74%	58%

Remark: The tilt acceleration limited condition F displays higher r.m.s. - values for roll acceleration than the condition G (limited tilt velocity). This is probably due to a necessary longer acceleration phase resulting in a higher roll velocity, that generates a higher r.m.s. - values.

Since motion dose also can be calculated from the r.m.s. - values as (Griffin 1990, ISO 1997):

$$MSDV_y = a_{y,wf,rms} \cdot t^{0.5} \quad [\mathrm{m/s^{1.5}}], \qquad [6.6]$$

$$MSDV_z = a_{z,wf,rms} \cdot t^{0.5} \quad [\mathrm{m/s^{1.5}}], \qquad [6.7]$$

$$MSDV_{RA} = \ddot{\varphi}_{c,wf,rms} \cdot t^{0.5} \quad [\mathrm{rad/s^{1.5}}] \qquad [6.8]$$

it is easy to compare motion doses calculated from time histories over the entire test part (about 40 min) by estimated doses based on the equations above and the r.m.s. – values calculated from PSD-spectra (about 5 min).

An example of such a comparison for roll acceleration motion doses is shown in Figure 29. The regression coefficient β is not 1 but just about 0.8. Which indicates an 25% overestimation from the 5 min part to the whole test part of 40 min. In these 40 min there is a passing of a station at low speed and some straight track sections that will not contribute to the accumulated motion dose. The coefficient of determination (r^2) is high (0.90) and the relation is significant ($F(1,13) = 127$, $p < 0.001$). It is clear that the selected section for frequency analysis is quite "representative" regarding r.m.s. - values and *MSDV*, at least for roll acceleration.

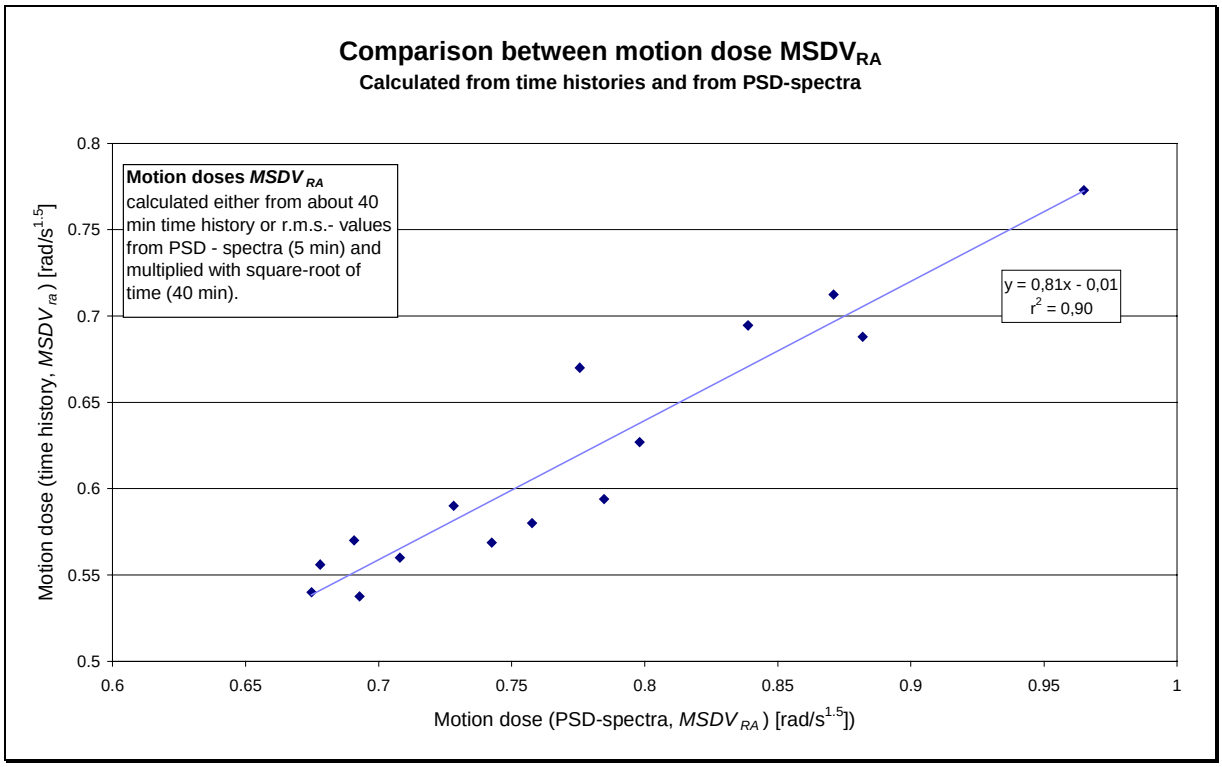


Figure 29 *Comparison between roll acceleration motion doses (MSDV$_{RA}$) calculated from time history (40 min) and from r.m.s.- values from PSD - spectra (5 min).*

The next step is to make a regression analysis between these calculated r.m.s. - values and the observed motion discomfort (*SMSI*), see Figure 30 and compare it with the earlier regression (Figure 26). They have a similar pattern as before.

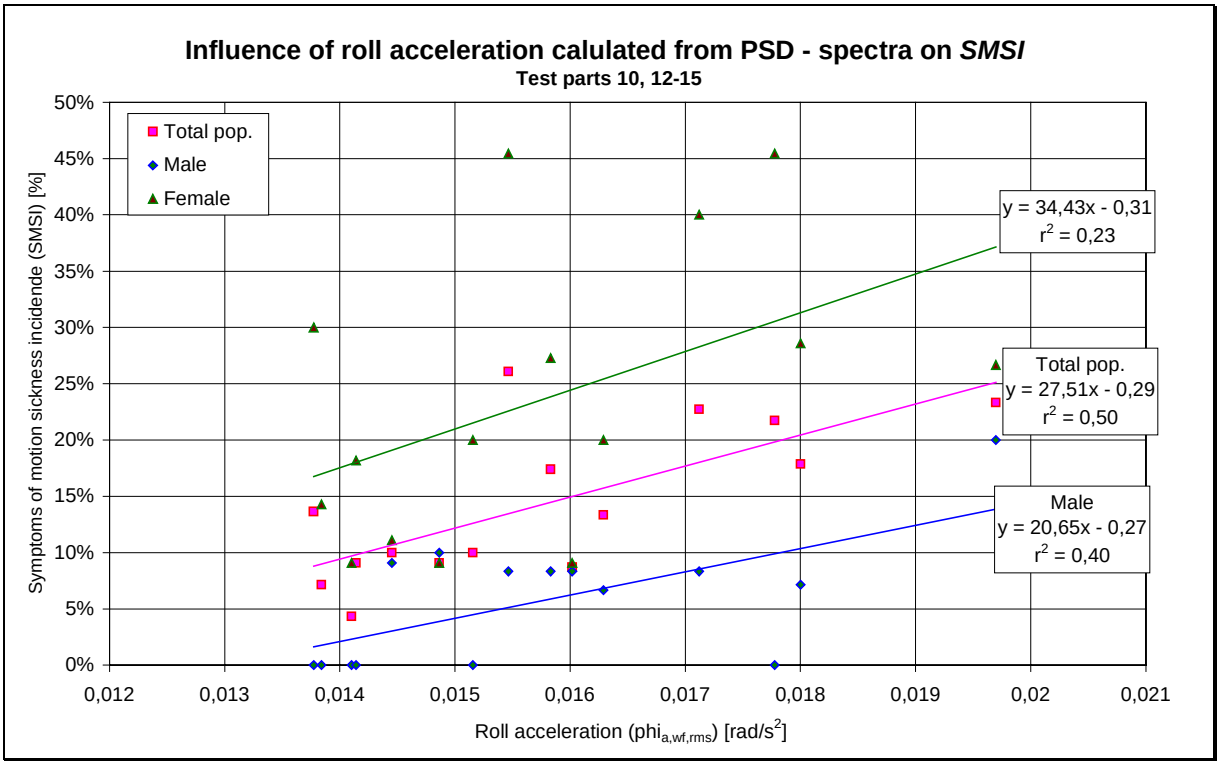


Figure 30 *Regression analysis between r.m.s.-values of roll acceleration weighted by wf and symptoms of motion sickness (SMSI).*

Alternative analysis

Attempts have been made to improve the fit between weighted r.m.s.-values and *SMSI*, by testing some other weighting filters, for example band pass filters from 0.04 - 0.5 and 0.04 - 1.0 Hz but these filters do not improve the coefficient of determination (r^2). For example, for BP-filter 0.04 –0.5 Hz, $r^2 = 0.34$ and for BP-filter 0.3- 0.5, $r^2 = 0.32$ compared with $r^2 = 0.50$ for w_f filter.

Another point is to test whether roll acceleration or roll velocity is the main cause of motion sickness in this case. Unfortunately roll velocity and roll acceleration are concurrent factors and for the test conditions (A and G) they are highly correlated. A higher roll acceleration magnitude will cause a higher roll velocity magnitude. However, condition F with the limitation of tilt acceleration, this correlation is lower. A demand of a higher roll velocity can not meet with a higher magnitude of roll acceleration (because of the limitation) but instead the roll acceleration phase is increased in time instead. Therefore using condition F offers a possibility of testing whether any difference exists between provocation from roll acceleration or roll velocity, see Figure 31.

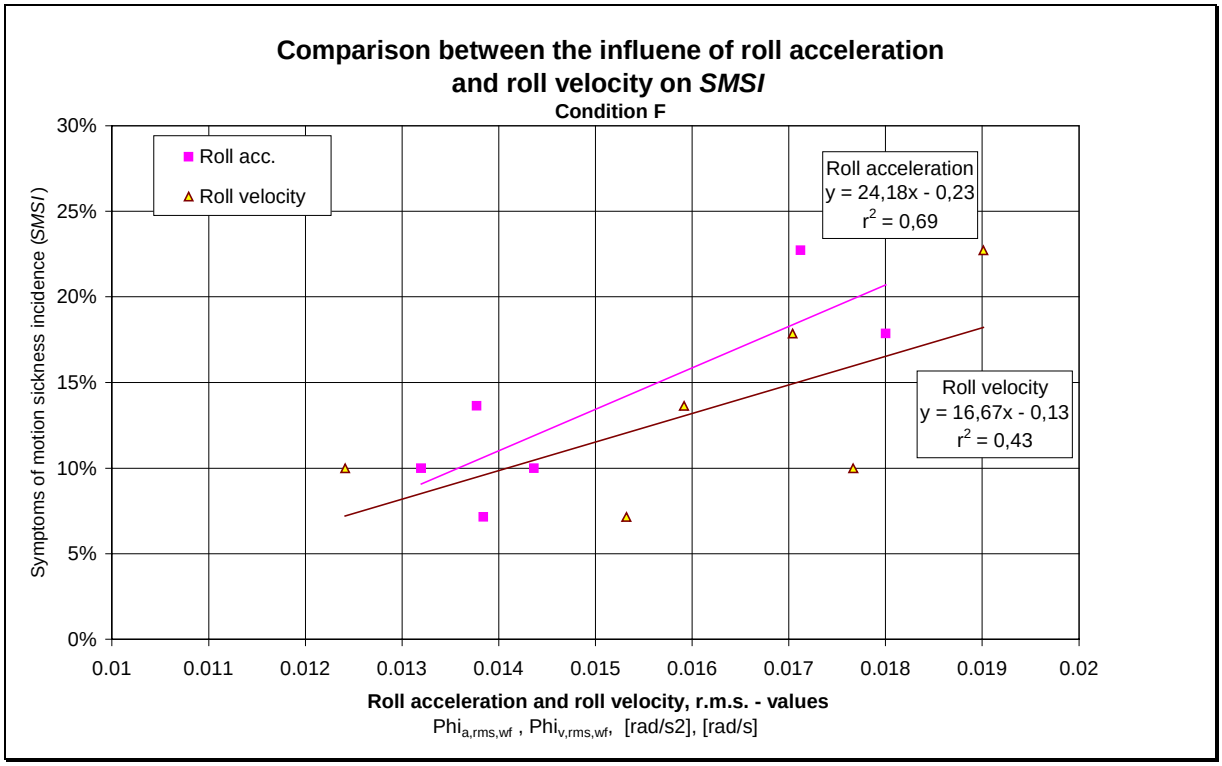


Figure 31 *Comparison between the influence from r.m.s.-values of roll acceleration and roll velocity on symptoms of motion sickness (SMSI).*

From this limited investigation (with only 6 data points per test cases) there is an indication that r.m.s – values calculated from roll acceleration may have a better correlation to *SMSI* than the corresponding roll velocity. This indicates that the corresponding motion dose from roll acceleration is better correlated with motion dose from roll velocity.

6.3.8 Summary and conclusions

A tilt compensation of 55% showed to be the most favourable of the examined conditions. Both conditions F and G show a significant reduction of symptoms of motions sickness incidence (*SMSI*) in the order of 30 - 45%. Differences in estimated ride comfort, frequency of comfort disturbances and rated ability to work or read are small and not significant.

Females reported significantly two to three times higher values or about 10-percentage units. of *SMSI* than male There are also indications that limited tilt speed and/or tilt acceleration may reduce symptoms. There was a significant reduction of *SMSI* for females travelling backwards compared with those travelling forwards. Sitting next to a window or not, did not influence *SMSI* significantly.

Average ride comfort was estimated in the range of 4.0 - 4.2 on a five-grade scale, from 1 (very poor ride comfort) to 5 (very good ride comfort). There was no significant difference between all the studied conditions.

The frequency of comfort disturbances as well as the estimated ability to work and read in the conditions F and G do not differ significantly from condition A.

The higher *SMSI* reported from the first and last test part probably indicates that this part of the track is more severe (nauseogenic) than the other part. This also means that the results (*SMSI*) from different test parts are more or less independent from each other, since the subjects have recovered from earlier motion doses. Different tracks (up and down line) may influence this further. A model for estimating nausea when leakage is present under fluctuating conditions has been put suggested by Kufver and Förstberg (1999), see also chapter 8.

SMSI correlates quite well with motion doses calculated from roll accelerations but less with the corresponding motion doses calculated from lateral or vertical accelerations.

Frequency analyses from a limited section of the test part between Linköping and Katrineholm show that the calculations from rm.s – values from w_f - weighted roll acceleration gives quite good prediction of motion dose values for the whole test parts. Tests with other extended weighting filters do not show better coefficients of determination than the w_f - filter.

There is a weak indication that roll acceleration is a better indicator of SMSI than roll velocity.

7 Tests in simulator

The tests were divided into two parts. Part I with seven test conditions and part II with altogether four plus two test conditions. In Part I combinations of different horizontal (lateral) and roll motion amplitudes were tested. In Part II the same horizontal motion was used with small variation of the applied roll motion as limited roll velocity, roll acceleration etc and a no added vibration condition. The simulator tests have been reported in Förstberg (2000a) and been presented at he following conferences (Förstberg 1999, Förstberg et al. 1999a).

7.1 Introduction

The train experiments, reported in the previous chapter, could only use a limited set of independent variables: train speed, tilt compensation ratio, limitation of tilt velocity or tilt acceleration. It is difficult to achieve conditions where there is only roll or only lateral acceleration by a train experiment. Therefore, it was decided to conduct a simulator study where horizontal acceleration and roll motion could be independently controlled but also combined to represent "train-like" conditions.

7.1.1 Objectives of the simulator tests

The main objectives of this experiment were:

Part I To investigate how different combinations of horizontal (lateral) accelerations and roll motions will influence motion sickness (nausea). The low-frequency lateral accelerations (cabin) and roll velocity (< 0.5 Hz) used in the tests are in the same order of magnitude experienced in tilting trains. Also, typical lateral and vertical vibrations found in trains were added to the motion conditions. These vibrations were in the frequency range of 0.5 – 15 Hz.

Part IIA To investigate how different special combinations of roll and/or horizontal motion will influence nausea ratings. These combinations were: limited roll velocity and limited roll acceleration as well as limited second derivative of the horizontal acceleration (smoothed ends – smooth corners). Also, vibrations were added in these conditions.

Part IIB Additional tests with a condition with no added vibrations.

Response variables were: ride comfort, comfort disturbances, ability to work/read, mental work ability, illness ratings and nausea ratings. Special interest was also the decay/leakage of nausea/illness ratings when the motion was stopped.

The tests took place in the VTI car-driving simulator, where the car cabin was removed and replaced with a "train" cabin with two seats from an *X2000*-train. The tests took place in June and August 1998.

7.1.2 Scope of the simulator tests

In a train environment, the low-frequency content of lateral and vertical accelerations together with roll and yaw motions are governed by alignment, cant, train speed and tilt system. Although there are many factors that will contribute to provoke nausea and motion sickness, this study is limited to investigate the influence of horizontal (lateral) acceleration together with different combinations of roll motion. Accepting these limitations, the test environment of the VTI car-driving simulator, capable of generating horizontal (lateral) and roll motions, was selected instead of using a test train. With a simulator, it is possible to generate combinations of horizontal and roll motions in a systematic order, which is not possible in a train. On the other hand, the simulator has other limitations, such as the length of permissible motion in the horizontal direction, maximum velocity and acceleration that can be generated by the moving system. In this case, it was possible to achieve a maximum acceleration of 1.1 – 1.2 m/s^2 in the horizontal plane during a 6 – 8.4 s test sequence. This acceleration level corresponds to a normal curving with a non-tilting train, as experienced by the passenger. For a tilting train, the corresponding lateral acceleration at track level and in the horizontal plane is typically 2 – 2.5 times larger than for a non-tilting train. Also, the roll angles used, in the test, are about half the amplitude normally encountered in tilting trains. However, the magnitudes of the rate of change of horizontal acceleration and roll velocity are of the right order.

Definitions

Definitions and terminology are shown in appendix A. Some terms may need to be explained for easier understanding. *Test run* is the individual test ride for each subject. It is normally 31 min in duration. Test *turn* is used for indicating what number of order, the subject was taking part in a test run. *Test condition* indicates what kind of motion condition the subject were experienced, i.e. test conditions reflects the test design. *Motion sequences* is the different motion patterns of the test motions. Different motion sequences build up a *total motion sequence* with the duration of 60 s. *Test sequence* is the sequence of events during a test run, i.e. what the subject was supposed to do at certain time points, during the test run. The term *horizontal* will be used for lateral acceleration in the horizontal plane and the term *lateral* for lateral acceleration in the plane of the cabin (simulator).

7.2 Simulator motion system and test design

7.2.1 Motion system

The car-driving simulator at VTI was used to provide horizontal and roll motion in the experiments, see Figure 32.

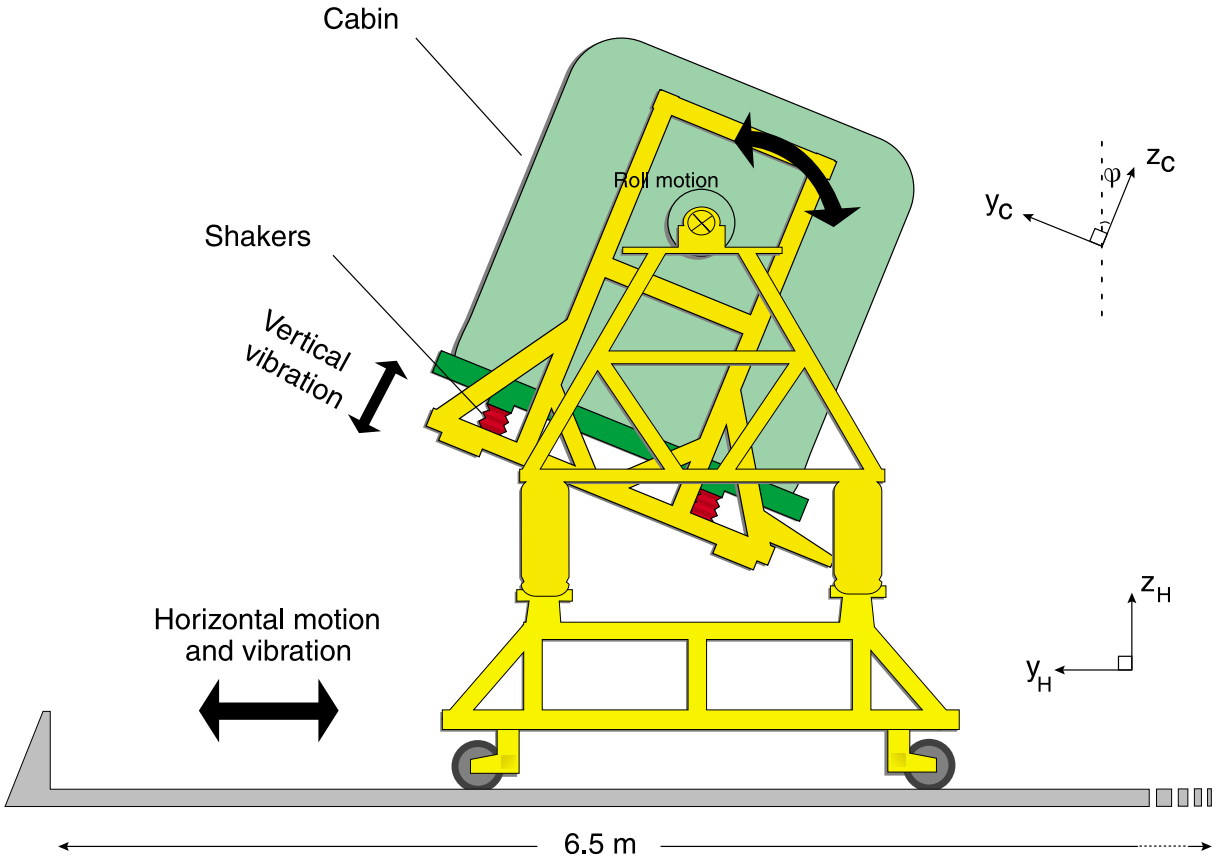


Figure 32 *Motion system of the simulator with the outer horizontal and roll motion system for low frequency motions and inner motion system (vibration platform) with shakers for high frequency vertical and roll vibration.*

Simulator capacity

The simulator has an outer motion system with the capacity of:

Horizontal displacement:	± 3.25	[m]		
Maximum horizontal velocity:	2.0	[m/s]		
Maximum horizontal acceleration:	2.0	[m/s^2]		
Roll angle:	± 24	[º]	(0.42 [rad])	
(Pitch angle:	± 24	[º]	(0.42 [rad])	Not used)

and an inner motion system (vibration platform) with the capacity of:

Vertical displacement:	± 0.050	[m]		
(Longitudinal displacement:	± 0.075	[m]		Not used)
(Roll angle:	± 7	[º]	(0.12 [rad])	Not used)
(Pitch angle:	± 4	[º]	(0.07 [rad])	Not used)

The simulator is described in more detail, for example in VTI Särtryck 106A, 150A and 279 (Nilsson 1989, Nordmark, Jansson, Lidström, & Palmkvist 1986, Törnros, Harms, & Alm 1997).

7.2.2 Physical environment

Cabin

On the moving platform, the normal car cabin was removed and a "train" cabin with the approximate dimensions 2 x 1.7 x 1.7 m was mounted. The rotation axis was 0.72 m above the floor of the cabin and 0.15 m to the left of the centre line. It was at about the chest level of the seated subjects. Inside were two second class seats (from *X2000* train) placed along the sides of the cabin with a narrow corridor between and behind the seats. The cabin walls were white coloured together with the ceiling and a wall-to-wall carpet covered the floor. Loudspeakers were placed underneath the chairs playing recorded background train noise; see below. Interior lights were provided from two spotlights and from a common background light. A curtain between the subjects prevented direct eyesight. The subjects were instructed not to talk to each other during the test. A picture showing an interior view of the cabin and a subjects' position is shown in Figure 33.

Figure 33 *Interior view of cabin with subject. The curtain between the two subjects is not shown in the picture.*

Background noise

Noise from the outside while the cabin was moving was clearly audible, even if measures had been taken to sound isolate the cabin. The main source from outside was the horizontal motion

generator, a hydraulic motor with pegs and chains connected to the moving platform. This sound was correlated with the horizontal velocity of the moving platform.

Background train noise from the load speakers inside the cabin: ~ 62 dB_A L_{eq}
Background noise from the outside, inside the cabin
while moving without added train noise: ~ 58 dB_A L_{eq}
Total noise level inside the cabin while moving and with train noise: ~ 64 dB_A L_{eq}

7.2.3 Motions sequences

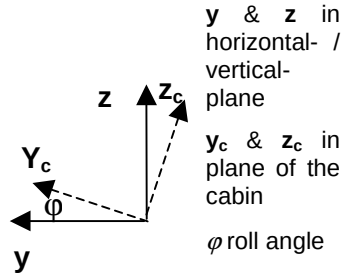
The selected motion sequences in the simulator should as closely as possible resemble a "real" acceleration pattern in a train when running into and leaving a curve. Therefore, given the limitations of the simulator, what low-frequency accelerations would appear in a train if track is moved 6.5 m sideways? Typical curves in a railway environment have *transition curves* where the radius varies and *circular curves* where the radius is constant. Changing radius means (train speed being constant) changing lateral acceleration (horizontal, track and car body plane) and with a constant radius, there will be a constant lateral acceleration. The layout of transition curves is often of the clothoid type, i.e. the curvature (inverse radius) is changing linearly with the distance travelled along the line. This means that the lateral acceleration is changing linearly with time. The selected basic motion sequence selected was therefore trapezoidal and not sinusoidal. The limitation of horizontal displacement to about 6.5 m meant that the acceleration and retardation of the moving cabin had to take place within that distance. It restricted the combinations of maximum acceleration level and the duration of the motion cycle. Three motion sequences were used; the first was relatively simple lasting about 6 s, the second was long and complex with a test part lasting about 8.4 s and the third was short resembling a long-wave track irregularity. They are described below.

Definition of roll motion

The motion sequences were created from three basic motion sequences of horizontal accelerations. Each sequence was integrated to determine if the horizontal velocities and horizontal displacements were within the capacity of the motion system of the simulator. Roll angles (φ_c) for the roll motions were generated from these horizontal accelerations according to the formula:

$$\varphi_c = k_c \cdot \arctan(a_{yH} / g) \qquad [7.1]$$

where a_{yH} = horizontal (lateral) acceleration [m/s^2]
g = gravitational acceleration (9.81 m/s^2)
k_c = degree of tilt compensation ($0 \leq k_c \leq 1$)
φ_c = roll angle [rad]



The roll angles generated by this formula [7.1] compensate the horizontal acceleration to $k_c \cdot$ 100 %. This means, if k_c = 1, that the passenger inside does not perceive any nominal lateral acceleration, when the cabin is tilted with this angle φ during horizontal acceleration of the cabin. Roll velocity and roll acceleration were derived from roll angle by time differentiation.

The total motion sequence consisted of a 60 s sequence, built up from three different motion sequences. The total motion sequence then repeated itself for 31 min for the whole test run.

Motion sequence 1

The motion sequence 1 was a 6 s long sequence, consisting of, see Figure 34:

1. A 1.2 s part with uniform increase in acceleration up to a maximum horizontal acceleration in the horizontal plane of 1.1 m/s^2 (corresponding to a transition curve). Horizontal jerk is 0.92 m/s^3. The corresponding roll angle for 100% compensation is 6.4 ° (0.112 rad) with roll velocity 5.4 °/s (0.094 rad/s).
2. A 0.6 s part with constant horizontal acceleration (corresponding to a circular curve).
3. A 1.2 s part with retardation back to zero acceleration. (Parts 1 –3 have a total duration of 3 s.)
4. The next 3 steps were the same as step 1 – 3 but with a negative sign. Thus, the total sequence is corresponding to a reverse curve.

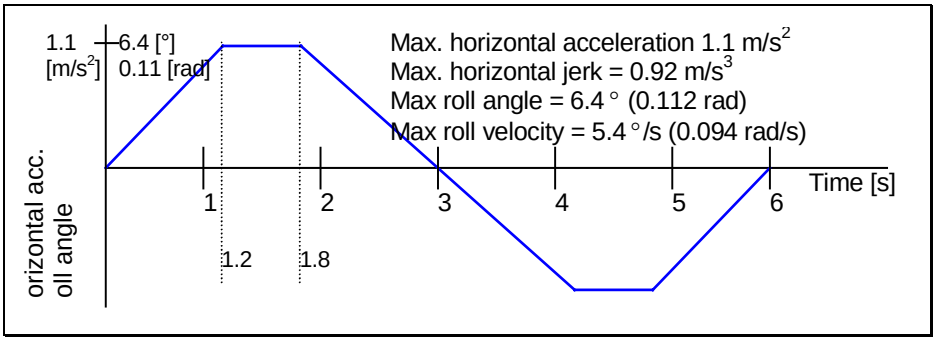


Figure 34 Motion sequence 1. Layout for 100% horizontal acceleration and 100% roll motion.

Motion sequence 2

One way to achieve somewhat higher accelerations and longer "transitions curves" is to start the motion sequence with an initial horizontal velocity. Therefore, this motion sequence starts with an acceleration part, then the test part and at last a retardation part. The test part was increased to 8.4 s and together with acceleration and retardation parts the total time duration was 22 s, see Figure 35.

The motion sequence 2 consisted of:

1. A 7 s part with low magnitude of horizontal acceleration of the cabin without roll motion.
2. An 8.4 s main test part resembling the sequence 1 but the maximum horizontal acceleration was instead 1.22 m/s^2 with the corresponding maximum roll angle of 7.1 º (0.124 rad). The duration of transition parts were 1.8 s and the part with a constant horizontal acceleration was 0.6 s. Maximum horizontal jerk was 0.68 m/s^3 and maximum roll velocity was 4.0 °/s (0.069 rad/s).
3. A 6.6 s retardation part with low magnitude acceleration and without roll motion.

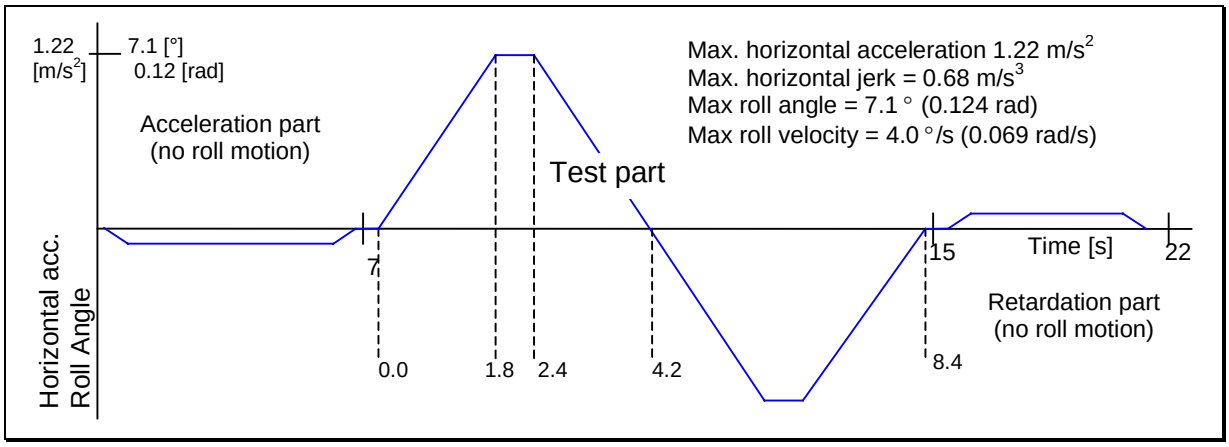


Figure 35 Motion sequence 2. Layout for 100% horizontal acceleration and 100% roll motion.

Motion sequence 3

The motion sequence 3 was made to resemble a long wave irregularity in the horizontal (lateral) track alignment. The irregularity had a duration of 3 s. It repeated itself with a negative sign so the total duration was 6 s. The horizontal displacement was about 0.15 m and the maximum horizontal acceleration was 0.18 m/s^2, see Figure 36. The cabin was able to roll during this motion according to the test condition in question.

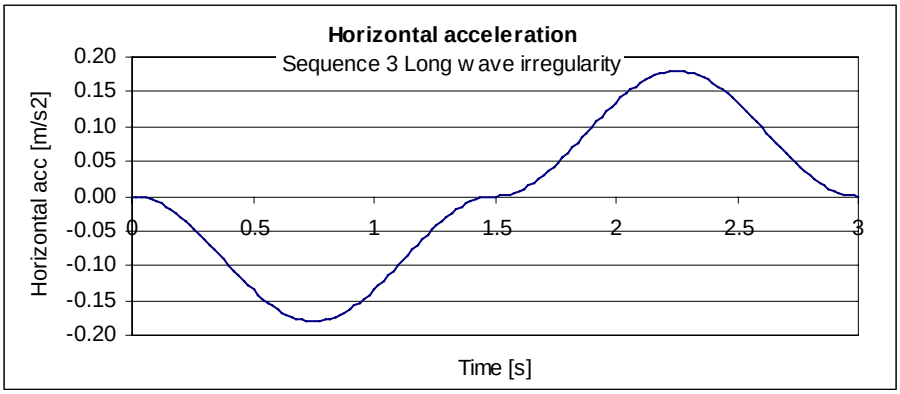


Figure 36 Motion sequence 3 (Long wave irregularity).

Total motion sequence

The total motion consisted of a 60 s sequence was first made up from two sequences 1, then one sequence 2 and then once again the sequence 1 (modified with a factor 0.921)[27]. After this two sequences 3 were inserted and at the end of the sequence a few seconds of almost no motion was inserted in order to adjust the zero point of horizontal motion, see Figure 37. Appendix B shows examples of the motion quantities for the different motions conditions. This total motion sequence was repeated 31 times for the whole test run.

[27] This because the sequence 2 stopped with less lateral distance from the zero point on the simulator track.

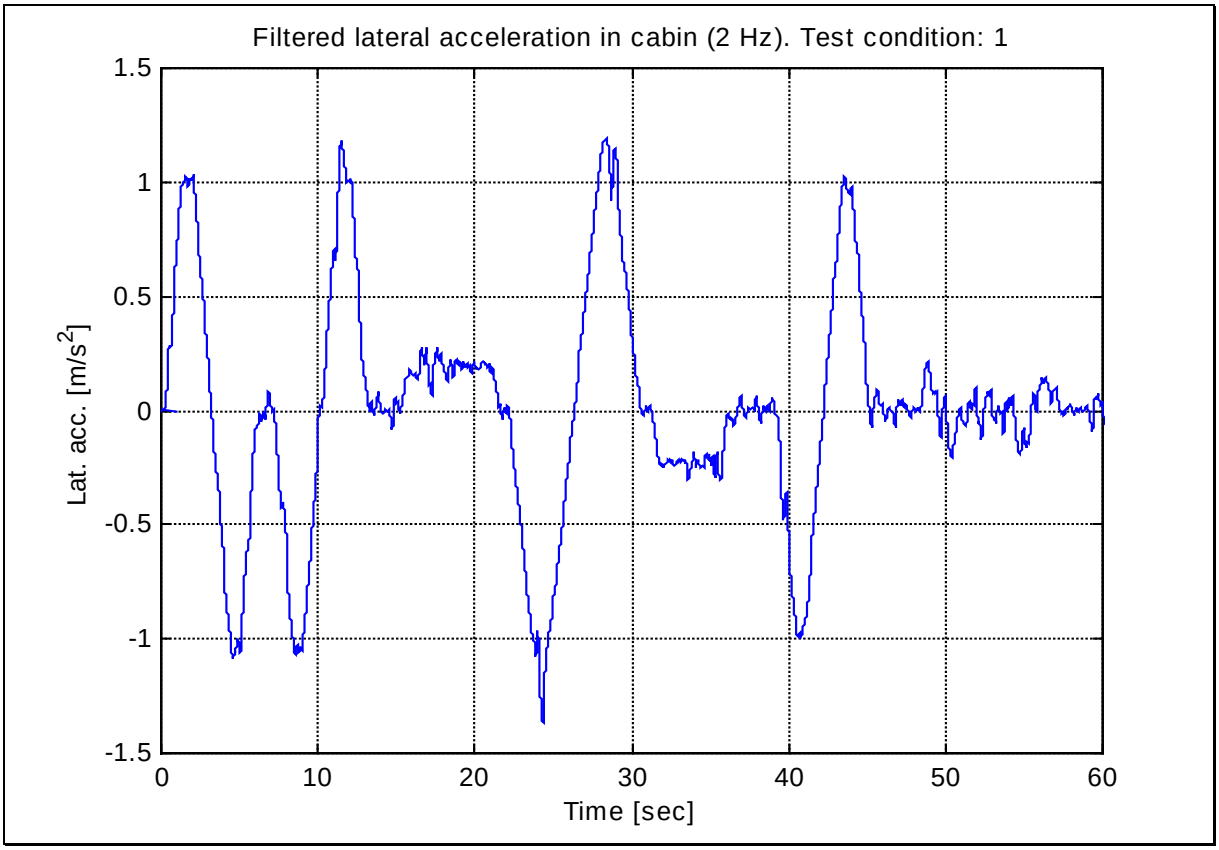
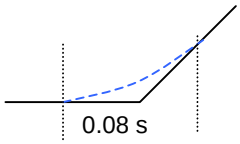


Figure 37 *Lateral acceleration in the cabin for the motion condition 1 (H100R0) with only horizontal motion, low-pass filtered with 2 Hz. Horizontal and vertical vibrations were added. Note: In the condition 1 the lateral acceleration in the cabin is equal to horizontal accelerations.*

Limitation of roll acceleration in corners "kinks"

Corners "kinks" in the horizontal accelerations and roll angles were rounded and spread out during 0.08 s. This lead to a limitation of roll acceleration to 67 °/s^2 (1.17 rad/s^2) for sequence 1 and 50 °/s^2 (0.86 rad/s^2) for sequence 2 for the fully compensated roll motion.



Comparison with motion environment in tilting trains

A comparison between the motion environment in trains (tilting, non-tilting) in Sweden (*SJ*) and Norway (*NSB*) and the two large motion sequences in the simulator cabin is shown in Table 26.

Table 26 *Typical maximum values of horizontal and lateral acceleration, jerk and roll motion parameters in Swedish and Norwegian train environment (tilting and non-tilting) and corresponding values in the simulator cabin (for the two different motion sequences).*

Typical maximum / minimum values	*Tilting trains*		*Non tilting trains*[i]		*Simulator cabin*		*Units*
	SJ	*NSB*	*SJ*	*NSB*	*Seq. 1*	*Seq. 2*	
Horizontal acceleration	2.6	2.8	1.9	1.9	1.1	1.2	[m/s^2]
Lateral acc. in track plane	1.6	1.8	1.0	1.0	-	-	[m/s^2]
Lateral acc. in car body plane	0.5	0.8	1.3	1.25	1.1[ii]	1.2[ii]	[m/s^2]
Min. time in transition curve	3.1	2.0	3.5		1.2	1.8	[s]
Horizontal jerk	0.8	1.4	0.55		0.9	0.7	[m/s^3]
Lateral jerk (train car body)	0.2	0.4	0.45	0.8			[m/s^3]
Roll angle (ref. horizontal plane)	12	11.5	-	-	6.4	7.1	[^{o}]
	0.21	0.20			(0.11	0.12)	[rad]
Roll velocity	4.4	5.4	1.5	3.6	5.4	4.0	[^{o}/s]
	0.077	0.094	0.026	0.064	(0.094	0.070)	[rad/s]

Remarks: i .Example from category B train in Sweden and express trains in Norway
ii In condition with no roll motion
Table modified from Kufver (1998) and Kufver & Gåsemyr (1999).
SJ = Swedish State Railways, *NSB* = *NSB BA* (Norwegian State Railways).

Thus, the simulator can generate motions with approximately the same magnitude of horizontal jerk and roll velocity perceived by the passengers in a tilting and non-tilting train. However, the time scale is much shorter. The motion sequence 1 takes 6 s while passing a reverse curve by a train is an order of 15 – 20 s. This means that the generated frequencies in the simulator are much higher than in a typical train motion environment with the possible consequences that the motions in the simulator is much more nauseogenic than in a tilting train.

Added vibrations

To all test conditions, except for condition 11, horizontal and vertical accelerations were added in the frequency range 0.5 – 15 Hz. The vertical accelerations were added through the shakers at the inner motion system and the horizontal acceleration through the outer motion system. The vertical shakers have the capacity of higher frequency output than the horizontal driving system. The acceleration signals were extracted from a measurement from earlier tests with *SJ X2000* train. The vertical accelerations in cabin had maximum variation $(a_{zv}) = \pm 0.28$ m/s^2 with an r.m.s – value $(a_{zv,rms}) = 0.1$ m/s^2 and a vertical motion of ± 0.005 m. The corresponding values for the horizontal acceleration were: $(a_{yH}) = \pm 0.23$ m/s^2 , $(a_{yH,rms}) = 0.07$ m/s^2 and a horizontal motion of ± 0.2 m. The duration of these signals was 7 s and it was repeated over and over.

7.2.4 Test conditions

The test conditions were divided into two parts. Part I was designed to test horizontal and roll motion influence on nausea and the part II was designed to test different roll (tilt) strategies when the overall horizontal motion was determined. It was intended to test limitations in roll acceleration or roll velocity as well as transition curves with smoothed ends or corners (Part IIA). One condition was included with no added vibrations (Part IIB).

Part I

The above total sequence (60 s) of horizontal (lateral) acceleration was denoted 1.1 m/s^2, from the maximum value of horizontal acceleration in motion sequence 1. A corresponding roll motion was generated as 100% compensation of this horizontal acceleration using Equation [7.1]

above (k_c = 1), giving a maximum roll angle of 6.43 º (0.112 rad). To get other test conditions the horizontal acceleration was scaled to get a 75% copy (max value 0.825 m/s^2) and the roll motion was scaled to get 56% and 75% copies[28] 3.62º (0.063 rad) and 4.82º (0.084 rad), respectively. The seven different test conditions with their corresponding numbers are shown in Table 27.

Table 27 Test conditions shown as functions of maximum values of horizontal acceleration and roll angles for test sequence 1.

Max. roll angle *Max. roll velocity*	0 [º] 0 [º/s] (0%)	3.62 [º] 3.0 [º/s] (56%)	4.82 [º] 4.0 [º/s] (75%)	6.43 [º]; (0.112 [rad]) 5.3 [º/s]; (0.094 [rad/s]) (100%)
Max. horizontal acceleration				
1.1 [m/s^2] (100%)	1 (k_c = 0.0)	2 (k_c = 0.56)	3 (k_c = 0.75)	4 (k_c = 1.00)
0.825 [m/s^2] (75%)		5 (k_c = 0.75)	6 (k_c = 1.00)	
0 (0%)			7	

Mnemonics

For mnemotechnical reasons the following mnemonics is used for the different test conditions:

Condition 1	H100R0	(H = Horizontal (lateral), R = Roll)
Condition 2	H100R56	
Condition 3	H100R75	
Condition 4	H100R100	
Condition 5	H75R56	
Condition 6	H75R75	
Condition 7	H0R75	

This scheme allows for comparison along the rows (same horizontal acceleration but increasing roll motion) or along columns (same roll motion but decreasing horizontal acceleration). Comparisons can also be made between different amounts of tilt compensation: 100% (condition 4 (H100R100) and condition 6 (H75R75)) or 75% (condition 3 (H100R75) and condition 5 (H75R56)). Thus, the scheme gives three possible directions of comparisons.

Part II

All conditions in this part are derived from condition 3 with full (100%) horizontal acceleration and 75% roll motion (k_c = 0.75). The different conditions are described in Table 28.

Conditions 8 (LRA) and 9 (LRV) use the same horizontal acceleration as the reference condition 3 (H100R75) does. In track design, these conditions correspond to a changed superelevation ramp but an unchanged transition curve. In condition 10 (SE), the time function of the horizontal acceleration has the same as the time function of the roll angle. A smoothening at the start and end of the transition curves eliminates kinks in curvature and roll angle. In track design, condition 10 corresponds to a change of the type of transition curve as well as the type of superelevation ramp (Kufver 1999). Condition is based on condition 3 with the difference that no added vobrations

[28] 75%·75%. = 56%

7.2.5 Test design

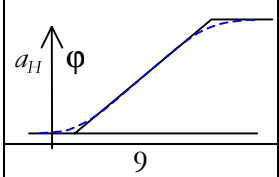
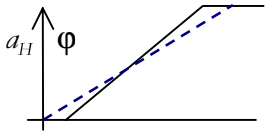
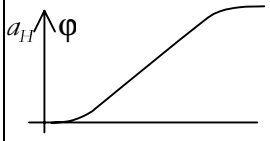
Designs for Part I

In part I, most subjects participated either in all seven conditions or in four conditions (repeated measurements). Some subjects only took part in one condition selected randomly.

Repeated measurements (within subjects design)

For the repeated measurements two designs were applied, one for seven conditions (Tables 14 and 29) and one for four conditions (Table 15). For this, a Latin square[29] of order seven and a Latin square of order four were used. There should also be the same number of subjects in each group.

Table 28 Conditions involved in part II tests (horizontal acceleration (a_{yH}): solid lines, roll angle (φ_c): dashed lines).

Condition	*Description - mnemonics*
3	*Reference condition (H100R75)* Condition 3 with horizontal acc max of 1.1 m/s^2 and 75% of roll motion (4.8 [º]).
8 	*Limited roll acceleration (LRA)* The roll acceleration was limited and increased in duration to 0.4 s instead of normal 0.08 s. This limited the roll acceleration to 13.4 and 10.0 [º/s^2] for the short and long motion sequence, respectively. The roll acceleration started and ended 0.2 s before each "kink" in horizontal acceleration.
9 	*Limited roll velocity (LRV)* The roll motion started 0.2 s before the horizontal acceleration started and correspondingly ended 0.2 s after the rise of horizontal acceleration was completed. The roll acceleration was the same as in condition 3, but the time for duration was reduced to 0.06 s (from 0.08s), giving a 25% reduction in roll velocity.
10 	*"Smoothed corners" (SE)* Limited roll acceleration and limited second derivative of horizontal acceleration. The horizontal acceleration has the same shape as the roll angle in condition 8.
11	*No vibration (NV)* Same as condition 3 (H100R75) but without added horizontal and vertical vibrations.

Remark: In figure $a_H = a_{yH}$ and $\varphi = \varphi_c$..

[29] A Latin square is characterised by that a test condition is only used once in a row and once in a column (see also Appendix A2). Both rows and columns can be permuted. Table 29 shows the used Latin square of order 7, where the columns have been randomly permuted. The permutation is used to prevent order effects, for example, that condition 2 always follows condition 1.

Table 29 *Latin square for seven conditions in Part I with seven turns and seven test groups, with randomly permuted columns. The table shows the planned conditions for each turn.*

	The number of the test run (turn)						
Group	*1*	*2*	*3*	*4*	*5*	*6*	*7*
A	1	4	2	5	7	6	3
B	2	5	3	6	1	7	4
C	3	6	4	7	2	1	5
D	4	7	5	1	3	2	6
E	5	1	6	2	4	3	7
F	6	2	7	3	5	4	1
G	7	3	1	4	6	5	2

However, due to the possibilities of the different subjects to come and participate in the tight time schedule, the order in Table 29 had sometimes to be broken.

For subjects only participating in four turns, they were distributed into two groups: one with the conditions no. 1, 2, 3 and 4 and another with the conditions no. 3, 5, 6 and 7. They were tested according to Latin Square of order 4. The condition no. 3 was used as a common link between these groups.

Randomised design

Test subjects, only taking place in one turn, were randomly distributed among the test conditions, as far as it was possible.

Test deigns for Part II

The test subjects in part IIA participated in four different test conditions and a Latin square of order 4 was used. In Part IIB there were two test conditions, see Table 30. Subjects were randomly selected to one of these test condition groups (IIA or IIB). The condition 3 was used as a reference condition linking Part IIA and Part IIB together with Part I.

Table 30 *Conditions for the test part II.*

	Conditions
Part IIA	3, 8, 9 & 10
Part IIB	3 & 11

7.2.6 Test subjects

Advertisements for test subjects were displayed on notice boards at The Linköping University (LiU) and on VTI's web-site. About 155 subjects applied to the test. Of those 155 subjects, 90 were males and 65 females. The applicants had marked their preliminary self-rated sensitivity to motion sickness in three grades: low (1), medium (2) and high (3), see Table 31.

Table 31 Number of applicants to the test.

		Male	*Female*	*Total*
Sensitivity	(1) low	70	30	100
(preliminary	(2) medium	18	25	43
self-estimated)	(3) high	2	10	12
Total		90	65	155

The males had significantly lower average level of self-rated sensitivity for motion sickness than the females, see Table 32. No correlation with age was found. Mean age for males was 25.4 years and females 25.8 years and the median age was 24 years for both genders.

Table 32 Male and female applicants' mean self-rated sensitivity to motion sickness on a 3 – grade scale.

Sensitivity	*N*	*Mean sensitivity*[i]	*Standard deviation*	*95 % conf. interval for mean* *Lower bound*	*Upper bound.*
Male	90	1.24	0.475	1.14	1.34
Female	65	1.67	0.704	1.50	1.85
Total	155	1.42	0.619	1.32	1.52

Remark: [i] Sensitivity grades: low = 1, medium = 2 and high = 3.

Selection

Part I

Earlier tests (Förstberg 1997a and summarised in Chapter 6) have shown that there is a large difference in the female/male response to motion regarding nausea. Therefore, about the same number of females and males were randomly selected from the test applicants from the preliminary sensitive classes; low and medium. This was done because too high sensitivity subjects were believed to be too sensitive to the motion conditions with supposed high nausea ratings. Secondly, there were too few male subjects with high sensitivity.

Originally 21 subjects were selected according to the rules above to take part in all seven turns and additional 16 subjects were selected to take part in four turns. However one of the 21 subjects had to interrupt the test run with a severe nausea and therefore was not evaluated any further. Of the 16 subjects selected for four turns, 11 subjects took part in the tests. Addition subjects were then needed and 8 subjects took part in one turn and 4 subjects in three turns, see table 33.

Of the total of 205 evaluated test runs, 140 test runs were made by subjects taken in part in all seven test condition, additional 46 test runs with four or five turns. The remaining 19 test runs, 7 subjects were taking part in only one turn and 12 subjects in three turns. This means that 42 subjects took part in at least one turn and they were evaluated.

Table 33 Number of subjects taking part in the different turns in the test part I.

	Turn 1	*Turn 2*	*Turn 3*	*Turn 4*	*Turn 5*	*Turn 6*	*Turn 7*	*Total*
Male	19 (18[i])	16	16	14	10	9	9	92
Female	24	19	19	17	12	11	11	113
Total	43 (42[i])	35	35	31	22	20	20	206 (205[i])

i Number of subjects taking part and evaluated.

Statistics for age and sensitivity for all subjects, taking part in at least in one test run, are shown in Table 34. Subjects, taking part in the test, now rated their sensitivity to motion sickness on a seven grade scale from 1 (very low sensitivity) to 7 (very high sensitivity).

Table 34 Statistics for subjects taking part in the first turn, test part I.

		Male	*Female*
Number		18	24
Age mean	[year]	25.5	25.1
Age std. dev.	[year]	8.2	5.4
Age median	[year]	23	23
Age range	[year]	17 – 48	19 – 38
Sensitivity[i] mean[ii]		2.7	3.25
Sensitivity std. dev.		0.75	1.2
Sensitivity median		3	3
Sensitivity range		2 - 4	1 - 5

Remarks: i Self-estimated on a 7 grade scale from very low (1) to very high (7).
ii t-test, 2 tailed $p \leq 0.1$. Likelihood ratio asymptotic significance $p \leq 0.03$
std. dev. = standard deviation

Part II

In test parts IIA and IIB, subjects were selected in three different categories with about 5 in each category. These categories were high sensitivity female and medium sensitivity males and females. This was done to get a more sensitive group than in test part I, because of the much smaller expected differences between the alternatives, see Table 35 and 36. One subject in Part II vomited during her first turn but she took part in all her four turns.

Table 35 Statistics for subjects taking part in the first turn, part IIA.

		Male	*Female*
Number		5	11
Age mean	[year]	24.2	24.7
Age std. dev.	[year]	6.0	9.3
Age range	[year]	17 - 32	18 – 51
Sensitivity mean[i]		2.4	3.5

Remark: i On a 7 grade scale from very low (1) to very high (7).

Table 36 Statistics for subjects taking part in the first run (turn). part IIB.

		Male	*Female*
Number		6	9
Age mean	[year]	22.7	23.4
Age std. dev.	[year]	5.2	3.1
Age range	[year]	18 - 28	17 – 27
Sensitivity mean[i]		3.3	3.0

Remark: i On a 7 grade scale from very low (1) to very high (7).

Safety and consent issues

The subjects were informed of the purpose of the test in beforehand and they might get sick in the test. They made a written approval of taking part of the test. They had the right to leave the test at any time. Their safety was secured by a number of ways including emergency stops for subjects opening cabin doors, etc.

7.2.7 Test procedure

When the test subjects first arrived to the test site, they answered a questionnaire of background variables. These were: age, gender, how often they had travelled on different kinds of transportation (cars, buses, trains etc.), how often they had had nausea in those transportation modes and an estimation of their sensitivity to motion sickness. Then they also filled out form that they accept the test conditions (they might get ill) and they were informed that they were allowed to withdraw at any point during the test. After that, they followed a test sequence of the following order:

Test sequence

Before each test run (turn):

Questions of well being, medication (possibly), tiredness and then 1 min of p-deletion test (p-test)[30]. The p-test was done in order to judge if the mental work ability (alertness) was altered during the test caused by nausea. For examples of p-tests and questionnaires, see Appendix F.

After this administration of pre-test questionnaire, the subjects were taking their seats in the cabin. Subjects were asked to read when not answering the questions or doing the p-test. They were instructed not to talk to each other and due to a curtain between them they could not have direct eye contact. After closing the door and an initialisation process of the simulator system, the cabin started with a slow lateral motion to the right to reach a "zero" point of the track. The actual test run started and stopped from this position. The subjects were then asked to do the following procedure at the specified times. (Stated times below refer to the start of the test run).

During each test run:

Starting at	*Action*
0 min	Start of test run. 1 min p-test
1 min	Rating of nausea and illness
6 min	Rating of nausea and illness
10 min	1 min p-test
11 min	Rating of nausea and illness
16 min	Rating of ride comfort, nausea and illness
20 min	1 min p-test
21 min	Rating of nausea and illness
26 min	Rating of nausea and illness
30 min	1 min p-test
31 min	Stop of test run. Rating of ride comfort, work ability, nausea and illness

The test run stopped after 31 min and the cabin returned to the starting point. Subjects then left the cabin and remained in the testing room for further questions for about 10 min, see below.

[30] p-deletion test (p-test): A test where the subjects were asked to find and mark as many p's as possible during 60 s in random letter matrices. See further explanation under evaluation parameters and Appendix E.

After each test run:
36 min Rating of nausea and illness
40 min 1 min p-test
41 min Rating of nausea and illness
42 min End of test, subjects were free to leave

If a subject wanted to leave the cabin (for causes like moderate or strong nausea), the cabin was stopped and the subject could leave it. For the remaining subject the test was continued as soon as possible. About 5% of the test runs were interrupting the test in this way. They normally came back to their next run. The interrupting subjects answered another set of questionnaire with questions focused only on rating s of nausea and illness. This could take up to 30 min after disembarking the cabin. This was administrated because it was important to monitor the recovery from nausea and the subjects' well being over a longer period of time. These data were useful to determine time constants for "leakage" of nausea and illness ratings.

For the remaining test subjects in the cabin, their nausea rating were probably reduced because of the no motion condition during the stop. On the other hand, knowing that the subject next to you had been suffering nausea to a degree that they wanted to stop the test run, might be provocative. The stop took about two – three minutes.

Test runs was sheduled from 8:00 in the morning until 21:00 in the evening, during two weeks in June 1998 and two weeks in August 1998. Latest start was scheduled at 20:00. Each test "session" normally took about 45 – 55 min.

7.2.8 Response variables and evaluation

Nausea and illness ratings

The main response from the subjects regarding nausea and well being were measured on a five and four grade scale:

Nausea rating (*NR*)	Illness rating (IR_{mod}) modified	IR_{org} (original)
0 = No symptoms	0 = I feel all right	0 = I felt all right
1 = Light symptoms but no nausea	1 = I do not feel quite well	1 = I felt slightly unwell
2 = Light nausea	2 = I feel rather unwell	2 = I felt quite ill
3 = Moderate nausea	3 = I feel bad	3 = I felt absolutely
4 = Strong nausea	(4 = I feel very bad, not used)	dreadful
(5 = Vomiting, not used)		

Grades and scales for judging the degree of motion sickness have been developed by Graybiel et al. (1968). This scale has been modified and a practical scale for rating of nausea has been developed by Golding with different co-authers (Golding et al. 1997, Golding & Kerguelen 1992, Golding & Markey 1996). For field studies a scale of rating illness (*IR*) has been developed by Lawter (1988) and Lawter and Griffin (1986, 1987). Golding's nausea rating scale has been adapted to this experiment as *NR*. For a possibility to have a reference to earlier train studies (Förstberg 1996, described in Chapter 6), the illness ratings modified scale (IR_{mod}) have also been used. The IR_{mod} is called *IR* scale throughout the thesis.
Some care has to be taken when using *NR* and *IR* scales. These grades, expressed verbally, may not be at equal distances from each other. This means that *NR* and *IR* are not necessarily proportional against experienced nausea or motion sickness (illness) for the subjects. On the other hand, there is no objective graded scale for nausea ratings. Five subjects with light symptoms (*NR* = 5 x 1) is equally valued as one vomiting subject (*NR* = 5). Nevertheless, practical tests

show that these scales are working well enough for this purpose (Griffin and Golding, personal communication).

Evaluated parameters for nausea and illness are:

Nausea Rating (*NRX):* Mean value for subjects' *NR* at minute *X*
Illness Rating (*IRX*): Mean value for subjects' *IR* at minute *X*
Example NR26 means NR after 26 min test motion.

Statistical considerations

Since these nausea and illness ratings are rather alike, there should be a strong correlation between them. A Spearman correlation analysis shows a significant correlation of 0.756 ($p < 0.001$, n = 42) for the subjects in the first turn.

There is however a problem in the subjects' responses on this scale. More than half of the subjects' responses to nausea and illness in the test, are *no symptoms* and *feel all right*. This gives distributions that are skewed. Normally, statistics based on the normal distribution are not applicable without care and maybe require some kind of transformation of data. Table 38 shows an example of a Kolmogorov-Smirnov tests (Siegel & Castellan 1988) for the subjects' estimated nausea at 26 min (*NR26*), testing if the distribution is of the Poisson type.

Table 37 One sample Kolmogorov-Smirnov test of Poisson distribution for subjects' nausea ratings (NR26). Responses are from the first test turn.

		NR26
Number of subjects		42
Poisson parameter[a,b]	Mean	1.36
Most extreme difference	Absolute	0.06
Kolmogorov–Smirnov Z		0.39
Asymp. significance (2-tailed)		0.998

Remark: a. Under the assumption that the tested distribution is Poisson distributed.
b. Calculated from data.

The parameter *NR26* may be Poisson distributed and a suitable transformation is the square root transformation[31] (Montgomery 1991). The result is that *NR26* cannot be regarded as normally distributed. Thus, when calculating the significance of a test hypothesis or using analysis of variance (ANOVA), a variable transformation should be used for *NR*26. Practical tests with *NR*26 have shown that the differences between evaluations with non-transformed and transformed variables are minimal. Therefore most evaluations are made with non-transformed variables but great care is needed. Some other methods may be needed.

Ordinal multinomial distribution

Nausea ratings (*NR*) and illness ratings (*IR*) belong to a distribution called ordinal multinomial. Ordinal means that there is a strict order between the different grades of *NR* and *IR*, i.e. $NR = 0 < NR = 1 < NR = 2 < NR = 3 < NR = 4$. Multinomial implies that there is a probability p_i for a rating in each grade i (class i) and $\sum p_i = 1$. This distribution is well suited for evaluation of this kind of responses.

[31] Possible transformations are for Poisson distributions: $z_i = \text{sqrt}(y_i)$ or $z_i = \text{sqrt}(1 + y_i)$. Sqrt = square root. (Montgomery 1991)

Test based upon the ordinal multinomial distribution and the use of generalised linear models (GLZ) see an short example in appendix A7 (Dobson 1990, McCullagh & Nelder 1989, Wiklund 2000).

Non-parametric tests

Non-parametric tests may be used when testing the significance of a model. In this case, no transformation is needed, since no assumption is done concerning the distribution of responses. A typical non parametric test is Kruskal-Wallis test (Siegel & Castellan 1988).

Repeated measures

The used test designs, in this test, involved both repeated measures as well as normal randomised design of test subjects. One way to cope with this mixed design is to use subjects as an explanation factor (if possible as a random factor) in the analysis of significance of the test hypotheses (Wiklund 2000).

Response variables, i.e. observed means, estimated marginal means and expected values

Observed means are the normal mean or average value of a sample. Confidence intervals are calculated with standard deviation for each variable and the use of Student's distribution.

Estimated marginal means are calculated together with analysis of variances (ANOVA). It assumes both a normal distribution of samples and a linear model behind the explanation variables. It considers all entered values and creates a linear model. Therefore, it is a better estimation of the "true" mean than the observed mean. If the model is perfectly balanced the observed mean and the estimated marginal mean is the same. Estimated marginal means are calculated at the mean value at the possible entered covariates[32]. This method has the advantages that the influence from the covariate variables will be minimised[33]. The covariates used in the evaluation are shown in different tables and figures. Confidence intervals are calculated from the error in the regression model, usually making them smaller than the corresponding intervals for the observed means.

Population means (expected values)[34] are calculated from the ordinal multinomial distribution. The assumption made here is that the distance between each level of *NR* is one. The first advantage is that the difference between *population means* for the condition is fairly accurate although the exact levels are a little more uncertain. It depends on the standard error of the intercepts. See an example of calculating probability and *population means* in the appendix A7. The second advantage is that in an ordinal multinomial distribution for all turns (all test runs), where turn is entered as a explanation factor, the *population means* can be given for the first turn, second turn etc.

The term *population means for NR26 (first turn)* show that only the samples (e.g. *NR26*) from the first turn are used in the ordinal multinomial distribution. The term *population means for NR26 (all turns, estimated for the first turn)* shows that samples (e.g. *NR26*) from all turn are used in the ordinal multinomial distribution and the *population mean* is given (estimated) as responses from the first turn. Normally this is also said in the figures and tables. The advantage in using all turns but still get a estimation for the first turn is that all samples are used for both a higher accuracy and an estimation with no adaptation. (The *observed means* and the *estimated marginal means* for the first turn and for all turn show quite different results due to adaptation of subjects).

[32] Covariates are quantitative explanation variables, used together with dependent variables to define a linear (regression) model. By taking the estimated marginal means the effects from the covariate variables are integrated out.

[33] From the helpfile for the statistical evaluation program *SSPS*.

[34] Population mean (expected value) = $E[x] = \sum (x \cdot f(x))$, where $f(x)$ is the distribution of x. The expected value corresponds to the observed mean value, if the number of samples are high enough. The observed mean is calculated from the samples and the population means from the distribution of samples.

Symptoms of motion sickness (*SMS*) and nausea percentage (*NP*)

The concept of *symptoms of motion sickness* (*SMS*) and *symptoms of motion sickness incidence* (*SMSI*) was used in the train experiments (Förstberg 1996, see Chapter 6). *SMS* was based on the quantities: *dizziness* (0, 1), *nausea* (0, 1) and *illness ratings* (0 – 4)[35], but in the simulator experiment dizziness was not recorded. Dizziness had very little influence on *SMS* as the main influence came from illness and nausea. Subjects were also omitted from the evaluation of *SMSI* in the train test, if they did not *feel well* at the start of the test ride. This was done, based on the observation that these subjects may later feel well at some point of the test run but could feel un-well in the end of the ride. In such a case, it was unclear whether the illness was a consequence of the test ride or not.

In the simulator experiment, *SMS* can be reformulated and be calculated based on nausea (*NR*) and illness (*IR*). *SMS* is then defined as a subject having either illness or nausea, i.e. $SMS = 0$, if $IR = 0$ and $NR = 0$ else $SMS = 1$. However, in the present report the term nausea percentage (*NP)* will be used not to confuse with *SMSI*. *NP* is defined as the percentage of subjects in a group that have $SMS > 0$.

p-deletion test

The p-test (p-deletion) test was used to measure the mental performance of the subjects. This test has been used to measure recovery from anaesthesia (Dixon & Thornton 1973, Gupta, Kullander, Ekberg, & Lennmarken 1995, Zuurmond, Balk, van Dis, van Leeuwen, & Paul 1989). Both the number of p's correctly marked under a certain time and the number of missed p's has been used. In this case, the subjects had to perform a search of lower case "p" in a random matrix of lower case letters, 40 letters wide and 50 letters high, under 1 min duration, every 10 min of the test run. Additional tests were also undertaken before the test run (pre-test) and after 40 min from start of test run (9 min after stop of motion). The letter matrix was created with random letters not containing p (a – o, q-z including w but excluding the Swedish letters å, ä and ö). Into this matrix, for each row, at two random columns the letter there was substituted by a "p". This meant, that in each row, there were two "p", except for a very few generated rows containing only one p. This could happen when the two random columns generated had the same number. In Appendix F an example of a p-matrix is shown.

Evaluated variables in this test are the number of p's found in one minute and the number of searched rows.

Ride comfort, comfort disturbances and work ability

The subjects' estimation of *average ride comfort* and *ability to work/read* was done on a five-grade scale from *very bad* to *very good*. Evaluated parameters are mean and standard deviation.

The subjects' estimation on *comfort disturbances* caused by shakings/shocks (laterally, vertically), large lateral accelerations (side-forces) and/or uneven tilt motion was done on a yes/no scale. Evaluation was the percentage of disturbed subjects. This was done in a similar manner as in the train experiments in 1994 and 1996 (Förstberg 1996 and se Chapter 6).

Evaluation of accelerations and roll motion

All test conditions were measured by accelerometers and a rate gyroscope were placed in a small box fastened on a surface parallel to the floor of the cabin. These signals were recorded by a

[35] The full *IR* modified five point scale (IR 0 – 4) was used in the train experiment but only the four point modified *IR* 0 –3 in the simulator experiment.

laptop computer during a total motion sequence of 60 s. The measured signals were: lateral and vertical accelerations (low pass filtered at 30 Hz) and roll velocity (low pass filtered at 10 Hz).

The *MATLAB* program was used for evaluation of measured signals.

Statistical evaluation programs

The statistical programs *SPSS* (Statistical Program for the Social Sciences) and *STATISTICA (StatSoft 1995),* together with *EXCEL*, have been used for evaluation of statistical quantities. SPSS was used mainly for analysis of variances (ANOVA) and regression, *STATISTICA* for tests based on ordinal multinomial distribution. *EXCEL* was used for aggregating all analyses.

7.3 Results from simulator tests

The results are presented in four areas:

- background variables,
- nausea and illness ratings (*NR*, *IR*) from part I, and from part II,
- nausea percentage (*NP*), and leakage of *NR*, *IR*,
- p-deletion tests, ride comfort, discomfort and ability to work and read.

7.3.1 Background variables

Sensitivity, travel experience, previous experience with motion sickness and gender

Although most of the subjects in the test were selected equally from two groups of low and medium sensitivities to motion sickness, there still exists a difference in self-estimated sensitivity between genders, when all test runs are aggregated. The genders' previous experience with motion sickness in different transport modes is significantly different although the experience with travel is not. There is a small difference between the two genders concerning if they felt they were rested before the test but this difference is not significant. About 14% of the males felt that they were *not rested* compared with about 23% of the female subjects.

Table 38 shows differences in mean values for self-estimated sensitivity, travel experience and motion sickness experience for the two genders at the first turn. Although there is only a difference at the 10% significance level in self-estimated sensitivity between male and females, there is clear difference in previous nausea experience. Note that there is no difference in previous travel experiences.

Table 38 Differences in self-estimated sensitivity to motion sickness, travel experience and previous nausea in travel between the male and female subjects at the first turn.

	Gender	*N*	*Mean*	*t*	*df*	*Significance (2-tailed)*
Sensitivity[i] (1st turn)	Male	18	2.72	-1.690	40	0.1
	Female	24	3.25			
Travel experience[ii] (1st turn)	Male	18	3.9	-0.061	40	0.9
	Female	24	4.0			
Previous nausea exp[iii]. exp. (1st turn)	Male	18	2.06	-2.648	40	0.01
	Female	24	3.62			

Remarks: [i] Sensitivity is estimated on a scale from 1 (no sensitivity) to 7 (very large sensitivity).

[ii] Travel experience is the sum of how often the subjects have travelled with *X2000*, normal train and aeroplane during the last year, with the numerical coding of 0 = 0 times, 1 = 1 – 2 times, 2 = 2 - 6 times, 3 = 7 – 12 times and 4 = more than 12 times per last year. Maximum possible value is 12 = (3 * 4).

[iii] Previous experience of nausea, is the sum of nausea experience in car, bus, ship, aeroplane, normal non-tilting train and tilting train in the last five years, with the numerical coding 0 = no, 1 = sometimes, 2 = many times. Maximum possible value is 12 = (6 * 2).

Correlation between gender, age and sensitivity to motion sickness

Correlations between age, gender, sensitivity, previous motion sickness experiences in different transport modes, travel experiences and resulting nausea in the simulator test (*NR*26) are shown in Table 39. Sensitivity is weakly correlated with gender (r = 0.27; $p \leq 0.08$; females have higher sensitivity) but not correlated with age (r = -0.18; $p \leq 0.25$). However, age is strongly negatively correlated with motion sickness in cars (r = -0.55; $p << 0.001$) and almost significantly correlated with nausea rating (*NR26*) in tests (r = -0.296; $p \leq 0.05$).

Table 39 Spearman's rank correlation between age, gender, sensitivity to motion sickness, motion sickness experience in cars, tilting trains (X2000), total travel experiences and nausea ratings in the test.

Spearman's rank correlation		Age	Gender	Sens.	MS X2000	MS car	MS tot	Travel exp.	*NR*26
Age	Corr.	1							
	Sign.	-							
Gender	Corr.	-0.056	1						
	Sign.	0.719	-						
Sens.	Corr.	-0.177	0.270	1					
	Sign.	0.249	0.076	-					
MS X2000	Corr.	0.024	0.134	0.406**	1				
	Sign.	0.878	0.391	0.007	-				
MS car	Corr.	-0.548**	0.291	0.549**	0.184	1			
	Sign.	0.000	0.055	0.000	0.237	-			
MS tot	Corr.	-0.248	0.352*	0.635**	0.418**	0.772**	1		
	Sign.	0.113	0.022	0.000	0.006	0.000	-		
Travel exp	Corr.	0.050	-0.006	0.241	0.189	0.165	0.220	1	
	Sign.	0.756	0.969	0.129	0.242	0.303	0.179	-	
NR26	Corr.	-0.296	0.238	0.317*	0.405**	0.356*	0.417**	0.320*	1
	Sign.	0.051	0.120	0.036	0.007	0.018	0.006	0.042	-

Remarks ** Correlation is significant at the 0.01 level (2-tailed).
* Correlation is significant at the 0.05 level (2-tailed).
MS X2000, MS car = Previous experiences of motion sickness in *X2000* and in cars.
MS tot. = Previous experiences of motion sickness in car, train, aeroplane, buses, ships and *X2000* are added together into one variable.

7.3.2 Influence from exposure time and test conditions on nausea and illness ratings (Part I)

Forty-three subjects took part in test part I, together they made 206 test runs. One of the subject (test run) was not further evaluated because he was interrupting the test with a very strong response after about 13 min ride and was incapable of any further testing. The total responses from all these 206 test runs are shown in Table 40. As main response variable the nausea ratings after 26 min test time (*NR26*) have been selected since this variables usually gives best differences between the test conditions.

Table 40 Nausea rating after 26 min for all subjects in all test runs taking part in test part I.

NR26	*Male test runs*	*Female test runs*	*Total test runs*	
No symptoms	57	55	112	54.4%
Light symptoms	27	22	49	23.8%
Light nausea	5	22	27	13.1%
Moderate nausea	3	5	8	3.9%
Strong nausea		9	9	4.4%
Almost vomiting*	1		1	0.5%
Total	93	113	206	100%

Remark: * This subject was not further evaluated, because of his strong response. He interrupted the test after approx.: 13 min and had tested the condition 3. He did not take part in any further testing.

Remark

Great care has been taken to prove that the nausea ratings *NR26* between the different test conditions are significant for the first turn. This is done because of the statistical difficulties of the repeated measures of subjects and the decreasing *NR* responses (adaptation) from the subjects. In the first turn, all subjects are "naive" to the test situation. If the responses (*NR26*) are significantly different for the test conditions for the first turn and the statistical tests considering all test runs (turns) show the same results (significant difference between the test conditions), than the significance can be considerate as proved. The argumentation to show the significance is first to use a non-parametric test (no assumption of any distribution), then statistical tests based on ordinal multinomial distribution and at last on the analysis of variance (ANOVA) (assumption of normal distribution). With the ANOVA test and estimated marginal means, it is easy to find confidence intervals for the response variables, in most of the cases *NR26*.

Significance and nausea ratings for the first turn

The influence of time on nausea and illness ratings (NR and IR)

The influence of time on nausea and illness ratings (*NR*, *IR*) is strong, see Figure 38. There is a steady increase of *NR* and *IR* from the ratings at 6 to 26 min with time and then there is a small decrease for the rating at the nominal time of 31 min. This reading is probably made at approximately 32 min due to a number of questions to answer in the questionnaire at the stop of the test run. Therefore, the nausea ratings are already decreasing. The 36 and 41 min readings show a fast decay (leakage) of both *NR* and *IR*.

In the figure, there are drawn curves according to the net dose model of estimated nausea ratings (Kufver & Förstberg 1999 and Chapter 8). These curves are drawn with a maximum *NR* and *IR* at 31 min (according to the stop of motion) and than showing the leakage of *NR* and *IR*. Time constant in the increase as well as in the decrease is the same for *NR* but not for *IR*.

For most of the conditions the highest values of nausea and illness ratings are at 26 min, therefore it is most convenient to use these responses (*NR26*, *IR26*) in order to compare the different conditions. Alternatively the average values from the ratings at 21, 26 and 31 (32) min may be used (*NRmean*).

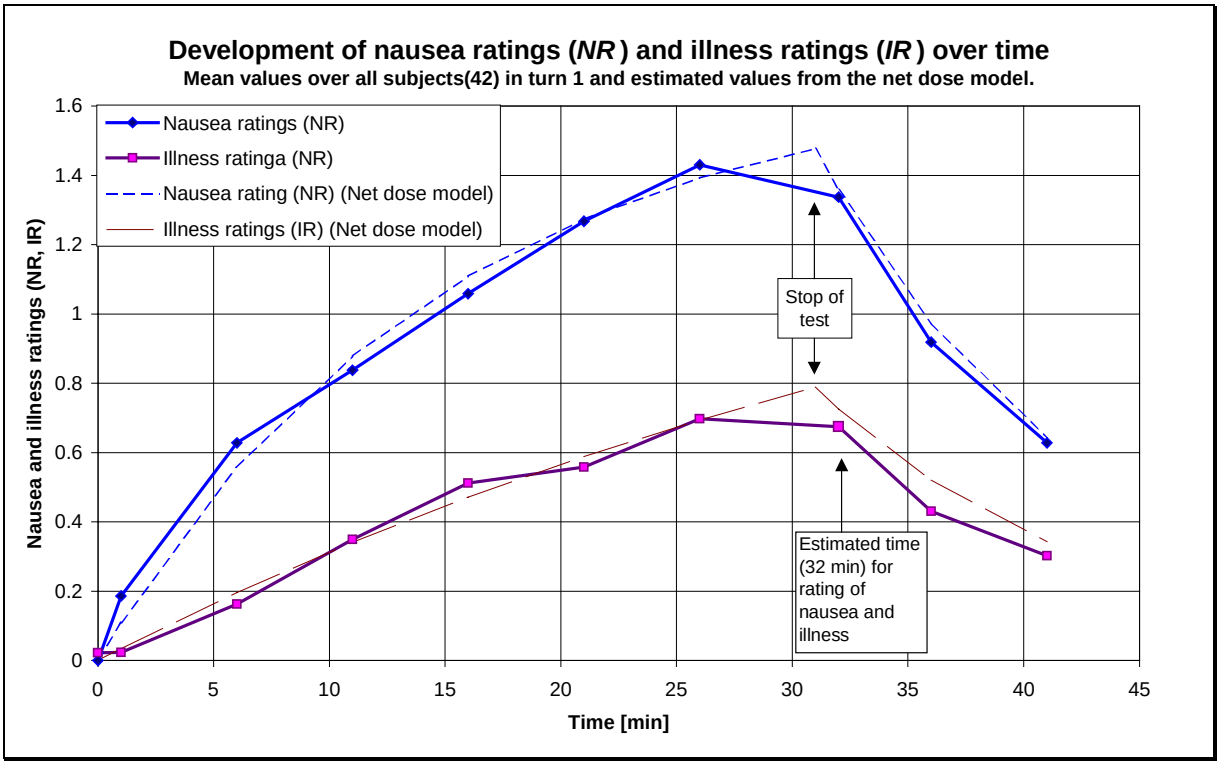


Figure 38 *Influence from motion on nausea and illness ratings (NR, IR) during tests. Average responses from all subjects after the first turn. Test stops after 31 min but probably subjects made their rating at about approximately 32 min.*

*Tests of main effects regarding nausea ratings (*NR26*)*

The number of subjects participating in some of the test conditions were few in the first turn. However, it may be interesting to study *NR* responses at 26 min (*NR26*) for the different conditions, see Figure 39. In this figure, the standard error[36] and the number of subjects is indicated for the different conditions. There were large differences in magnitude of *NR* between first turn and the coming test turns. In the first turn, all subjects are "naive" to the conditions in the test and not affected by any previous testing. The question is then, if there is any significant difference between the test conditions and if the severity of the conditions change during the test turns?

Non-parametric test of main effects

After the first turn (turn), a Kruskal-Wallis test[37] of the test hypothesis H0: *Conditions do not influence the nausea ratings*, gives an asymptotic significance of $p \leq 0.02$. The H0 must then be rejected and the alternative hypothesis H1: *Conditions do influence the nausea ratings*, must be accepted. The results are shown in Table 41 for the test variable nausea rating at 26 min (*NR26)* and *NRmean*[38] for the different test conditions. Also the *subjects' self-estimated sensitivity* differs significant on *NR26* ($p \leq 0.028$) and *NRmean* ($p \leq 0.018$) but *gender* is not a significant variable on *NR26* and *NRmean* ($p \leq 0.08$) (Förstberg 2000a).

[36] Standard error = standard deviation / $(N)^{0.5}$, where N is the number of observations (subjects).
[37] A non-parametric test, which do not use any assumption regarding the distribution of the tested variable. It uses only the ranking order of the different ratings (Siegel & Castellan 1988).
[38] *NRmean* = mean of the following variables: *NR21*, *NR26* and *NR31*.

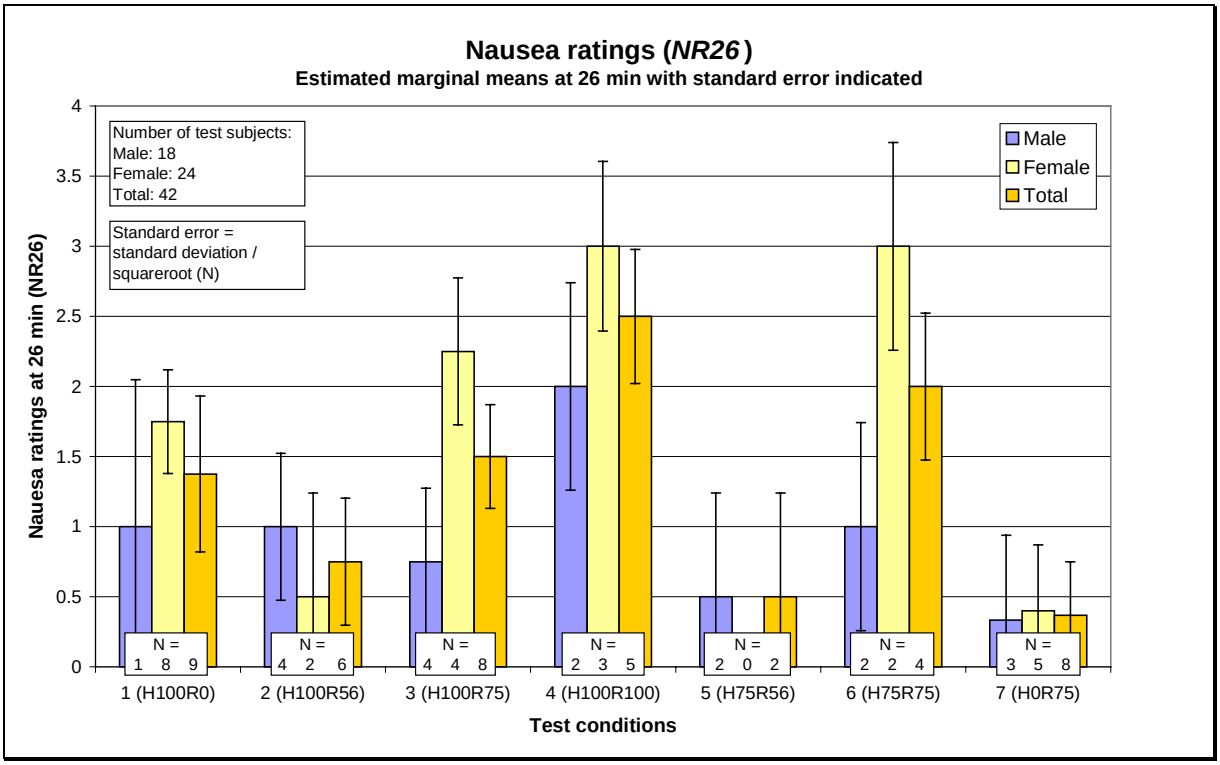


Figure 39 *Nausea rating after 26 min for the first turn for test subjects with standard error indicated, if it exits. Indicated are the number of subjects (total and for each gender) for the different conditions.*

Table 41 *Test statistics for Kruskal-Wallis test regarding differences in test conditions.*

Condition	*NR26*	*NRmean*
Chi-square (χ^2)	15.174	13.87
df	6	6
Asymp. Sign (p).	0.019	0.031

Test based on *NR26* normally gives lower significance (p) than test based on *NRmean* and therefore *NR26* will be used in the future.

The ordinal multinomial distribution

A better alternative is to use a suitable distribution for the response data, in this case, the ordinal multinomial distribution. The multinomial distribution is as like the binomial distribution but it has several levels. Each level has a probability p_i and $\sum p_i = 1$. Figure 40 displays *NR26* for the different test conditions according to the ordinal multinomial distribution. Notice the about 40% probability to have *NR26* = 4 (strong nausea) for the condition H100R100. The corresponding probability to have *NR26* = 4 for the roll only condition (H0R75) is very low (< 0.5%). Instead the probability to have no symptoms (*NR26* = 0) for H0R75 is high (73%). The ordinal multinomial probability distribution gives a very clear and understandable picture of the responses.

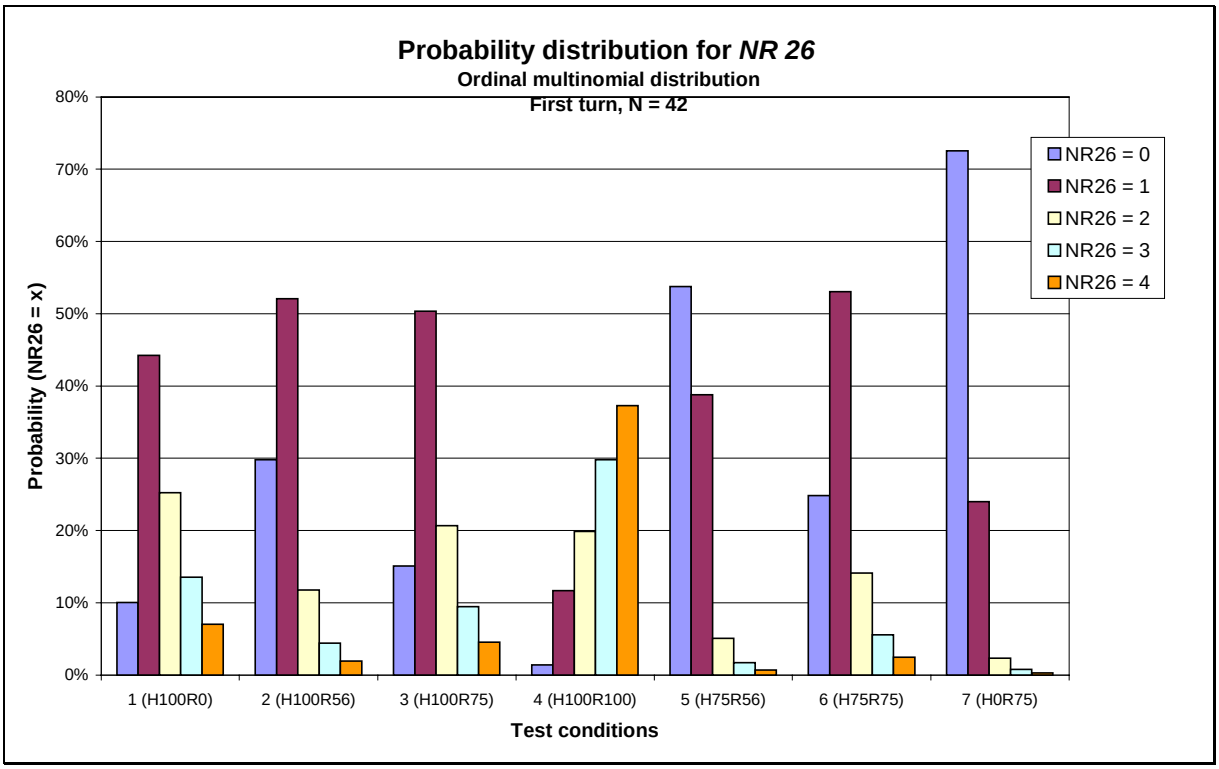


Figure 40 Ordinal multinomial distribution for NR26 from the first turn.

Test of main effects based on the ordinal multinomial distribution

Table 42 show tests of the main effects for test condition on *NR26* based on the ordinal multinomial tests (with logit link function) (Dobson 1990, McCullagh & Nelder 1989). These show that condition is a significantly variable on 5% level ($p \leq 0.012$).

Table 42 Test of main effects on NR26 regarding test condition.

	df	*Wald Stat.*	*Significane. p*
Intercept	4	34.88	0.000
Test condition	6	16.37	0.012

Remark: Distribution: Ordinal multinomial. Link function: Logit.
For a definition of Wald statistics, see Appendix A.

Population means - Expected values

Population means (expected values)[39] from the ordinal multinomial distribution are easily calculated. The assumption made is that the distance between each level of *NR* is one. The main advantage is that the difference between population means for the different conditions are fairly accurate but the exact levels are more uncertain. This depends on the standard error of the intercepts. See an example of calculating probability and population means in the appendix A7.

Figure 41 displays these values for male, female and total. A comparison with observed means (cf. Figure 39) show that these agree for most test conditions but for condition H75R75 the expected values are much lower. This is probably due to both few data and some data with high

[39] Expected values = $E[x] = \sum(x \cdot f(x))$, where f(x) is the distribution of x.

NR giving a high mean value (*NR26* = 2) but fitting these data into the model together with all other data reduces the population mean (*NR26* = 1.1).

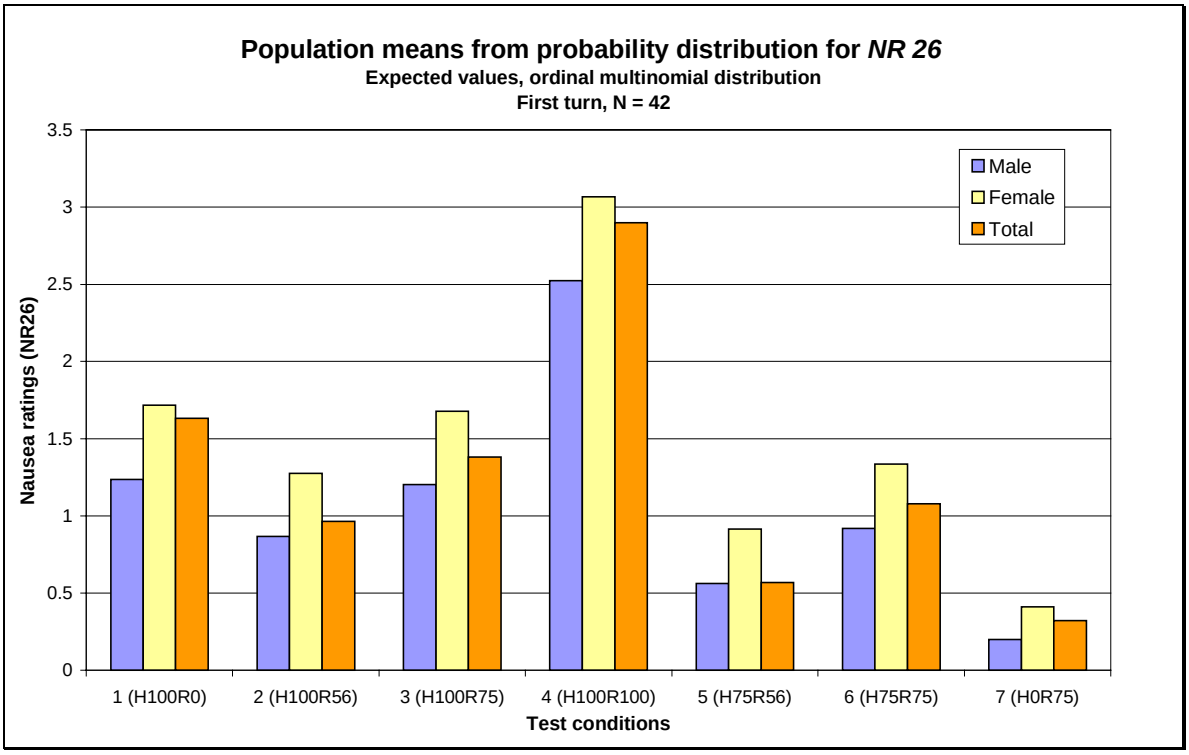


Figure 41 *Expected values from ordinal multinomial distribution for NR 26 for the different test conditions.*

Analysis of variance (ANOVA)

An analysis of variance (ANOVA) of condition, gender and sensitivity does not give any different results then the above results. Conditions is a significant explanation variable for the nausea ratings (*NR26*) on 5% level ($p \leq 0.02$). A post-hoc analysis according to Tukey (Keppel 1991) show that condition 4 is significantly different from condition 7 at 5% level ($p \leq 0.02$). Together are the explanation variables condition and gender as well as motion and sensitivity significant variables on the 5% level.

Summary

Nausea ratings (*NR26*) varies significantly different between the different test condition on 5% level. There is a significant difference between condition 4 (H100R100) and condition 7 (H0R75). Gender and self-estimated sensitivity are together with one by one with condition significant explanation variables.

Significance and nausea ratings for all test turns

Time influence on nausea and illness ratings

The average female, male and total responses for nausea and illness ratings (*NR*, *IR*) from all test turns (test part I) are shown in Figure 42 together with estimations from the net dose model (see Chapter 8). The responses for the different conditions are shown in Figure 43.

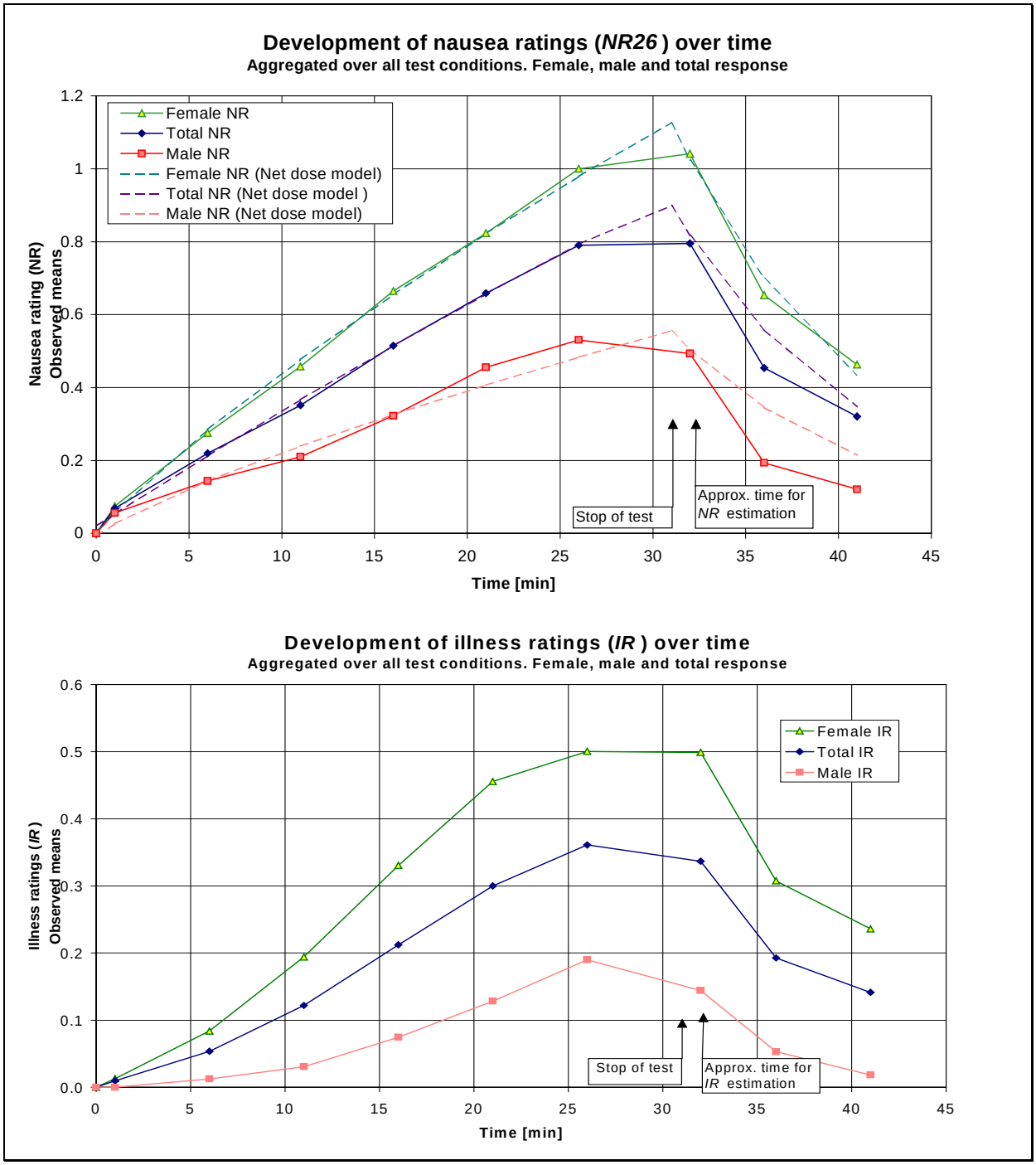


Figure 42 *Development of nausea ratings (NR) and illness ratings (IR) over time of the test. Average responses from all subjects and from all evaluated 205 test runs. Female, male and total responses are shown. The test stops after 31 min.*

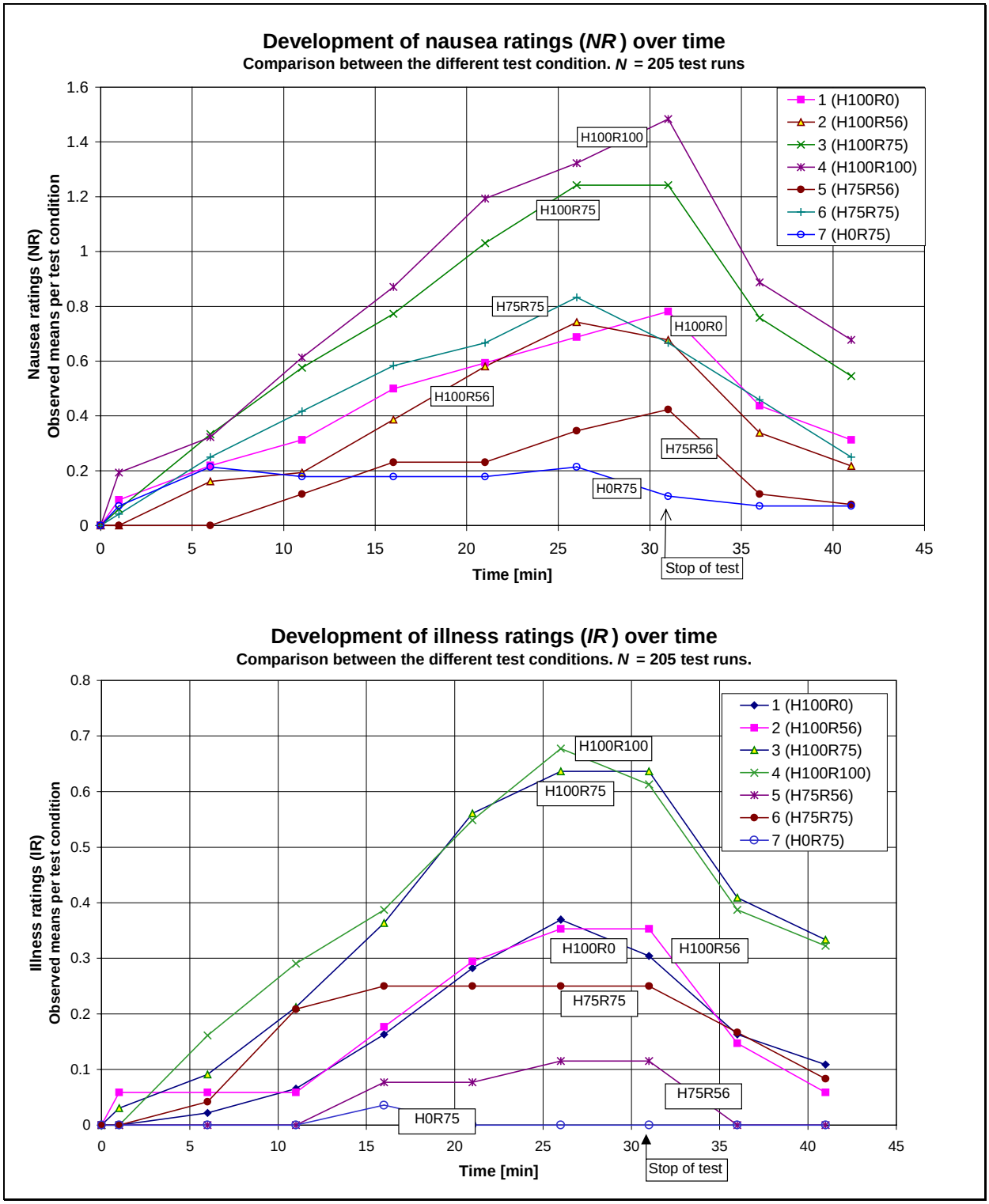


Figure 43 *Development of nausea and illness ratings (NR, IR) during the time of the test run, separated for the different conditions, for the evaluated 205 test runs .*

Remarks and observations:

Some aspects of the results are obvious:

- There are large differences in female and male *NR* and *IR* responses. The discrepancy between male and female mean self-estimated sensitivity (male =2.72; female = 3.25)[40] can not fully explain this large difference in responses.
- The different test conditions causes very different nausea and illness ratings.
- The ratings are lower when all turns are averaged than for the first turn (compare Figure 38 with Figure 42).
- After 31 min *NR* and *IR* are rapidly decreasing (leakage).
- The ratings at 31 min do not usually follow the same increase in *NR* (*IR*) as the previous ratings. This effect may be explained by a time delay from the test run's stop to the subject's estimation of his/her response because of answering other questions in the questionnaire.

Significance tests

Since the test design was mixed with both repeated usage of subjects (mostly four and seven times) and single usage, special measures have to be taken. According to Wiklund (2000), one way of handling this is to use the variable subject as an explanation variable in the analysis. This can be done by enter subject either as a random factor or as an independent factor.

Significance test based on the ordinal multinomial distribution

By using the ordinal multinomial distribution, significance tests show that subjects, test condition and turn are significant variables for explaining the variation in *NR26*, see Table 43.

Table 43 Test of main effects on NR26 regarding subjects, test condition and turn.

	df	*Wald Stat.*	*Sign. p*
Intercept	4	103.55	0
Subjects	41	70.67	0.003
Test condition	6	43.04	1.1E-07
Turn	6	38.43	9.3E-07

Remark: Distribution: Ordinal multinomial. Link function: Logit.
For definition of Wald statitics, see Appendix A3.

The variation between the different subjects is significant. However, further analysis with more explanation variables besides conditions and subjects will give pivot elements close to zero. This will give uncertain results in the tests. Therefore, the variable subject has to be omitted from further analysis. Table 44 shows the same test as above but without subjects as a variable for a comparison. The result is that the significance for test condition and turn is somewhat lowered but still very high.

[40] On a seven-grades scale: No sensitivity (1) to very high sensitivity (7).

Table 44 Test of main effects on NR26 regarding test conditions and turn

	df	*Wald Stat.*	*Sign p*
Intercept	4	130.30	0
Condition	6	28.85	6.5E-05
Turn	6	19.98	0.003

Remark: Distribution: Ordinal multinomial. Link function: Logit

Since it is possible to remove subjects as an explanation variable and still have very low significance levels for condition and turn, is possible to continue the significance tests. Table 45 shows a corresponding test on the variables gender, condition, turn and self-estimated sensitivity. All variables are significant, except gender on 5% level. This is due to the effect of self-estimated sensitivity, see Table 46, where gender is a significant variable. These two variables are varied together, since females rated their sensitivity higher than males.

Table 45 Test of main effects on NR26 regarding gender, condition and self-estimated sensitivity.

	df	*Wald Stat.*	*Sign p*
Intercept	4	124.59	0
Gender	1	3.69	0.054
Condition	6	31.46	0.00002
Turn	6	22.71	0.0009
Sensitivity	4	22.03	0.0001

Remark: Distribution: Ordinal multinomial. Link function: Logit

A testing of not only main effects but also interaction effects between condition, gender and turn show that there are no significant 2-way interaction effects, see Table 46.

Table 46 Test of main effects on NR26 regarding gender, condition and turn including interaction effects.

	df	*Log-Likelihood*	*Chi-Square*	*Sign. p*
Intercept	4	-246.6		
Gender	1	-242.4	8.41	0.004
Test condition	6	-228.4	28.09	0.00009
Test turn	6	-216.4	23.94	0.0005
Gender * condition	6	-213.8	5.23	0.51
Gender * turn	6	-212.7	2.28	0.89
Condition * turn	33	-193.7	38.00	0.25

Remark: Likelihood type 1 test.
Distribution: Ordinal multinomial. Link function: Logit

Summary

The test on ordinal multinomial distributions show that test condition, turn and gender or test condition, turn and self-estimated sensitivity are significant explanation variables for the variation of nausea ratings (*NR26*).

Analysis of variance (ANOVA)

The usual way of testing significance in behavioural science is by using the analysis of variance (ANOVA). The analysis assumes that the response variable is normally distributed (Keppel 1991). In this case, *NR26* not normally distributed. However, it is still interesting to test nausea and illness rating (*NR*, *IR*) with this test and thereby obtain *estimated marginal means* with *confidence intervals* for these variables. The estimated marginal mean are calculated at the mean of entered covariate variables, giving a more "true" mean than the observed mean which can be influence by the covariate variables[41], see Appendix A3.

Since the test design involved both subjects taking part in only one turn and up to seven turns, subject has to be entered in the analysis as a variable to take care of the repeated usage of subjects. Table 47 shows that both condition, subjects and turn are significant explanation (independent) variables in explaining the variance of nausea ratings (*NR26*) ($p < 0.001$).

Table 47 Tests of main effects (ANOVA) on NR26 regarding condition, subjects and turn.

Source		*Type III Sum of Squares*	*df*	*Mean Square(MS)*	*F*	*Sign. p*
Intercept	Hypothesis	68.381	1	68.381	64.510	5.75E-13
	Error	134.092	126.5	1.060[i]		
Test	Hypothesis	25.685	6	4.281	6.409	4.7E-06
condition	Error	104.197	156	.668[ii]		
Subject	Hypothesis	99.072	41	2.416	3.618	3.94E-09
	Error	104.197	156	.668[ii]		
Turn	Hypothesis	10.431	1	10.431	15.617	0.0001
	Error	104.197	156	.668[ii]		

Remarks: i 0.224 MS(Subject) + 0.776 MS(Error). ii MS(Error).
ANOVA with subjects entered as random factor, turn as a covariant variable.

However, entering subjects as a factor in the analysis make it difficult to enter other variables in the analysis, due to convergence of the ANOVA is problematic. Therefore, the variable subject has to be omitted from further analysis. Table 48 thus shows the same test as Table 47 but without subject entered as a random factor.

Table 48 Tests of main effects (ANOVA) on NR26 regarding condition and turn.

Source	*Type III Sum of Squares*	*df*	*Mean Square*	*F*	*Sign. p*
Corrected Model	40.126	7	5.732	5.556	7.46E-06
Intercept	62.809	1	62.809	60.872	3.49E-13
Conditions	30.311	6	5.052	4.896	0.0001
Turn	8.824	1	8.824	8.552	0.0039
Error	203.269	197	1.032		
Total	373.000	205			
Corrected Total	243.395	204			

Remark: $r^2 = 0.16$ (Adjusted $r^2 = 0.13$). Turn is entered as a covariant variable.

The resulting significance levels are slightly decreased but still the significance is very high. This model explains about 17% of the variation of the responses. This shows that *further analysis is possible without using subject as a variable in the analysis.*

[41] Covariates are quantitative explanation variables used together with dependent variables to define a linear model. See also explanations in Appendix A3.

Post hoc analysis

A post hoc analysis (Keppel 1991) according to Tukey (assuming equal variances) and according to Tamhane (not assuming equal variances) shows significant differences between two groups of conditions: between condition 3 (H100R75) and conditions 5 and 7 (H56R56, H0R75) and also between condition 4 (H100R100) and conditions 5 and 7 (H56R56, H0R75) at the 1% level.

Improved model

Another model can be achieved after accepting that *self-estimated sensitivity* of the subjects and *adaptation to the motion environment* after repeated participation (i.e. number of turns) are strongly influencing the responses. One way to enter these variables in the ANOVA is to use them as covariates. Table 49 shows an improved model and now sensitivity is the most significant variable, followed by condition, turn and gender. This model explains 33% of the variation of nausea ratings. The two-way interaction gender * condition is not significant, implying that genders do not respond (very) differently from each other concerning type of test condition. However, there are some differences between the gender that is showed later.

Table 49 An analysis of variance (ANOVA) on nausea ratings (NR26) with respect to condition and gender. Turn and sensitivity entered as covariates.

Source	*Sum of Squares*	*df*	*Mean Square*	*F*	*Sign.*
Corrected model	81.264	15	5.418	6.315	8.2 E-11
Intercept	0.173	1	0.173	0.201	0.654
Sensitivity	22.326	1	22.326	26.025	8.1 E-07
Turn	7.144	1	7.144	8.328	0.004
Gender	5.777	1	5.777	6.735	0.010
Condition	27.210	6	4.535	5.287	4.6 E-05
Gender * condition	7.340	6	1.223	1.426	0.207
Error	162.131	189	0.858		
Total	373	205			
Corrected Total	243.395	204			

Remark: $r^2 = 0.334$ (Adjusted $r^2 = 0.281$)

Summary

Condition, turn, self-estimated sensitivity and gender are shown to be significant variables at 1% level. This corresponds almost with the test with the ordinal multinomial distributions.

Influence from horizontal (lateral) acceleration and roll motion

One way to visualise the responses from the different conditions is to show the nausea ratings (*NR26*) in a plane, where the axes are horizontal acceleration and roll angle (just as the conditions are defined in Table 27) in Figure 44. Shown values are estimated means.

Estimated marginal means for females, males and all for subjects (total) are shown in Figure 45 together with approximate 90% confidence limits for the different conditions. The differences between the observed and marginal means are in most cases less than 20%.

Summary

Nausea ratings are increasing as both the magnitude of horizontal accelerations and roll motions are increasing. For females, there is a small minimum level for condition 2 (H100R56) and that maximum value is for condition 3 (H100R75) instead of condition 4 (H100R100).

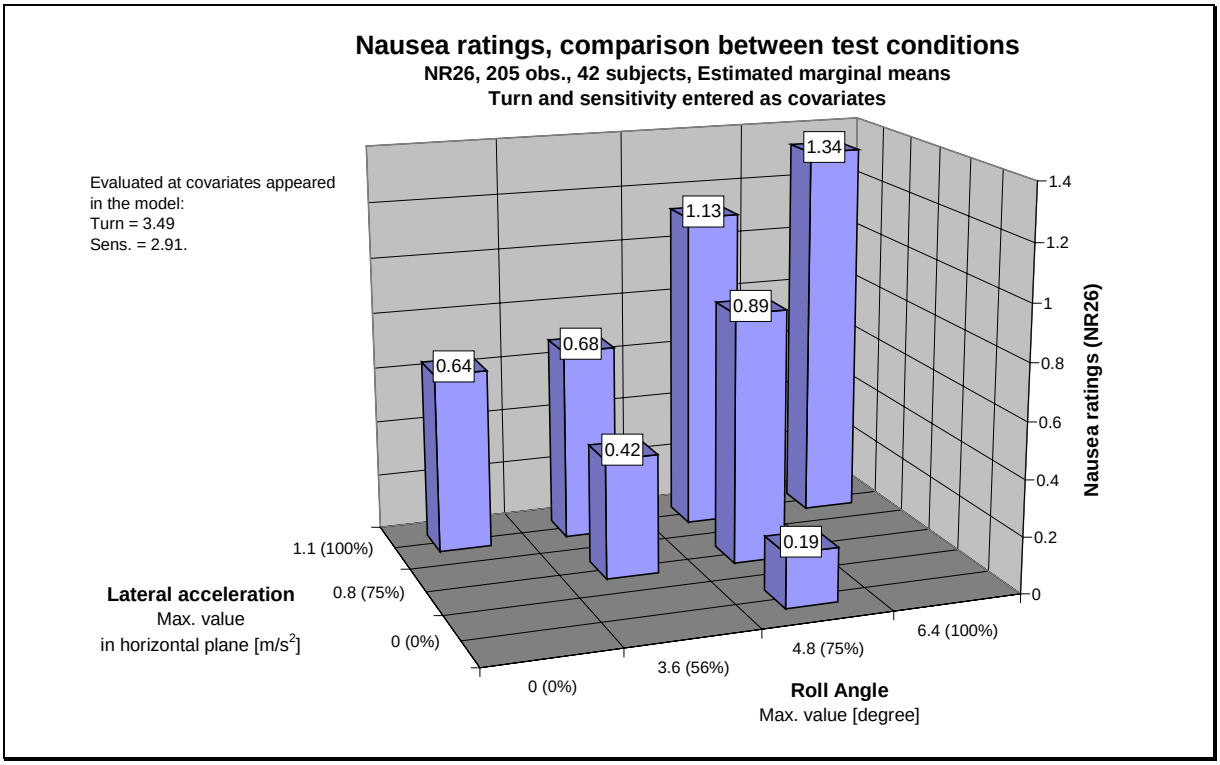


Figure 44 *Averaged results of Nausea ratings (NR26) for all subjects taking part in test part I. Based on estimated marginal means with sensitivity and turns entered as covariates.*

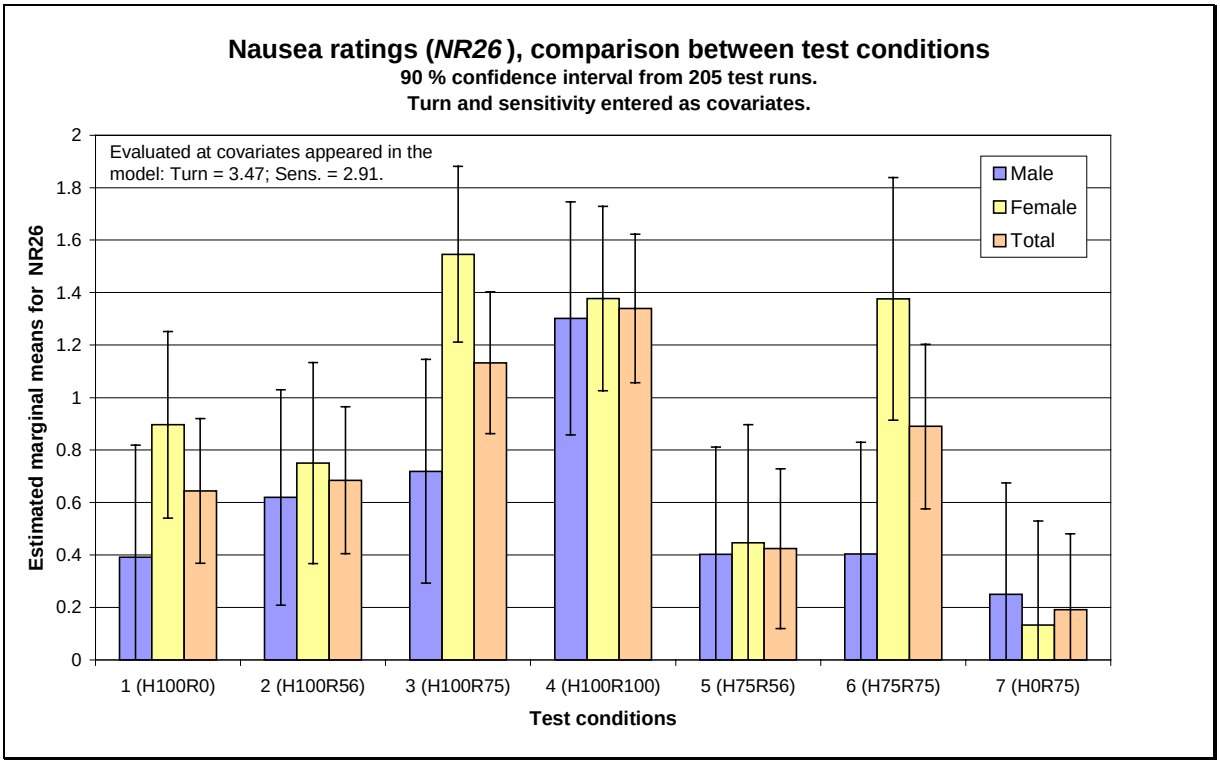


Figure 45 *Nausea ratings (NR26) for test part I for the different conditions with 90% confidence intervals. Displayed values are estimated marginal means with sensitivity and turn entered as covariates.*

Significance and nausea ratings for subjects taking part in all seven turns

Data from the subjects taking part in all seven turns is important in judging if the whole set of data for every subject is in agreement with this subgroup. Figure 46 shows the estimated marginal means for nausea ratings (*NR26*). A comparison with Figure 45 shows some small differences in mean values for *NR26*. Most of the differences are less than 0.1.

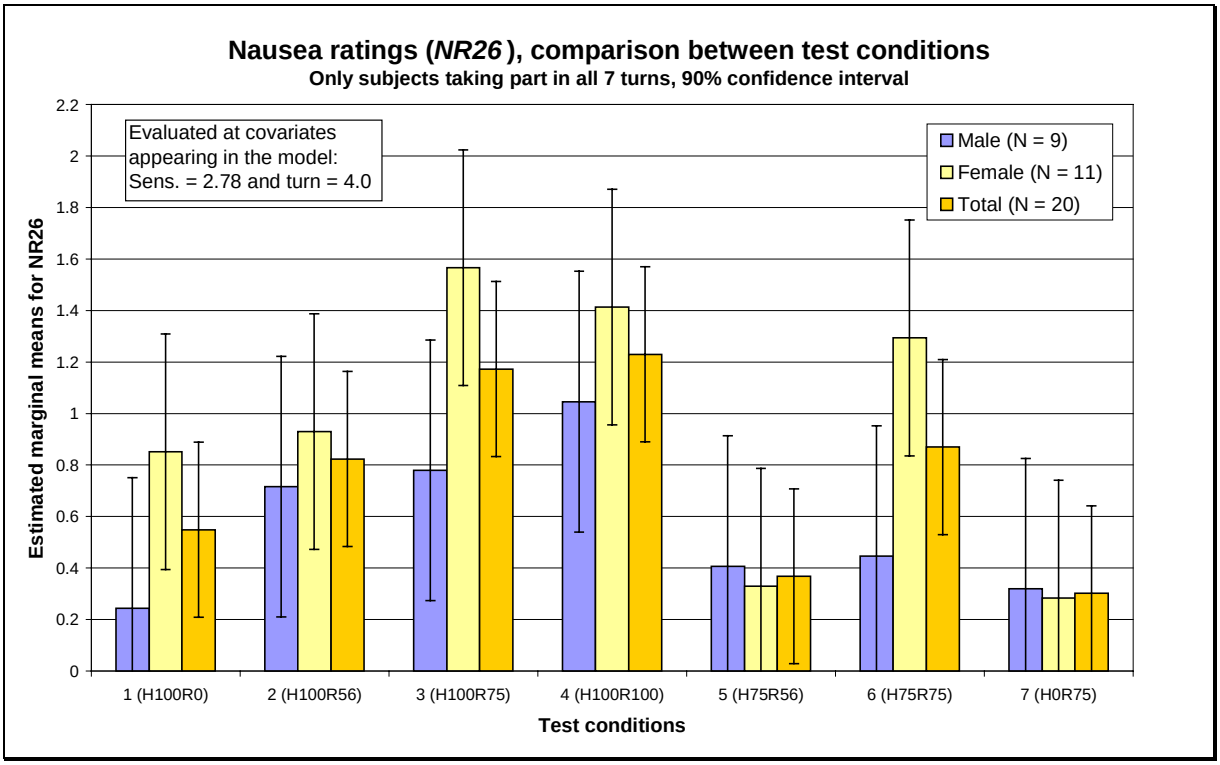


Figure 46 *Estimated marginal means for nausea ratings (NR26) for the subjects taking part in all seven turns. 90% confidence intervals are indicated. Sensitivity and turn are entered as covariates.*

Significance

A test of the main effects from the ordinal multinomial distribution of subjects, condition and turn on nausea ratings (*NR26*) shows all these variables are strongly significant, see Table 50.

Table 50 *Test of main effects on NR26 regarding subjects, test condition and turn for those subjects that took part in all seven turns.*

	df	*Wald Stat.*	*Sign p*
Intercept	4	74.30	2.78E-15
Subjects	19	44.86	0.0007
Test conditions	6	27.06	0.0001
Turn	6	22.80	0.0009

Remark: Distribution: Ordinal multinomial. Link function: Logit

Summary

The subset of twenty subjects taking part in 140 test runs do not show any large difference to the responses from the total number of test runs. Subjects, conditions and turn are shown as significant variables.

Influence of gender, sensitivity for the different test conditions (Part I).

Gender and sensitivity

Gender and self-estimated sensitivity are some of the most important variables for explanation of the differences of nausea ratings. Differences in *NR* for the genders in the simulator test may be explained by the difference of mean self-estimated sensitivity for motion sickness. Therefore, gender and sensitivity are partly concurrent variables and not independent of each other.

An analysis of variance (ANOVA) with self-estimated sensitivity entered as an independent variable instead of as a covariate variable together with gender and condition, show that the gender is no longer significant variable at the 5 % level ($p \leq 0.07$). Post hoc tests (Tukey) show that significant differences (at 5% level) exit between *NR*26 responses between sensitivity 1 and 4, between sensitivity 2 and 3 and between sensitivity 2 and 4. Two-way order interactions like condition * sensitivity, condition * gender and gender * sensitivity are not significant. This means that conditions giving high *NR,* will probably give it for both genders. A sensitive female will probably not respond very differently from a sensitive male.

Figure 47 shows the nausea ratings (*NR26*) separated in the factors: condition and sensitivity. Sensitivity is limited to three levels (1-2, 3 and 4-5), since the number of subjects with sensitivity 1 and 5 are low. It shows a total increase of *NR* from sensitivity 2 to 4, but the increase is different for each condition.

However, some conditions have different responses for the genders, for example conditions 1 and 6 (H100R0, H75R75). It may be possible to classify the conditions as high, medium and low provocative conditions with the following classification:

	Male	*Female*	*Total*
Highly provocative	Condition 4 H100R100	Conditions 3, 4 & 6 H100R75, H100R75, H75R75	Conditions 3 & 4 H100R75, H100R100
Medium provocative	Conditions 2 & 3 H100R56, H100R75	Conditions 1 & 2 H100R0, H100R56	Conditions 1, 2 & 6 H100R0, H100R56 H75R75
Low provocative	Conditions 1, 5, 6 & 7 H100R0, H75R56, H75R75, H0R75	Conditions 5 & 7 H75R56, H0R75	Conditions 5 & 7 H75R56, H0R75

For the low provocative motion conditions (5 and 7), it seems that neither non-sensitive nor sensitive subjects are responding to the motion stimuli. Highly provocative conditions (3 and 4) seem to be conditions with high content of both horizontal and roll motion.

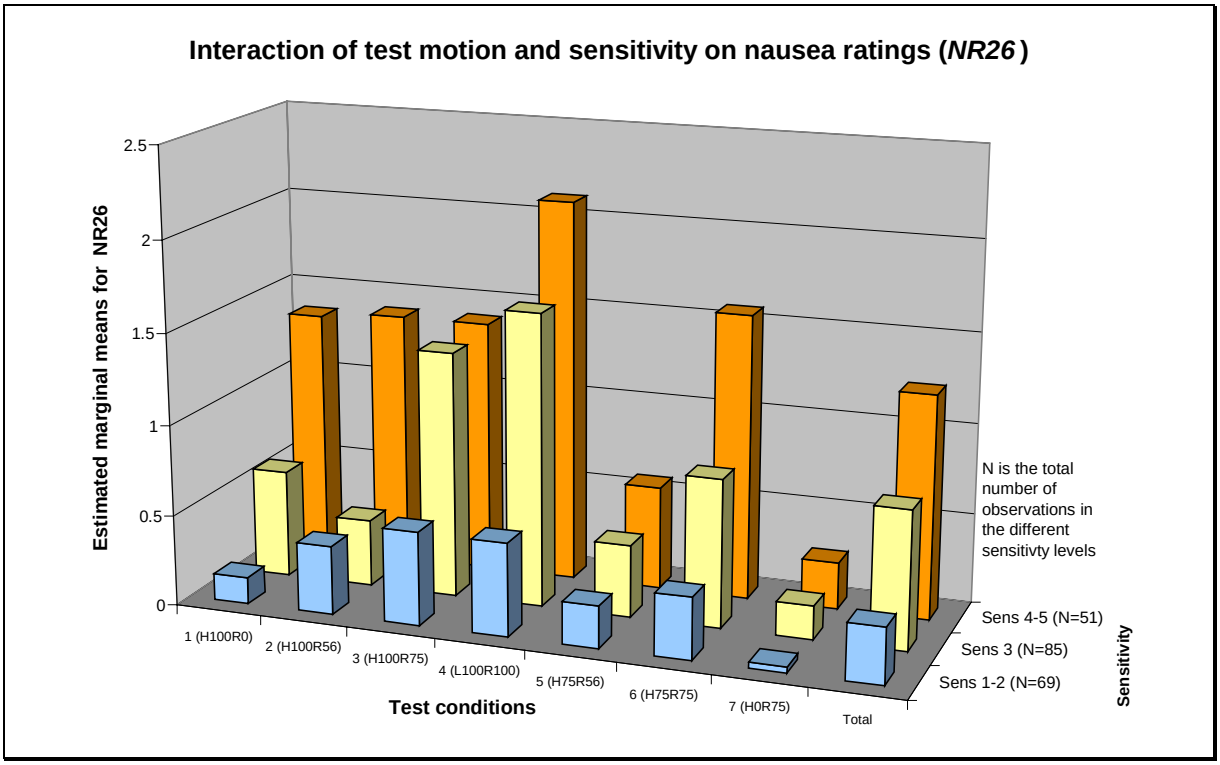


Figure 47 *Nausea ratings (NR26) for all subjects divided in conditions and self-estimated sensitivity. Sensitivity classes 1 and 2 are joined together and sensitivity classes 4 and 5.*

Sensitivity and gender vary together and not really independent. As a conclusion the influence from sensitivity on nausea ratings is strong and can be shown as in Figures 48 and 49. Females are more strongly affected than males according to their own estimation of sensitivity.

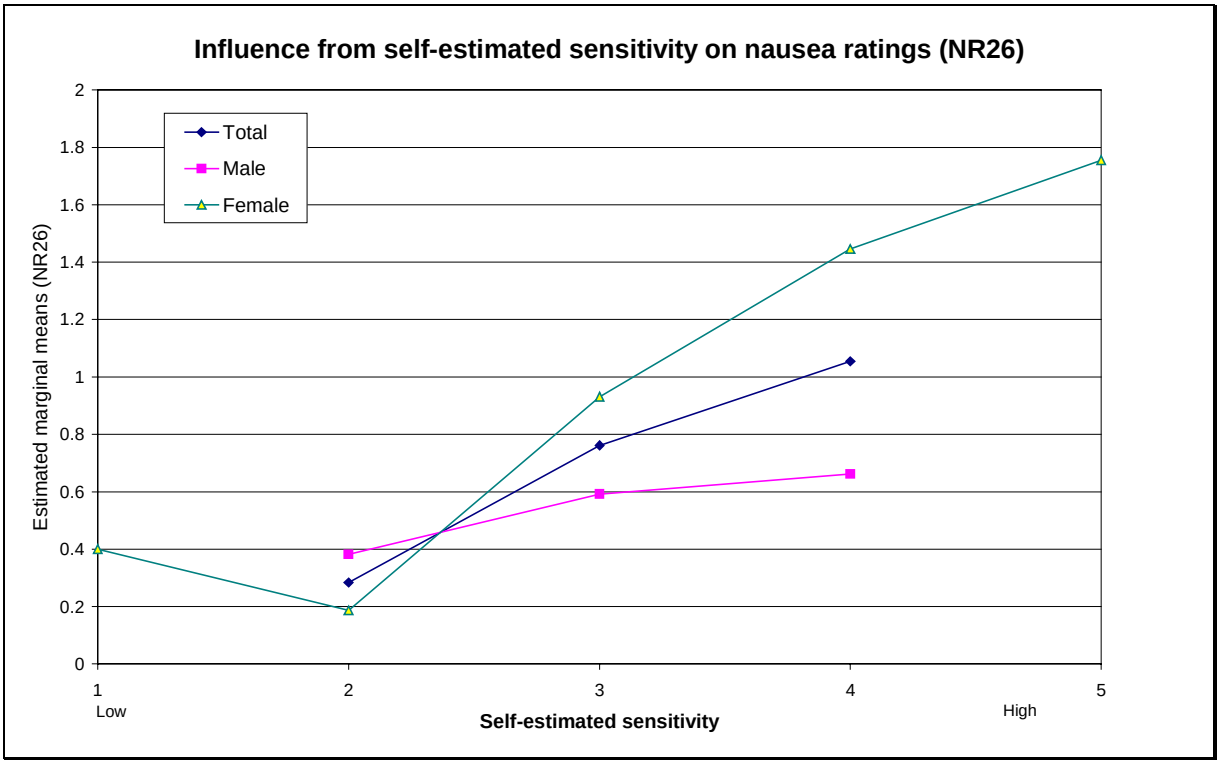


Figure 48 *Influence from self-estimated sensitivity on nausea rating based on all turns.*

The influence of sensitivity on nausea ratings (*NR26*) can also be shown with the ordinal multinomial distribution. Figure 49 shows population means (expected values) for *NR26* for each level of self-estimated sensitivity for the test conditions. The population means are calculated for all turn but the means are given as for the first turn. It is apparent that subjects (females only) that have rating their sensitivity to motion sickness as 1 (very low) is underestimating their true sensitivity (Figures 48 and 49).

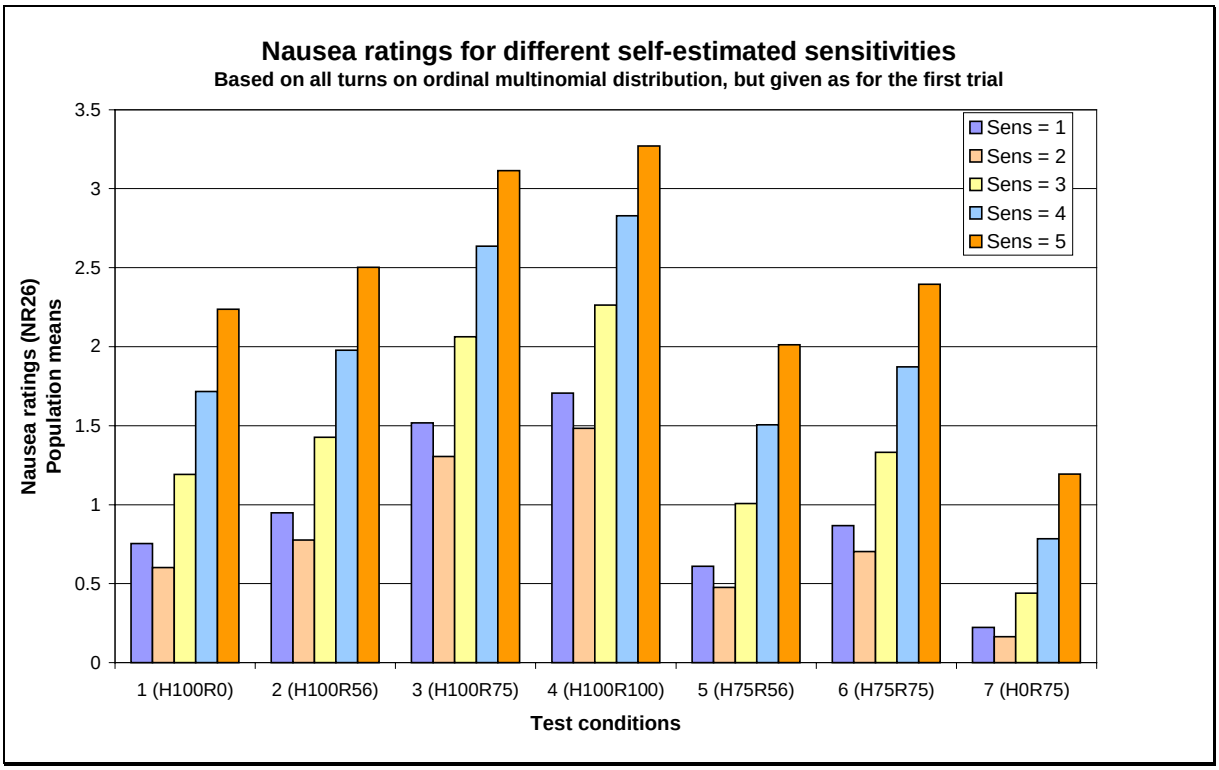


Figure 49 *Influence of self-estimated sensitivity on NR26 for the different conditions. The figure is based on ordinal multinomial distribution for data from all turn but given here as the response for the first turn.*

Rested or not rested – influence on nausea ratings

It seems that being rested at the start of the test has a great impact on the responses (*NR26*), see Table 52. In about 19% of the test runs, subjects were reporting at the test start that they were not *fully rested* (13 males, 14% and 26 females, 23%). Less than 8% of these (3 subjects) said they *did not feel alright* at the start, compared to 6% (10 subjects) from the rested group. No correlation was found between the variables *rested* and *feel all right* (most subjects reporting *not feeling all right* did so because they had a cold). Non-rested males displayed average nausea ratings (*NR26*) that was more than 100 % higher than rested males. Females displayed a lower increase with about 30%. Both male and females reached about the same average level of nausea ratings (*NR26* =1.13) when *not-rested*.

Table 51 Estimated marginal means for nausea ratings (NR26) for rested and not rested subjects with 90 % confidence interval.

	Est. marg. means	*Standard. error*	*90% confidence interval* *lower bound*	*upper bound*
Rested				
Male	0.55	0.105	0.38	0.72
Female	0.88	0.102	0.71	1.05
Total	0.72	0.072	0.60	0.83
Not rested				
Total[a]	1.13	0.173	0.85	1.42

Remark: [a] Female, male and total nausea ratings (*NR26*) for not rested subjects are about the same. Evaluated at covariates appearing in the model: sensitivity = 2.90, turn = 3.47.

Significance rested/not rested

The influence from rested and not rested subjects is significant on 5% level ($p < 0.02$). If gender is entered as a factor in the test, then the significance from rested/not rested is on the 10% level ($p < 0.06$), see Table 53.

Table 52 Test of main effects on NR26 regarding condition, turn, rested / not rested and gender.

	df	*Wald Stat.*	*Sign p*		*df*	*Wald Stat.*	*Sign p*
Intercept	4	118.16	0	Intercept	4	121.83	0
Condition	6	29.27	5.4E-05	Condition	6	28.13	8.9E-05
Turn	6	20.08	0.003	Turn	6	21.75	0.001
Rested/not rested	1	5.47	0.019	Rested/not rested	1	3.63	0.057
				Gender	1	7.63	0.006

Remark: Distribution: Ordinal multinomial. Link function: Logit.

A corresponding test with the effects of the variable *I did not feel all right* at the start of the test run show that it does not influence the response nausea ratings at all ($p < 0.52$).

Figure 50 shows the difference in estimated marginal means for *NR26* regarding condition and rested/not rested. Note the higher levels for "not rested" subjects and the great difference for test conditions 4 and 6 (H100R100, H75R75).

Summary

Self-estimated sensitivity is shown as a significant variable. Is seems that females underestimates their sensitivity compared to males. This may explain the relatively small difference between male and female mean sensitivity (3.25 / 2.7 ≈ 1.2) and in relation to large difference in nausea ratings (1.0 /0.55.≈ 1.8).

Not-rested subjects show significantly higher nausea ratings (*NR26*) than rested subjects. The largest differences are for conditions with high *NR26* for rested subjects. Not-rested male and female reached about the same *NR26* .

The influence of difference between *I feel all right* versus *I do not feel all right* at the start of the test runs on nausea ratings is zero.

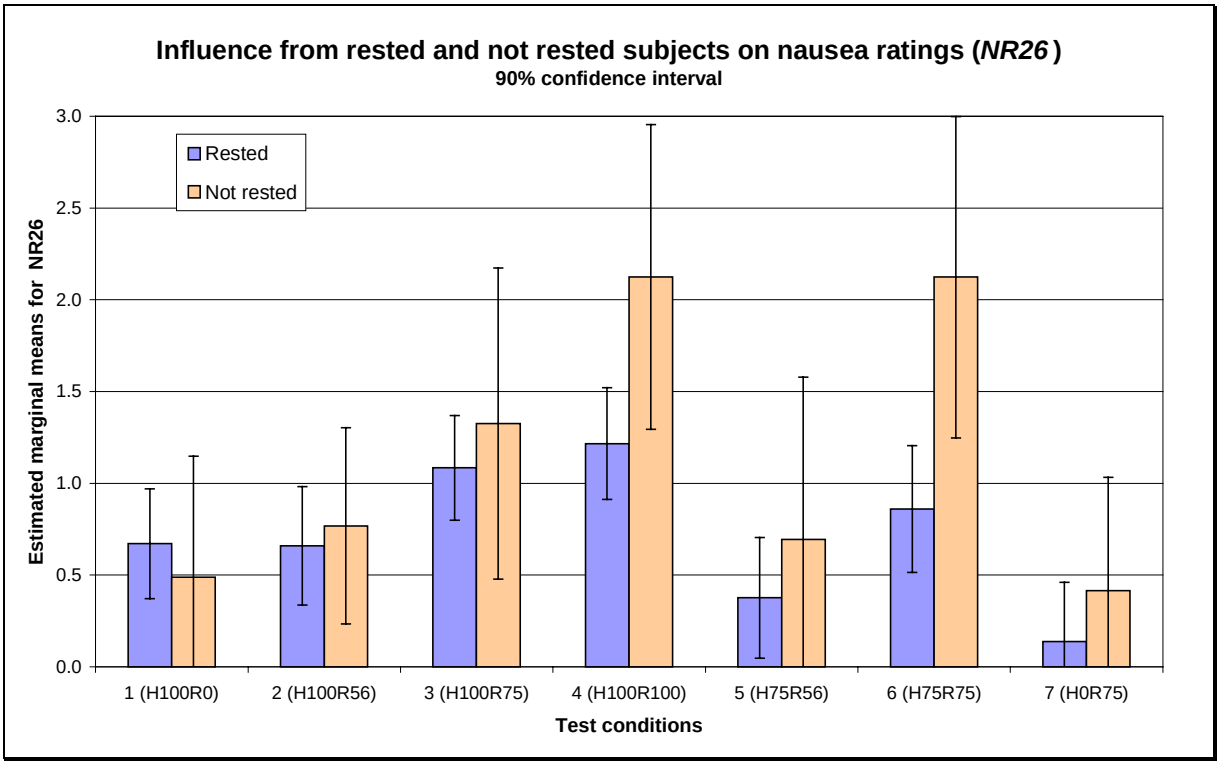


Figure 50 *Differences in nausea ratings (NR26) for rested and non-rested subjects. Altogether 33 test runs (19%) were made with non-rested subjects.*

Influence of turn (number of turns) and adaptation to motion conditions

During the course of the experiment, the number of subjects with moderate and strong nausea was decreasing, see Table 53. This indicates that the subjects are adapting to the test and the motion conditions.

Table 53 *Distribution of nausea symptoms for all evaluated subjects for each turn. The first part shows the number of subjects with different symptoms at 26 min and the second part shows the percentage of subjects with no symptoms and with symptoms at 26 min.*

		Turn 1	*Turn 2*	*Turn 3*	*Turn 4*	*Turn 5*	*Turn 6*	*Turn 7*	*Total*
Male	No symptoms	4	11	12	11	8	6	5	57
	Light symptoms	13	4	3	2	2	2	1	27
	Light nausea			1			1	3	5
	Moderate nausea	1	1		1				3
Total		18	16	16	14	10	9	9	92
Female	No symptoms	7	9	10	10	8	6	5	55
	Light symptoms	4	3	4	2	2	2	5	22
	Light nausea	6	4	5	2	1	3	1	22
	Moderate nausea	3			2				5
	Strong nausea	4	3		1	1			9
Total		24	19	19	17	12	11	11	113
Grand Total		42	35	35	31	22	20	20	205
Male	with no symptoms	22%	69%	75%	79%	80%	67%	56%	62%
	with symptoms	78%	31%	25%	21%	20%	33%	44%	38%
Female	with no symptoms	29%	47%	53%	59%	67%	55%	45%	49%
	with symptoms	71%	53%	47%	41%	33%	45%	55%	51%

This can also be illustrated as in Figure 51, where the nausea ratings (*NR26*) is averaged over all conditions for the different turns by subjects taking part in all seven turns.. The reduction of *NR26* is large, about 50% reduction after 3 –5 turns. There is a small increase in turn 6 and 7, which may be explained be proportional more tests with the "severe" condition than the for turn 3 –5.

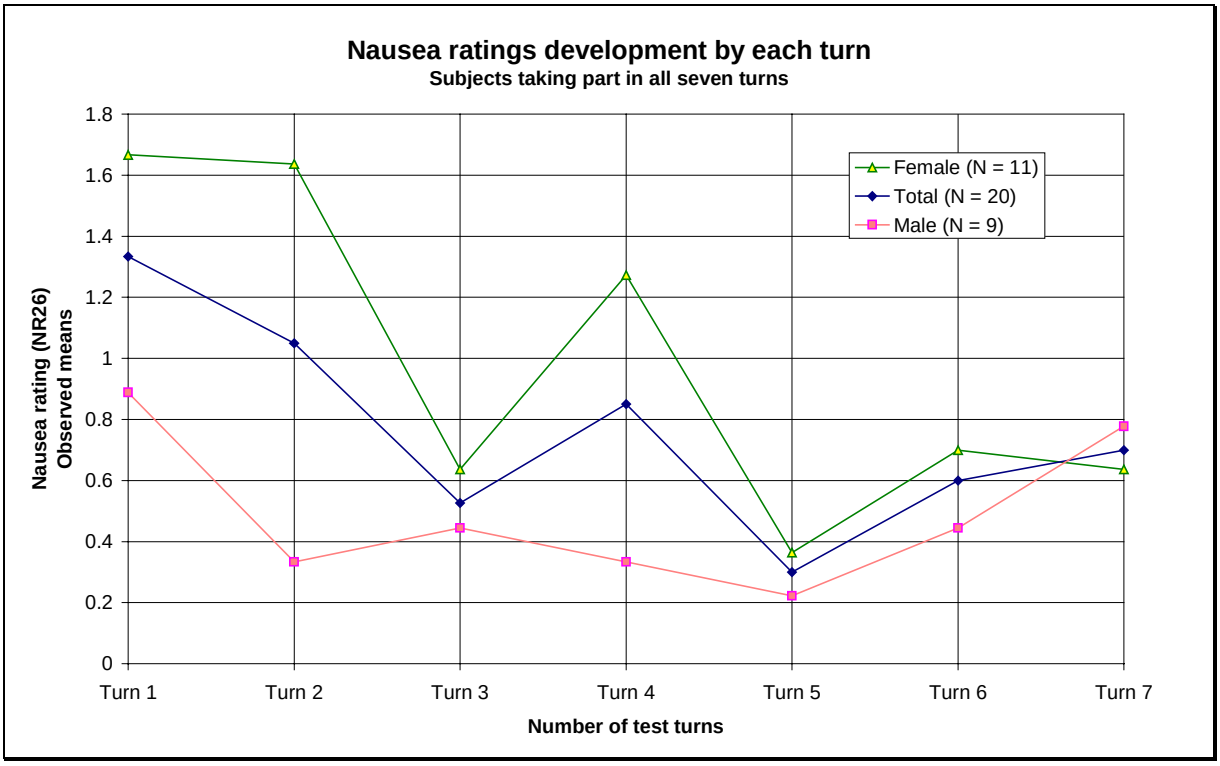


Figure 51 Nausea ratings (NR26) over the different turns for subjects taking part in all turns.

The variable turn is already shown as a significant variable. By studying those subjects, who have taken part in all seven turns, it is easy to see that they were less nauseous after three to four turns. For example, subjects who had to interrupt the test, during the two or three first test runs, could manage to fulfil a full test run in the later turns even though that they were taking part in severe conditions like 3 or 4.

For condition 3 (H100R75) it is possible to plot the estimated marginal means for the different turns, see Figure 52, since this is the condition that most of the subjects took part in. The adaptation to the motion is here clearly visible with a decreasing of *NR26* values with of –0.15 units per turn (r^2 = 0.62).

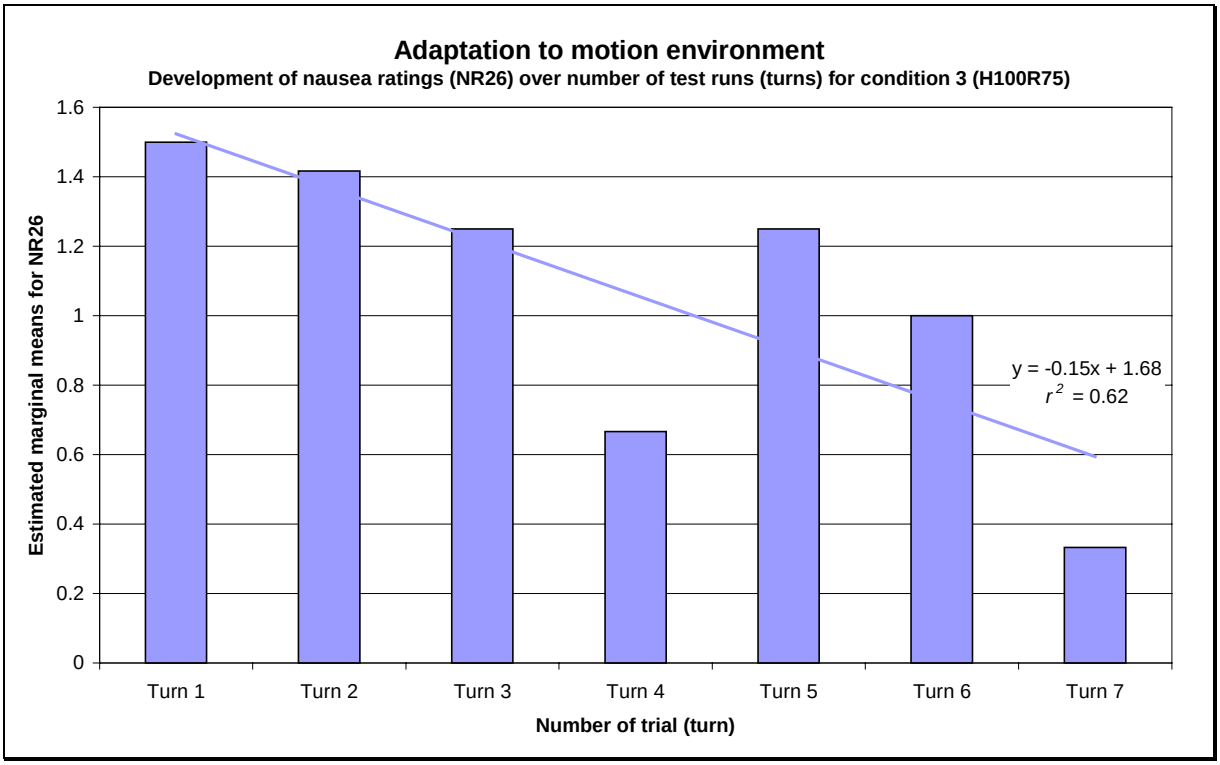


Figure 52 Development of nausea ratings (NR26 for condition 3 (H100R75).

Another interesting question is whether the subjects' provocation levels are not only decreasing during the turns but if test condition nauseogenic raking order is changed. Figure 53 shows a comparison between the observed means with population means (expected values) from ordinal multinomial distribution from data for the first turn only compared with data from all turns but given as for the first turn. With data from the first turn only, the observed means and the population means agree quite closely to each other with one marked difference for the condition 3 (H100R75). The observed and population means for the first turn indicates also the degree of severity of condition 4 (H100R100). In this condition, the subjects perceived no apparent lateral acceleration in the cabin. Condition 2 (H100R56) has lower nausea ratings than the pure horizontal condition H100R0. When regarding data from all test runs, the subjects seems to change their rating of the conditions. Condition 1 (H100R0) (horizontal motion only) is less provoking as in the first turn. It is slightly less provoking than condition 2 (H100R56) which provocation level has increased. The conditions 3 and 4 (H100R75 and H100R100) have almost the same provoking level.

Summary

Adaptation is significant and strong. As an average the nausea rating (NR26) are reduced to about 50% after 3 to 5 turns. However, for condition 3 (H100R75) the mean adaptation rate is about 0.15 *NR26* per turn. "Naive" subjects seems to more sensitive to pure horizontal acceleration and condition with high compensation (condition 4 and 6).

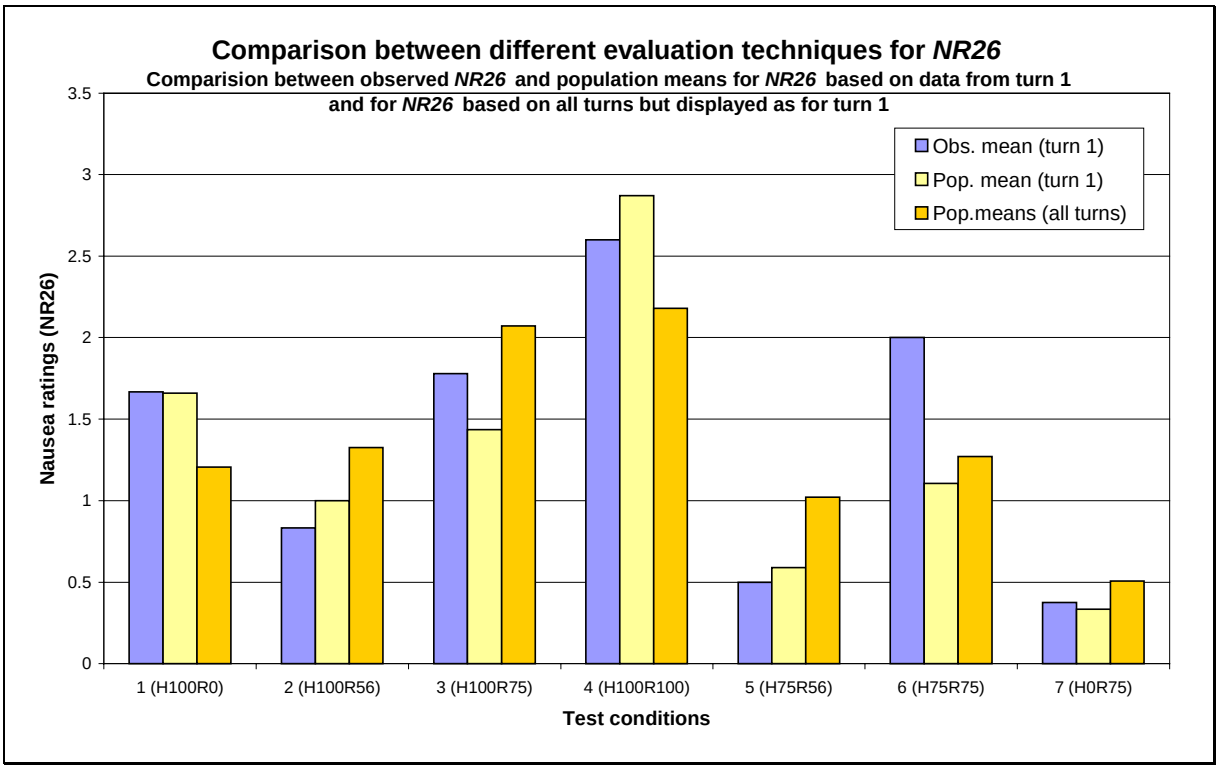


Figure 53 *Comparison between observed NR26 and population means for NR26 based on data from turn 1 only and for NR26 based on data from all turns but displayed as for turn 1.*

7.3.3 Influence from exposure time and test conditions on nausea and illness ratings (Part II)

The test part IIA was aimed to show the difference between standard condition 3 (H100R75) and any of the following conditions: low roll acceleration (LRA), low roll velocity (LRV) and when both roll and horizontal acceleration having "smoothed ends" (SE), cf. Table 28. The test part IIB was aimed at showing the difference between condition H100R75 with added vibrations and the same motion condition but without vibrations (NV).

Figure 54 shows the main results on nausea ratings (*NR26*) for the different conditions and gender. The LRV condition gave low *NR26* for males and the SE condition gave low *NR26* for females. The conditions LRV and SE show potential reductions of *NR26* with about 20 – 30%. The difference between no vibration condition (NV) and reference condition (H100R75) is not significant.

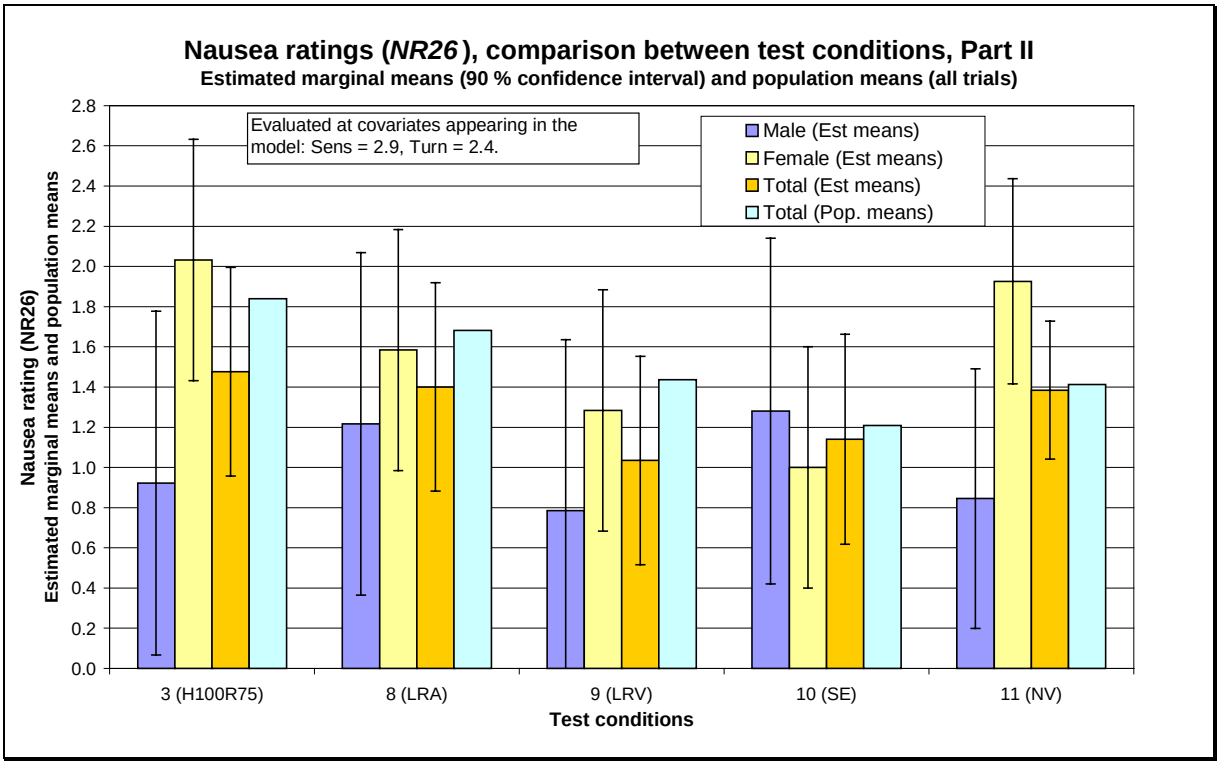


Figure 54 *Estimated marginal means for NR26 and expected NR26 (all turns) from test part II. The relative magnitude of condition 13 (NV) has been changed, so a comparison between part IIA and part IIB can be made.*

Significance

The nausea ratings (*NR26*) in Part IIA is significant different with respect to condition on the 10% level, see Table 59, but not regarding turn. Condition in Part IIB in non-significant, however turn is significant.

Table 54 *Test of main effects on NR26 regarding subjects, conditions and turn for Part IIA.*

	df	*Wald Stat.*	*Sign p*	*Log-Likelihood*	*Chi-Square*	*Sign p*
Intercept	4	37.71	1.29E-07	-89.24		
Subjects	15	30.57	0.010	-47.26	83.97	1.3E-11
Conditions	3	6.23	0.10	-43.89	6.73	0.08

	df	*Wald Stat.*	*Sign p*
Intercept	4	36.74	2.04E-07
Subjects	15	30.90	0.009
Conditions	3	5.43	0.14
Turn	3	3.83	0.28

Remark: Ordinal multinomial distribution. Link function: Logit.

Summary

By lowering the rate of roll velocity or roll acceleration, the nausea ratings are decreasing, especially for females.

7.3.4 Percentage with nausea and illness

The percentage of subjects having any kind of nausea symptoms (*NP*) and symptoms of motion sickness *SMS*[42] is high, especially for the first turns. *NP* and *SMS* are essentially the same since there is almost no one reporting *IR* >0 but still having *NR* = 0. Those, who started with *not feeling well* (*IR0* > 0) at start of the test run, do not have any significant influence on *NP26* or *SMS26*.

Separated on the different conditions, the percentage of subjects having any kind of nausea symptoms, varied considerably between different test conditions. Average *NP26* over all turn are shown in Figure 55. The percentage ranged from 15 – 62% for male subjects and from 20 – 76% for females. The strongest responses are from conditions 3 and 4 (H100R75, H100R100) and for females also from conditions 1 and 6 (H100R0, H75R75). This is about the same as for the estimated marginal means for *NR26*.

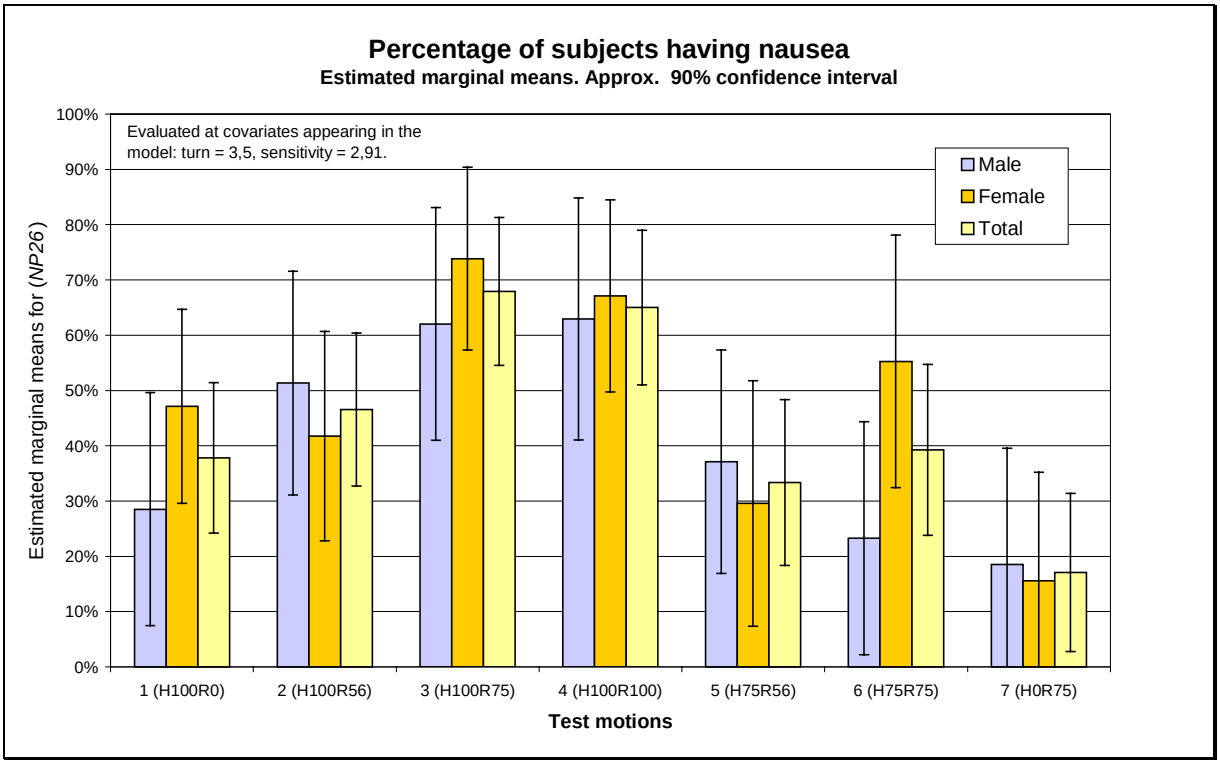


Figure 55 Nausea percentage (NP26) separated in male, female and total. 90% confidence intervals are indicated. Average over the all turns.

Regarding the first turn, the *NP26* or (*SMSI26*) are considerably higher than the average levels in Figure 55. Figure 56 show the observed *NP26* from the first turn together with population means given for the first turn. The population means are based on the binomial distribution for data from all turns.

[42] *SMS* and *NP* here defined as: *SMS* = 1 if *IR* > 0 or *NR* > 0, else *SMS* = 0.
NP =1 if *NR* > 0 else *NP* = 0.

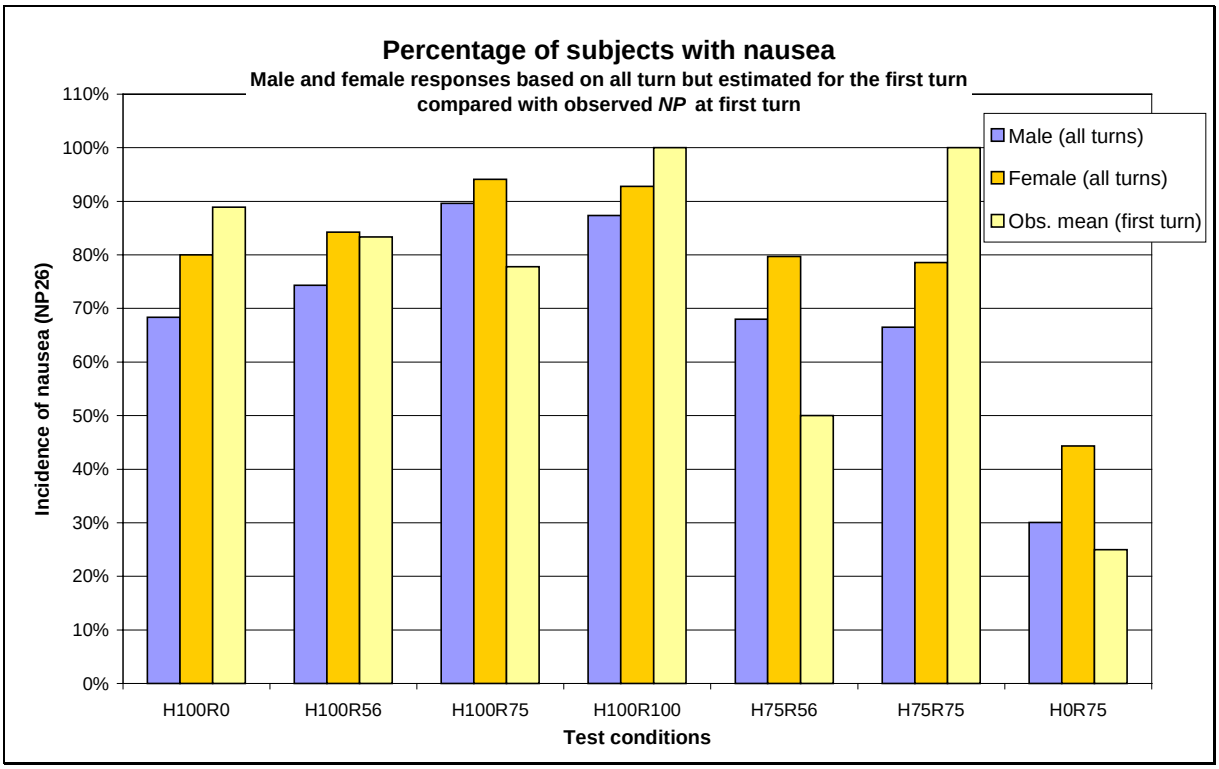


Figure 56 *Nausea percentage (NP26) for the different conditions. Male and female responses calculated from binomial distribution aggregated from all data but shown as NP26 for the first turn, together with the observed NP26 at the first turn.*

The observed *NP26*, in the first turn, are 100% for both conditions H100R100 and H75R75, those two with 100% tilt compensation. In these motion conditions, where the subject perceived no apparent lateral acceleration in the cabin, all of them are affected by some degree of nausea. After some turns, this high rate of nausea percentage is decreasing to reached the average levels as in Figure 55.

Significance

Test condition and turn are significant explanation variables for *NP26*, see Table 55.

Table 55 *Test of main effects on NP26 regarding subjects and condition and turn.*

	df	*Wald Stat.*	*Sign p*
Intercept	1	1.38E-06	1.00
Subjects	41	29.36	0.91
Condition	6	20.50	0.002
Turn	6	23.85	0.001

Remark: Distribution: Binomial. Link function: Logit

Summary

The nausea percentage (*NP26*) is high for most of the conditions. Two conditions had 100% of the subjects with some degree of nausea ratings at the first turn. The average *NP26* over all turns show about the same ranking order of nauseogenic motion as *NR26* do.

7.3.5 Decay of nausea ratings - leakage

Eight subjects had to interrupt the test runs due to nausea during test part I and further five subjects during test part II. These subjects were monitored during their recovery and answered questions every 5 min about their nausea and illness ratings. Table 56 shows the number of subjects, who had interrupted the test and the mean time to interruption. Figure 57 shows decrease of nausea and illness ratings during a period of 30 min. Displayed values are mean values. In these numbers are also included three subjects who had strong nausea at the end of the 31 min duration of the test runs. The exponential regression lines shown have high explanation values for the average values (r^2 = 0.99; 0.97 respectively) with a time constant of the decay of 15 min for *NR* and 14 min for *IR* (half time values are just about 10 min). However, some of the subjects had headache or other problems during a long time afterwards.

Table 56 Statistics on subjects who interrupted the test runs or had strong nausea after completed a full test run.

Condition		*Number*	*Percentage of test runs*	*Mean time to interrupt [min]*
2	H100R56	1	3%	16
3	H100R75	6	9%	19.8
4	H100R100	2	6%	16
6	H75R75	1	4%	21
8	LRA	2	14%	24
13	NV	1	7%	24
	Total	13	5%	20.0

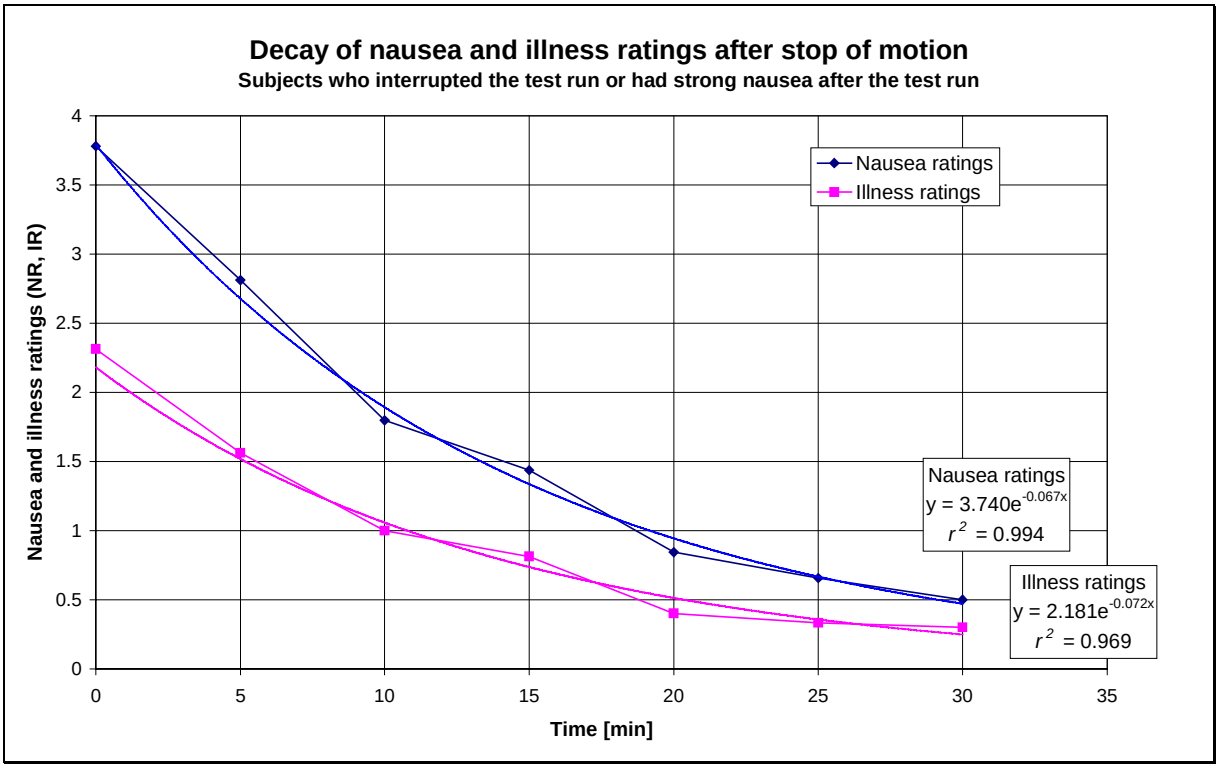


Figure 57 Decay (leakage) of nausea and illness ratings after stop of motion. Mean nausea and illness values for each 5 min are shown. Used subjects are those who interrupted the motion (N = 13) or having strong nausea after 30 min (N = 3).

One curious observation is that almost all interrupts happened at test runs starting in the morning (8:00 and 9:00), probably after breakfast, and in the early evening (17:00, 18:00 and 19:00) probably before they had an evening meal. (Starting times were from every whole hour between 8:00 and 20:00)

7.3.6 p-deletion test

The subjects made the p-test (p-deletion test) just before the test run started, entered the cabin and then again at 0, 10, 20, 30 and 40 min after the test start.

Learning effects

There is a very strong learning effect from turn 1 to turn 7, see Figure 58. The figure shows the mean number of marked p's at the start of the test run (p_0) and at the stop of the test run (p_{30}). The regression model for learning, i.e. mean number of found p's at the start of test runs for female is:

$$p_0 = 1.54 \cdot turn + 19.75 \qquad [7.1]$$

($r^2 = 0.96$, evaluated from average values per turn, N=7) (Female)

and the corresponding model for male is:

$$p_0 = 2.19 \cdot turn + 16.66 \qquad [7.2]$$

($r^2 = 0.96$, evaluated from average values per turn, N=7). (Male)

where p_0 is number of marked p's at the start of the test (0 min) and *turn* is the number of the test run. However, there is a large individual variation of the number of marked p's.

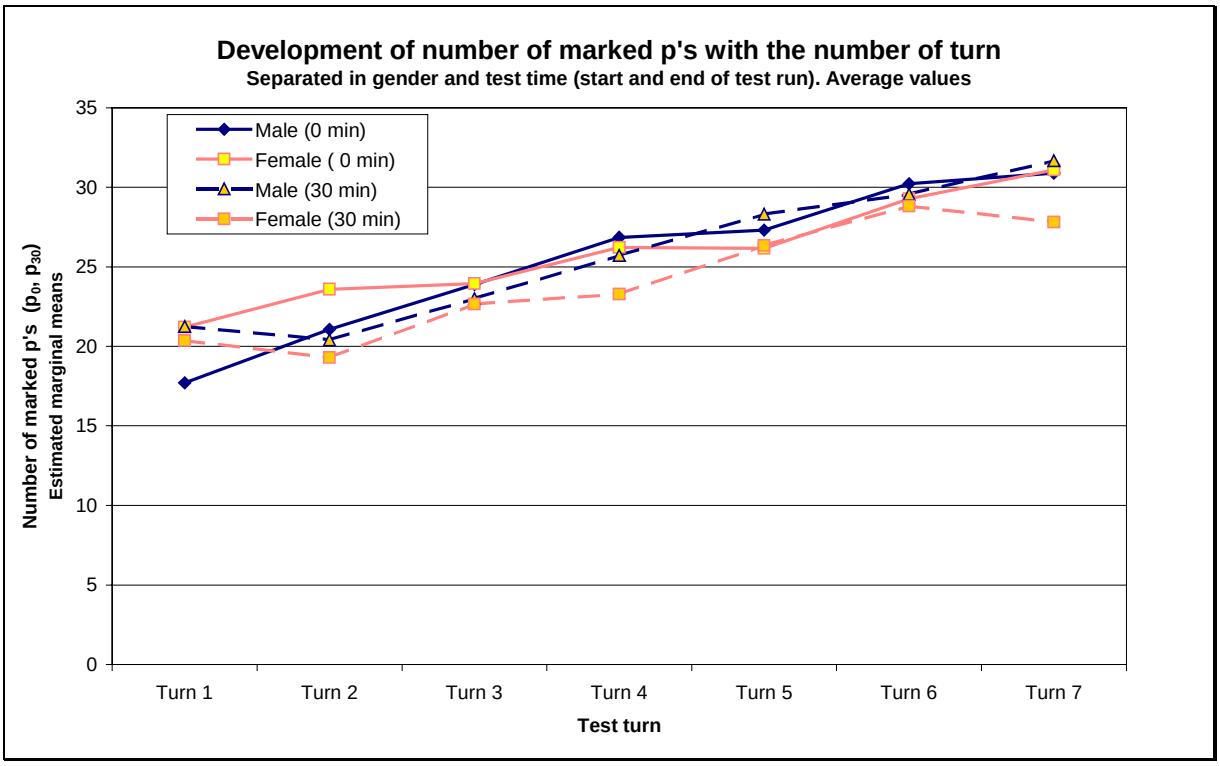


Figure 58 *Number of marked p's in the p-deletion test at the start (p_0) and at the end of the test run (p_{30}), averaged for each test turn for both genders.*

Effects of nausea

Since the number of marked p's varies with the number of the turn, a normalisation of the number of p's has to be done, before further evaluation. The score of marked p's for each subject and each turn is divided with the corresponding number of p_0 for that turn (according the equations above), to get a normalised value. Figure 59 shows the average normalised number of marked of p's before the test, at the start (0 min), at the end of the test (30 min) and after 10 min of rest (40 min), separated in the groups of different grades of nausea. The groups of moderate and strong nausea are combined, because the numbers of subjects in the individual groups were too small (N = 6 and N = 4). Subjects, who had interrupted the test run, are shown separately.

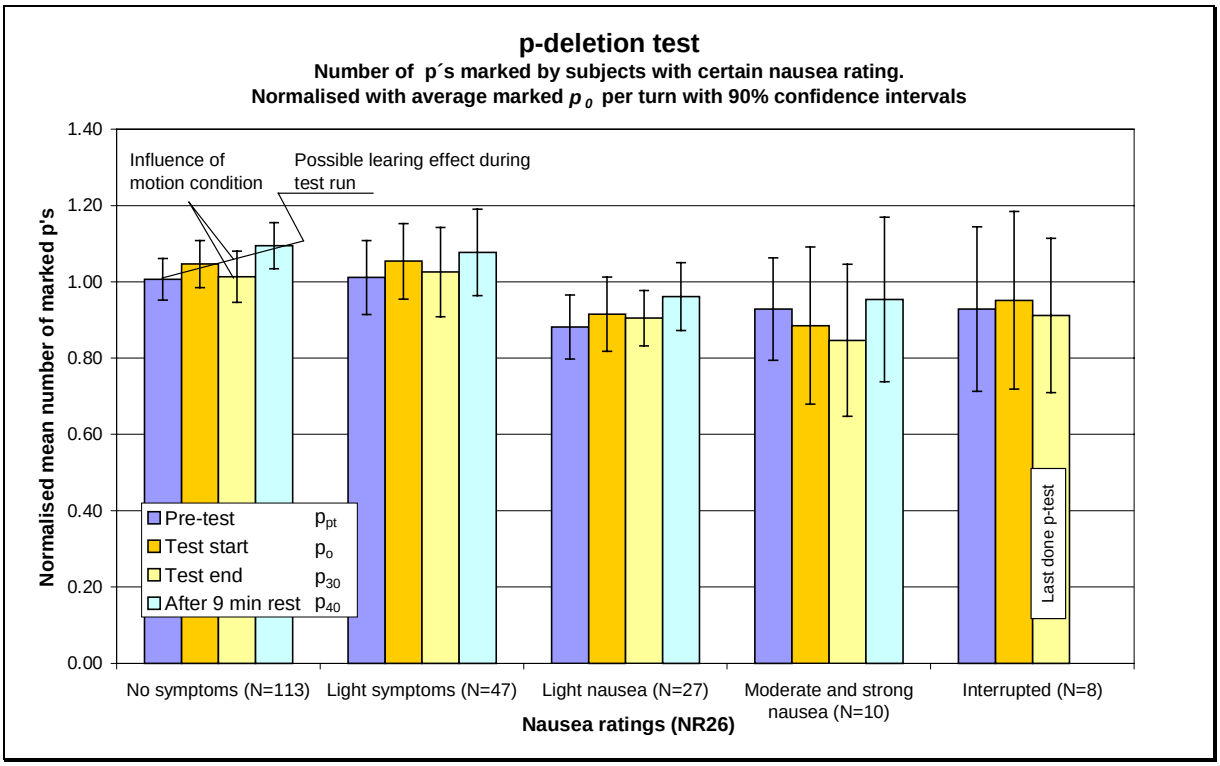


Figure 59 *Normalised number of marked p's before the test, at the start of test run, at the end of test run and after 9 min rest.*

It seems from Figure 58 that there is a small increase in the number of marked p's, clearly indicating a *learning effect* during the test, especially in the first three groups. The differences between the levels at the test end and the thought line between levels for pre-test, test start and after 9 min rest, may be a influence of nausea, see markings in Figure 59. However, it also seems that the number of marked p's at pre-test and test start are slightly decreasing with increasing of higher nausea ratings.

To test this hypothesis, a regression analysis of marked number of p's (before, at test start and test end), number of turns and nausea were performed on all test runs, see Table 57. The significance for the coefficient of the variable turn is very high ($p < 0.001$) while the coefficient for nausea rating (*NR26*) is from moderate to high ($0.13 < p < 0.001$). However, there were no significant differences between the different test conditions.

Table 57 Regression coefficients for the linear regression line: Number of p's = C + α·NR26 + β·(turn)

	Female			Male		
	p_{pt}	p_0	p_{30}	p_{pt}	p_0	p_{30}
C	19.88	21.35	21.25	17.86	17.73	19,57
α (*NR26*)	-0.65	-0.96*	-2.08***	-1.10	-1.82*	-1.98*
β (Turn)	1.44***	1.37***	1.20***	2.06***	2.16***	1.77***
r^2	0.30	0.25	0.27	0.35	0.35	0.27

Remark p_{pt} = number of p's before test
p_0 = number of p's at test start
p_{30} = number of p's at test end
Significance: * $p < 0.05$; *** $p < 0.001$

Summary

The difference between the number of marked p's between pre-test and 0 min shows a possible learning effect. The difference between 0 and 30 min may show a combination of learning and any nausea effects from conditions, whereas the reading at 40 min may show a possible recovery effect. Nausea ratings (NR26) have a significant influence on marked number of p's (mental work ability) both at start of the test run (p_0) and at the end of the test run (p_{30}).

7.3.7 Ride comfort and work/read ability

The subjects estimated their overall ride comfort, any comfort disturbances and ability to work and read on a five grade scale from 1 (very bad) to 5 (very good) for the different conditions. There is a strong (and significant $p << 0.001$) influence on estimated comfort values and work ability frim subjects' nausea ratings:

Rated ride comfort (31 min) = 3.1 - 0.5 · *NR26* + 0.6 · *ge* , (r^2 = 0.27, (*N* = 201[i])) [7.3]
Rated work ability (31 min) = 3.6 - 0.6 · *NR26* + 0.3 · *ge* , (r^2 = 0.38, (*N* = 201[i])) [7.4]

where *ge* = gender (= 0 male and 1 = female)

Remark: i Some observations are missing.

Coefficients for gender differences are positive with 95% confidence.

Because the strong influence from nausea ratings on comfort and work/read ability, comparisons between different conditions have to be made with subjects who had no nausea (*NR26* = 0).

Figure 60 shows the estimation of average ride comfort and ability to work/read for the different conditions. Since the nausea rating is strongly influencing theses comfort variables, the evaluation is done over subjects with no nausea ratings (NR26 = 0). There are modest differences in rated comfort or work ability between the different conditions. Conditions that provoke high scores of nausea ratings generally give less comfort and work ability. The greatest difference is between conditions 4 and 5 (H100R100 and H75R56). It is surprising that females generally estimates both comfort and work ability with higher values than males, in spite of they get more nausea, see the regression equations above. There are only small differences between estimated ride comfort at 16 and 31 min.

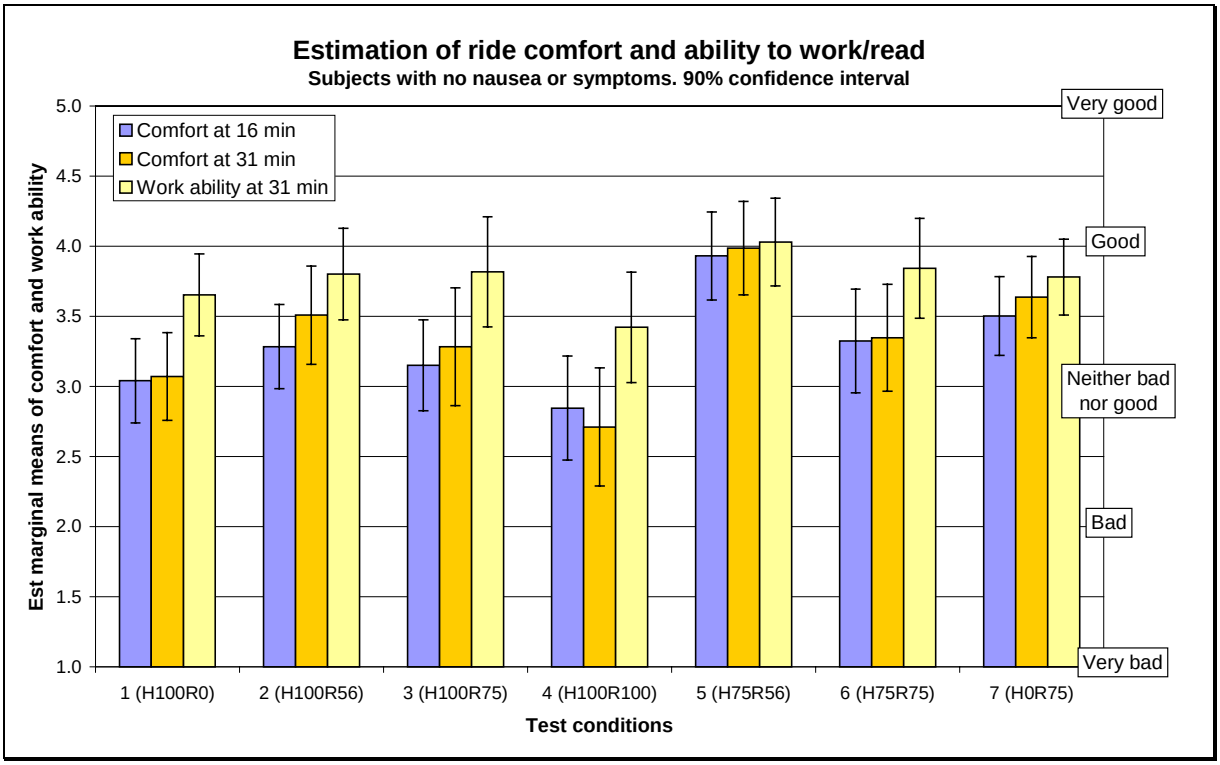


Figure 60 *Estimation of average ride comfort and work/read ability for the different conditions for subjects with no nausea (NR26 = 0). 90% confidence intervals are indicated.*

7.3.8 Comfort disturbances

The subjects also marked if they had any complaints on the ride comfort in four aspects:

Large lateral shakings
Large vertical shakings
Large lateral motions (side forces)
Uneven roll motion

The evaluation is with subjects with no nausea (*NR26* = 0) as before. The Nausea influence is strong. The percentage of subjects, with complaints varies a lot between different conditions. Just above 60% of the subjects complains that condition 1 (H100R0) have large horizontal motions (side forces). These complaints diminish as the roll motion increases to condition 4 (H100R100) but the complaints from vertical and lateral shakings as well as uneven roll motion increases, see Figure 61.

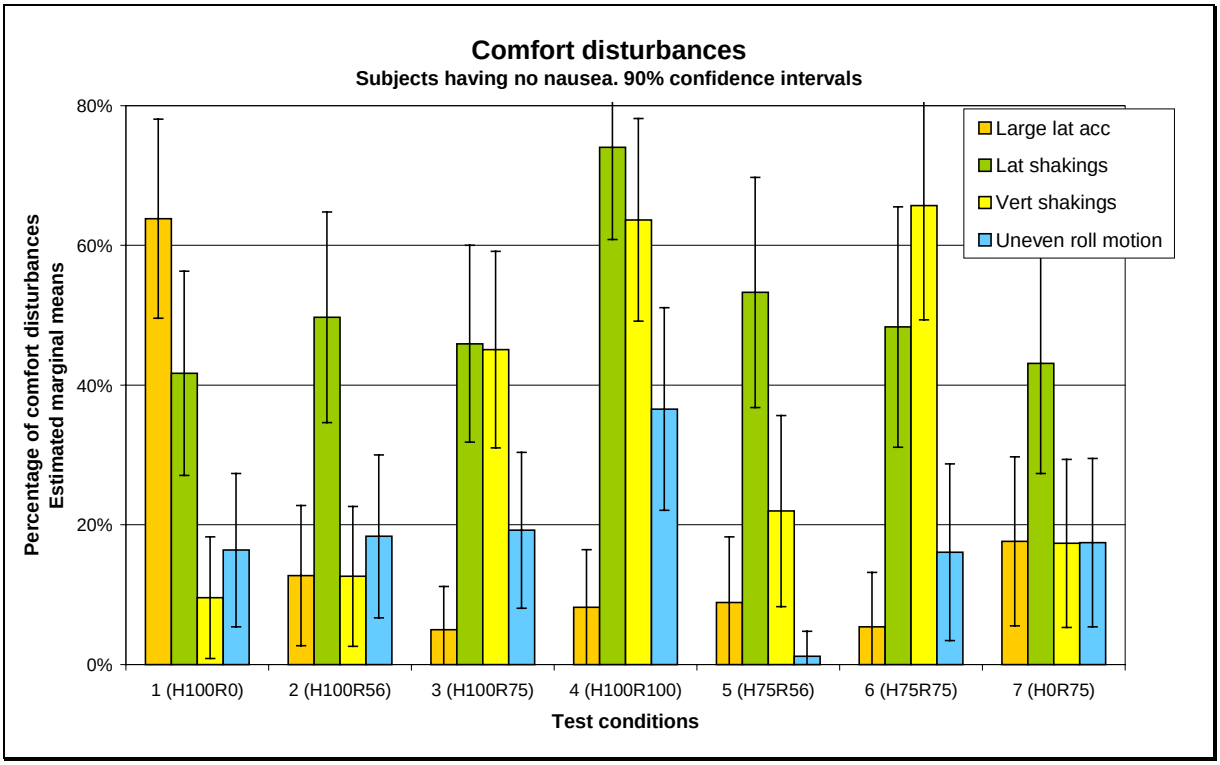


Figure 61 *Comfort disturbances for the different conditions for subjects with no nausea. 90% confidence intervals are indicated.*

P_{CT}

P_{CT} is an estimation of percentage dissatisfied passengers (Harborough 1986a, Harborough 1986b), see also Chapter 3.4.1 and Appendix D. A calculation of P_{CT} for seated passengers, for the motion sequence 1 with no vibration or other dynamics effects added, is shown in Table 58. P_{CT} is calculated from lateral acceleration (cabin), lateral jerk and roll velocity. Condition 1 with high lateral accelerations in the cabin level give relative high values of P_{CT} (13%) while condition 4 with high roll angles/velocity give relatively low values (1.8%).

Table 58 *P_{CT} estimated from the motion sequence 1 (lat acc = 1.1 m/s^2, transition time 1.2 s) and with no vibration or other dynamics effects added for the condition 1 – 4 , valid for seated passengers.*

Condition:	1 (H100R0)	2 (H100R56)	3 (H100R75)	4 (H100R100)
P_{CT}	12.8	3.1	1.2	1.8

Correlations

Table 59 shows correlations (Spearman) between different comfort factors and nausea. These correlations emphasise the picture given above. Discomfort is negatively correlated with ride comfort and work/read ability but positively correlated with nausea. Ride comfort and work/read ability are strongly correlated with each other and both are strongly negatively correlated with nausea.

Table 59 Correlations between ride comfort, discomfort work-/ read ability and nausea ratings (NR26) at the end of the test runs.

Spearman correlations		*Discomfort*	*Work / read*	*Ride comfort*	*Gender*
Discomfort	Corr. coeff.	1			
	Sign	-			
Work / read	Corr. coeff.	-0.279**	1		
ability	Sign	0.000	-		
Ride comfort	Corr. coeff.	-0.383**	0.676**	1	
	Sign	0.000	0.000	-	
Gender	Corr. coeff.	0.104	0.041	0.171*	1
	Sign	0.140	0.562	0.015	-
NR26	Corr. coeff.	0.309**	-0.525**	-0.444**	0.187**
	Sign	0.000	0.000	0.000	0.007

Remarks: ** Correlation is significant at the 0.01 level (2-tailed).
* Correlation is significant at the 0.05 level (2-tailed).

Summary

Nausea is strongly positively correlated with discomfort and negatively correlated with ride comfort, ability to work/read. Nausea slightly decreases the mental work ability (p-deletion test).

7.3.9 Motion conditions

Motions were monitored and recorded during test runs. The following motion quantities were recorded: vertical and lateral acceleration inside the cabin, and roll velocity. By time differentiation lateral jerk and roll acceleration were generated. Evaluation was done by filtering the quantities with various low-pass filters[43] including band-pass (BP) 0.08 – 0.35 Hz. (the simplified motion dose filter w_f). R.m.s.-values were calculated for these quantities over the 60s total motion sequences for all different test conditions. Table 60 shows r.m.s. - values for the BP – filtering motions. Figure 62 shows the maximum r.m.s.-values for these motions quantities filtered at different frequencies. Generally, the maximum value for lateral acceleration and lateral jerk are reached from test condition 1 (H100R0), except for jerk at 2 Hz. All other motion quantities reached their maximum values for motion condition 4 (H100R100).

[43] LP 0.25 Hz, LP 0.35 Hz, LP 0.5 Hz, LP 0.7 Hz, LP 1.0 Hz and LP 2.0 Hz.

Table 60 *R.m.s. values for some motion quantities, filtered with the band-pass filter BP 0.08 – 0.35 Hz (w_f).*

Test condition	*Vertical acc. [m/s^2]*	*Horizontal acc. [m/s^2]*	*Lateral acc. [m/s^2]*	*Lateral jerk [m/s^3}*	*Roll acc. [rad/s^2]*	*Roll velocity [rad/s]*
1 (H100R0)	0.0237	0.553	0.553	0.499	0.0008	0.0004
2 (H100R56)	0.0427	0.553	0.273	0.259	0.0335	0.0278
3 (H100R75)	0.0483	0.553	0.187	0.186	0.0452	0.0375
4 (H100R100)	0.0524	0.553	0.115	0.123	0.0605	0.0502
5 (H75R56)	0.0333	0.414	0.143	0.145	0.0336	0.0279
6 (H75R75)	0.0357	0.414	0.089	0.099	0.0451	0.0375
7 (H0R75)	0.0300	0.000	0.390	0.343	0.0452	0.0374
8 (LRV)	0.0484	0.553	0.178	0.173	0.0445	0.0371
9 (LRA)	0.0478	0.553	0.204	0.206	0.0401	0.0337
10 (SE)	0.0481	0.553	0.181	0.174	0.0445	0.0371
11 (NV)	0.0456	0.553	0.189	0.185	0.0452	0.0374

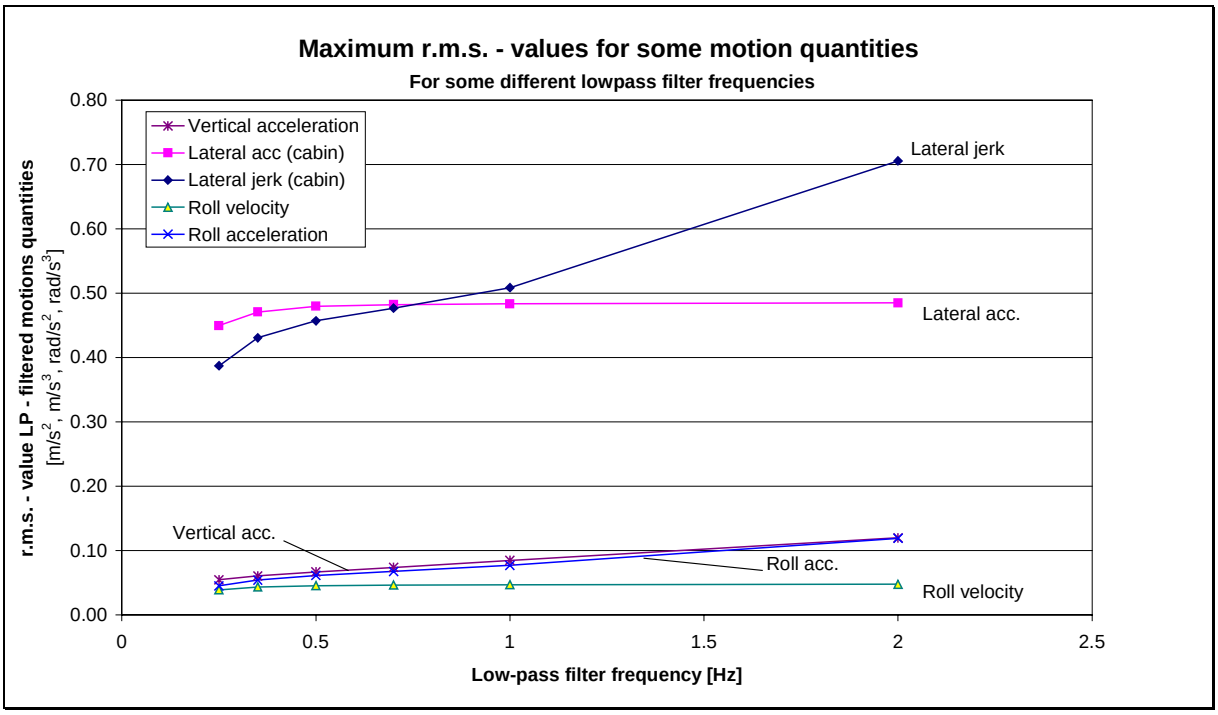


Figure 62 *Maximal r.m.s. - values for different motion conditions and quantities, low-pass filtered at different frequencies. Maximum values occurred for test condition 1 or condition 4.*

Notify the close relation in magnitudes between vertical and roll acceleration. They differ with about 10 - 20% between 0.25 to 1 Hz and are almost equal at 2 Hz. Roll acceleration can be calculated as the difference between two vertical accelerometers divided with the distance between them. If one of the accelerometers is fixed with zero vertical acceleration, the other one would also indicate roll acceleration.

The Figure 62 also indirectly shows that the upper low-frequency horizontal input from test motions is about 0.5 Hz, since r.m.s. – values for lateral (horizontal) acceleration and roll velocity is almost not increasing over this frequency. This is verified with a frequency analysis for the horizontal acceleration for the test condition 1 (H100R0), see Figure 63.

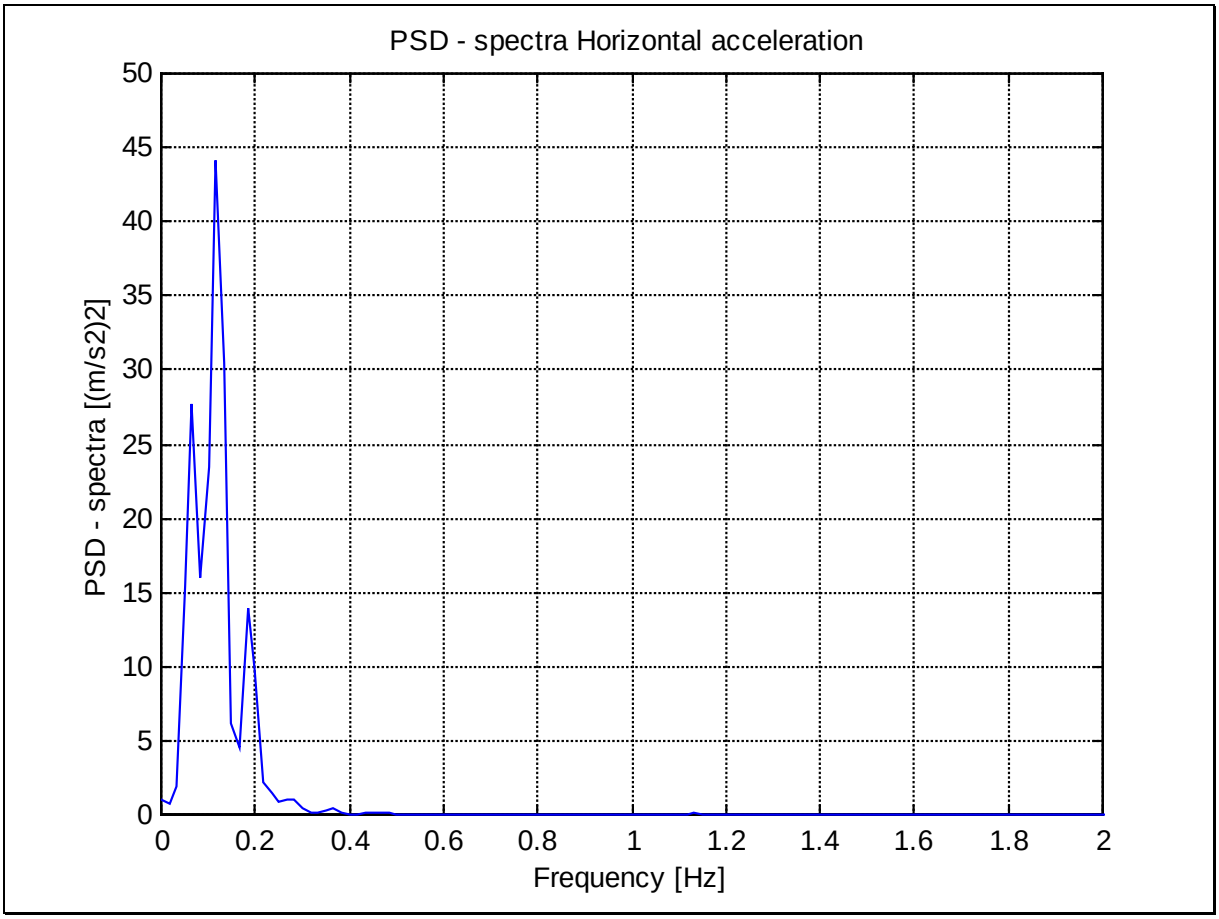


Figure 63 *PSD – spectra for horizontal acceleration, i.e. the lateral acceleration in cabin for test condition 1 (H100R0).*

Comparison

Typical r.m.s. – values obtained in the train test are shown in Table 61. They shows that vertical accelerations has the same order of magnitudes, lateral acceleration (car body) and roll acceleration are 2 – 3 times lower than the maximum values than in the simulator test (Table 60).

Table 61 *Typical r.m.s. – values for vertical, lateral (car body) and roll acceleration from the train experiment.*

w_f – *filtered r.m.s. - values*	*Vert acc* $[m/s^2]$	*Lat acc* $[m/s^2]$	*Roll acc* $[rad/s^2]$
Tilt condition A	0.079	0.145	0.018
Tilt condition G	0.077	0.191	0.016
Tilt condition F	0.077	0.198	0.015

7.3.10 Summary and conclusions (simulator experiments)

A summary of different reactions of discomfort and nausea when increasing the roll motion and keeping the lateral motion in the horizontal plane constant is shown in Figure 64. Note that ride comfort and ability to work/read are reported, in this figure, as the differences from the highest possible score to the actual mean values. All values are normalised with 1 as the highest possible discomfort. The magnitudes of "large lateral accelerations" are divided with 5 to allow an easier comparison with P_{CT}, predicted passenger dissatisfaction in curves transition (Harborough 1986b). The calculated P_{CT} –values are divided with 100.

Ride discomfort and disability to work/read show the most unfavourable values at 0% and 100% roll motion. Nausea ratings (*NR26* population means, all turns, normalised) are increasing with increased roll motion. P_{CT} instead decreases when the roll motion increases because the lateral acceleration perceived by the subjects decreases, except at 100% roll, where it increases slightly. The subjects' responses (comfort disturbances) to large lateral accelerations (side forces) are just about five times higher than P_{CT}. This means that the influence of roll motion is about the same both for P_{CT} and subjects responses. Comfort disturbances due to uneven roll motion correspond to some extent with *NR*.

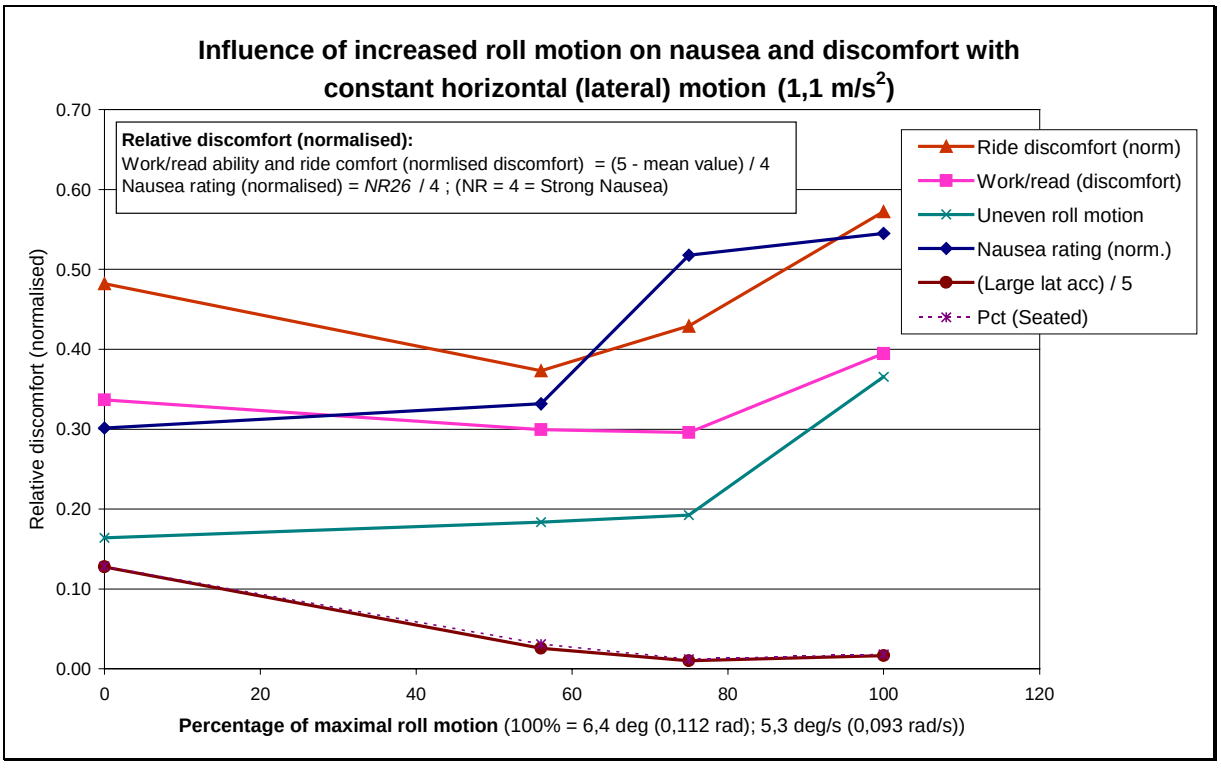


Figure 64 *Relative discomfort including nausea ratings, versus roll motion. All quantities are normalised with 1 as the highest possible discomfort.*

Conclusions

- Roll motions presented alone of the magnitude and frequency as in the present study are not very nauseogenic. This seems to be accordance with the sensory conflict hypothesis. Only small differences between gender in nausea ratings were found.
- Horizontal accelerations alone seem to be medium provocative. Horizontal motions seem to provoke females more than males. The relative sensibility for horizontal acceleration alone is decreasing, as subjects are getting more adapted to test conditions after some turns.
- Combinations of high roll and high horizontal accelerations, as those presented in this study, seem to be highly provocative. High compensation ratios alone are not necessarily nauseogenic. Modest roll and horizontal acceleration as for the condition (H75R56) show low nausea ratings.
- Ride comfort, comfort disturbances as well as the ability to work /read are affected by the degree of nausea. Both high horizontal acceleration and high roll motion have negative effects on these factors.

8 Model for development of motion sickness over time

The model is a joint work of the authors Kufver and Förstberg (1999).

8.1 The net dose model

The net dose model is developed based on the assumption that nausea is correlated to the *net dose of motion* D_N. The net dose is defined as the difference between the *perceived dose* D_P and the *accumulated leakage* D_L.

Models, that have been already been presented, are either mathematical difficult or grow with time and requires therefore some time limitations (Lawther 1988, Lawther & Griffin 1987, McCauley et al. 1976). They are suitable for exposure of provocative motions over a specific time or journey. However, there is a model that incorporates a second-degree time filter but there is no arguments for choosing this filter for the time development (Bles et al. 1998, Bos & Bles 1997, Bos & Bles 1998).

The proposed model is aimed only to explain the time dependency of the development of nausea. Directions of motion (longitudinal, lateral, vertical, roll, etc.) and frequencies are assumed constant during the whole exposure or approximately constant under a short period. Hence, the provocative motion may be described by a constant amplitude A or a variable amplitude $A(t)$, when amplitude varies with time t. This is the case for typical exposure during travelling with train, bus, car, ship, etc.

The perceived dose during a certain exposure time is assumed proportional to the product of amplitude A and exposure time Δt,

$$D_{P\Delta} = c_A \cdot A \cdot \Delta t \qquad [8.1]$$

or

$$D_{P\Delta} = c_A \cdot A(t) \cdot \Delta t \qquad [8.2]$$

if the amplitude $A(t)$ is approximately constant during the short exposure time Δt.

The leakage $D_{L\Delta}$ during a time interval Δt is assumed proportional to the accumulated net dose D_N at the end of the interval,

$$D_{L\Delta} = c_L \cdot D_N(t) \cdot \Delta t \qquad [8.3]$$

Hence, for an infinitesimally small time interval $d\tau$ the change of net dose D_N may be expressed as

$$dD_N = D_N(t+d\tau) - D_N(t) = c_A \cdot A(t) d\tau - c_L D_N(t) \cdot d\tau \qquad [8.4]$$

These processes are schematically shown in Figure 65.

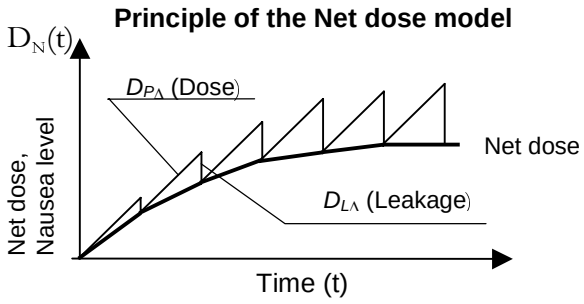


Figure 65 Principle of the net dose model. The dose is increased by the amount $D_{P\Delta}$ and decreased by amount $D_{L\Delta}$ in each time step.

Integrating [8.4] and with ($\tau = 0$, $D_N(0) = 0$) leads to the general formula:

$$D_N(t) = c_A \cdot \int_0^t A(\tau) \cdot e^{c_L \cdot (\tau - t)} d\tau \qquad [8.5]$$

Some observations may be done of the behaviour of this net dose function.

Start of exposure at experiment

Assume the actual net dose is approximately nil at the start of an experiment (where $t = t_s$) and the motion amplitude during the experiment is constant at the level A.

The net dose may then be expressed as

$$D_N(t) = c_A \cdot A \cdot \int_{t_s}^t e^{c_L(\tau - t)} d\tau = \frac{c_A \cdot A}{c_L} \cdot (1 - e^{-c_L \cdot (t - t_s)}) \qquad [8.6]$$

$t_s \leq t \leq t_e$

t_s = start of experiment, t_e = end of experiment

The shape of the function during exposure to constant amplitude is shown in the left part of Figure 66. for t $\rightarrow \infty$, then

$$D_N(t) = \frac{c_A \cdot A}{c_L} \qquad [8.7]$$

End of exposure

Assume that a dose D_{Ne} has been achieved at the end of the exposure time t_e

$$D_{Ne} = D_N(t_e) = \frac{c_A \cdot A}{c_L} \cdot (1 - e^{-c_L \cdot (t_e - t_s)}) \qquad [8.8]$$

If no further exposure is made, a pure leakage will appear

$$D_N(t) = D_{Ne} \cdot e^{-c_L \cdot (t - t_e)} \qquad [8.9]$$

$t \geq t_e$

See the right part of Figure 66.

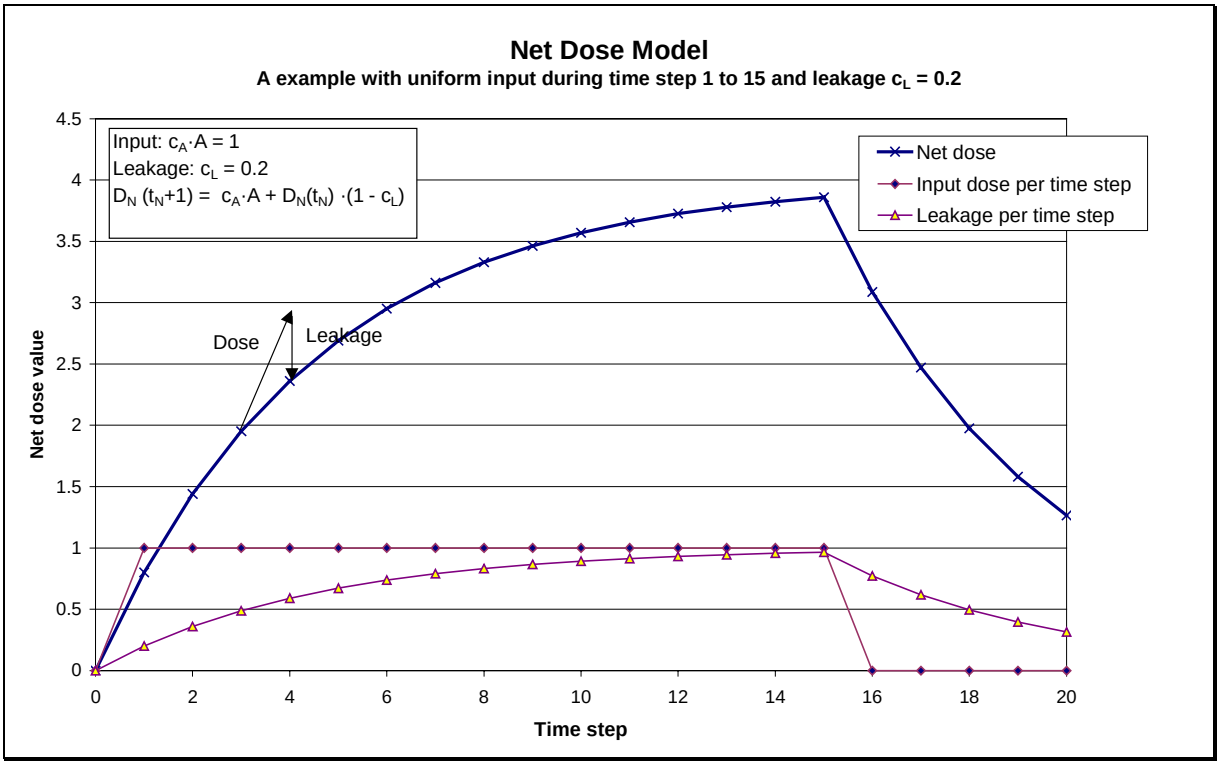


Figure 66 *Example of net dose model - exposure with fixed motion amplitude (left) and recovery period (right).*

Test of the net dose model

Estimation of the leakage factor c_L based on data collected during exposure (according to [8.6]) should be compared with an estimation of c_L based on data collected after exposure (according to [8.9]). If the assumptions above are correct, c_L should remain the same in both cases.

Threshold values

Normally, it takes some time before subjects show some degree of nausea. This may be explained by a time threshold t_0 or a dose threshold D_0. The later is done in Kufver & Förstberg (1999). Equations [8.7] may then be changed to [8.10] or [8.11].

$$D_N(t) = c_A \cdot A \cdot \int_{t_s+t_0}^{t} e^{c_L(\tau-t)} d\tau = \frac{c_A \cdot A}{c_L} \cdot (1 - e^{-c_L \cdot (t - t_s - t_0)}), \quad t_s + t_0 \le t \le t_e \qquad [8.10]$$

$$D_N(t) = 0 \;,\; t \le t_s + t_0$$

alternatively

$$D_N(t) = c_A \cdot \int_{t_s}^{t} A(\tau) \cdot e^{c_L \cdot (\tau - t)} d\tau - D_0 \qquad [8.11]$$

With a fixed amplitude [8.11] turn into

$$D_N(t) = c_A \cdot A \cdot \int_{t_s}^{t} e^{c_L(\tau-t)} d\tau - D_0 = \frac{c_A \cdot A}{c_L} \cdot (1 - e^{-c_L \cdot (t - t_s)}) - D_0 \qquad [8.12]$$

$$t_s \le t \le t_e$$

Eq. [8.11] can also be expressed as to insure that D_N is not negative:

$$D_N(t) = \max(c_A \cdot \int_0^t A(\tau) \cdot e^{c_L \cdot (\tau - t)} d\tau - D_0; 0) \quad [8.13]$$

For t $\rightarrow \infty$, then $D_N(t) = \frac{c_A \cdot A}{c_L} - D_0$ [8.14]

8.2 Experimental data

The net dose model has been fitted to data from different experiments. The first example, Figure 67, shows nausea ratings as averages from total 44 test subjects in simulator tests at VTI, reported in chapter 7 and in (Förstberg 2000a). The motions were cyclical with a period of 1 minute. A recovery period starts at the 31st minute (since the answers at the start of the recovery period were somewhat delayed, they are plotted at 32nd minute). The figure show a good agreement between observed nausea rating (*NR*) and the net dose model.

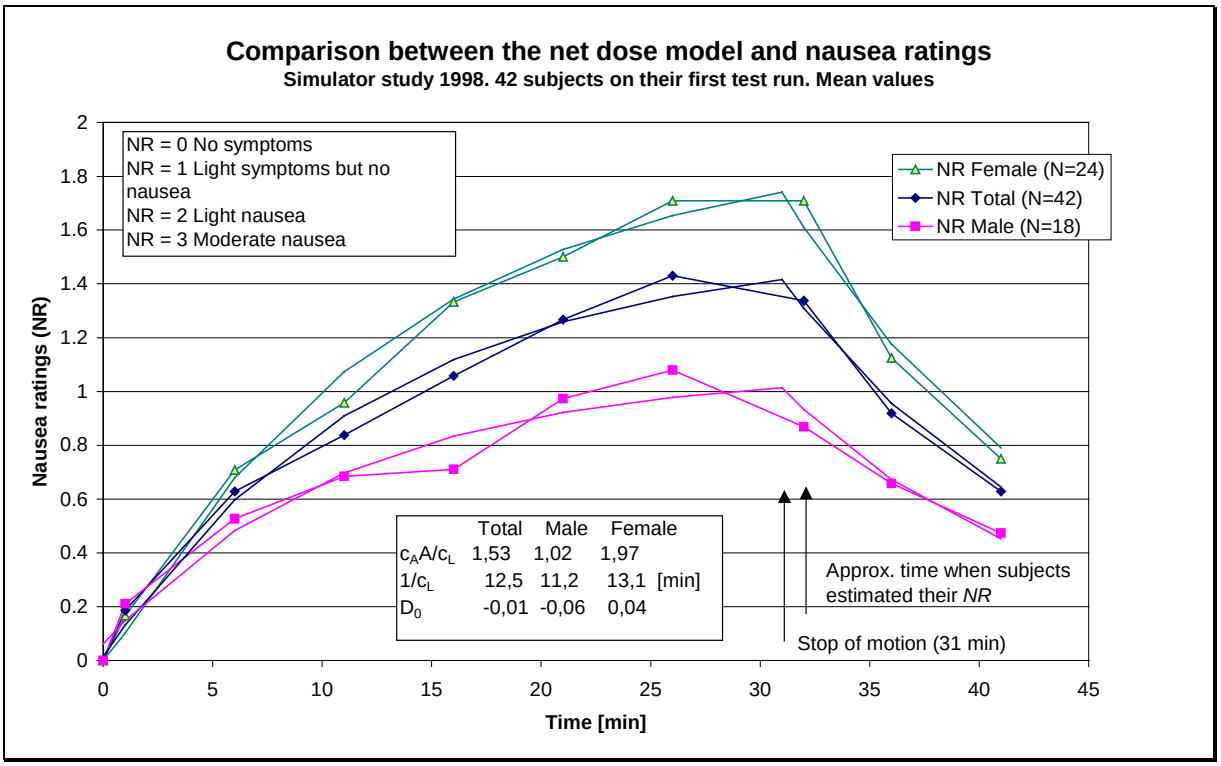


Figure 67 *Average responses from 42 different subjects and a fit of the net dose model to these data. Data were sampled each 5 min with start at 1 min after start of test run. Source: Simulator experiments from Förstberg (2000a).*

Figure 68 shows ratings on individual basis from the same experiment. The large differences in individual threshold doses D_0 should be noted. However, there are some problems when there are different threshold values for the subjects. When averaging individual responses this leads to an increase of time constant, because of the non-linear model (Eq. 8.13). Negative doses are substituted with zeros. In these cases, there will different time constants under the first provocation period and the recovery period.

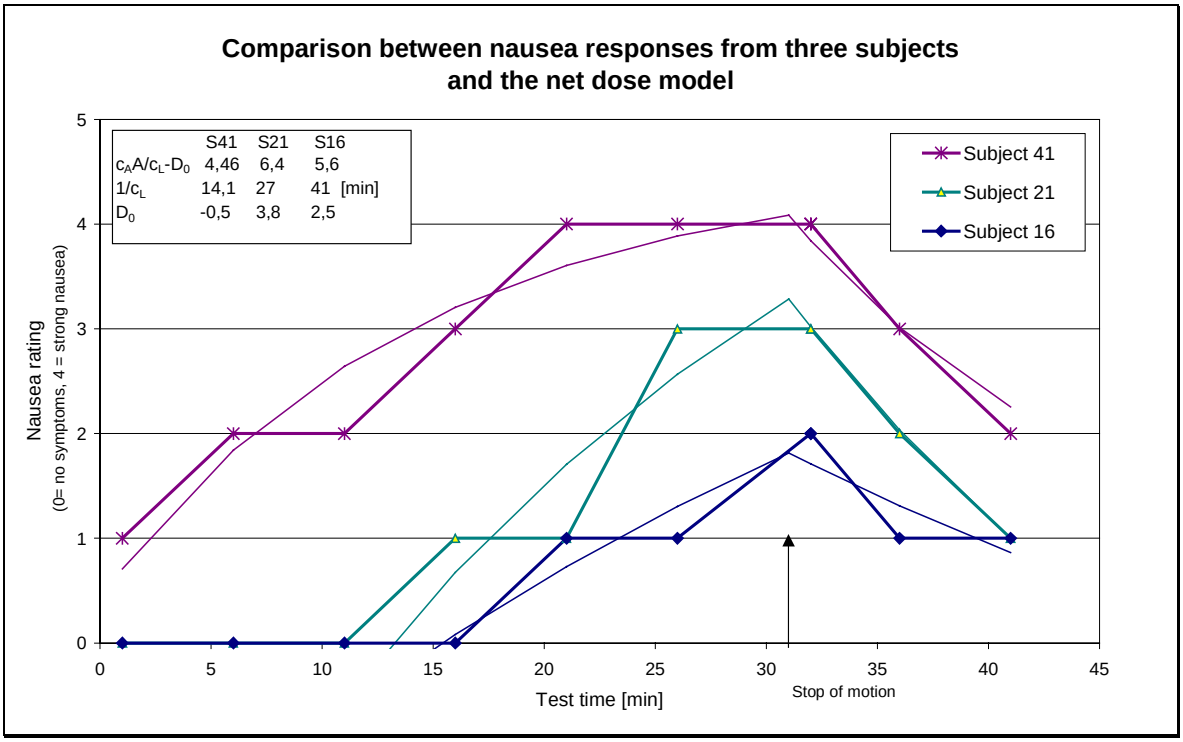


Figure 68 *Responses from 3 different subjects and a fit of the net dose model to these data. Data were sampled each 5 min with start at 1 min after start of test run. Source: Simulator experiments Förstberg (2000a).*

The third example is from an experiment done by Guignard & McCauley (1982), see Figure 69. They tested five different combinations of vertical accelerations. The provocative excitation was rather strong, with vertical accelerations of 1.3 m/s^2 r.m.s. at a frequency of 0.17 Hz combined with frequencies of 0.33 or 0.5 Hz. After 2 h conditions I and II had 50% *MSI* and condition V had 78% *MSI*. No recovery data are published. The model fits the data rather well.

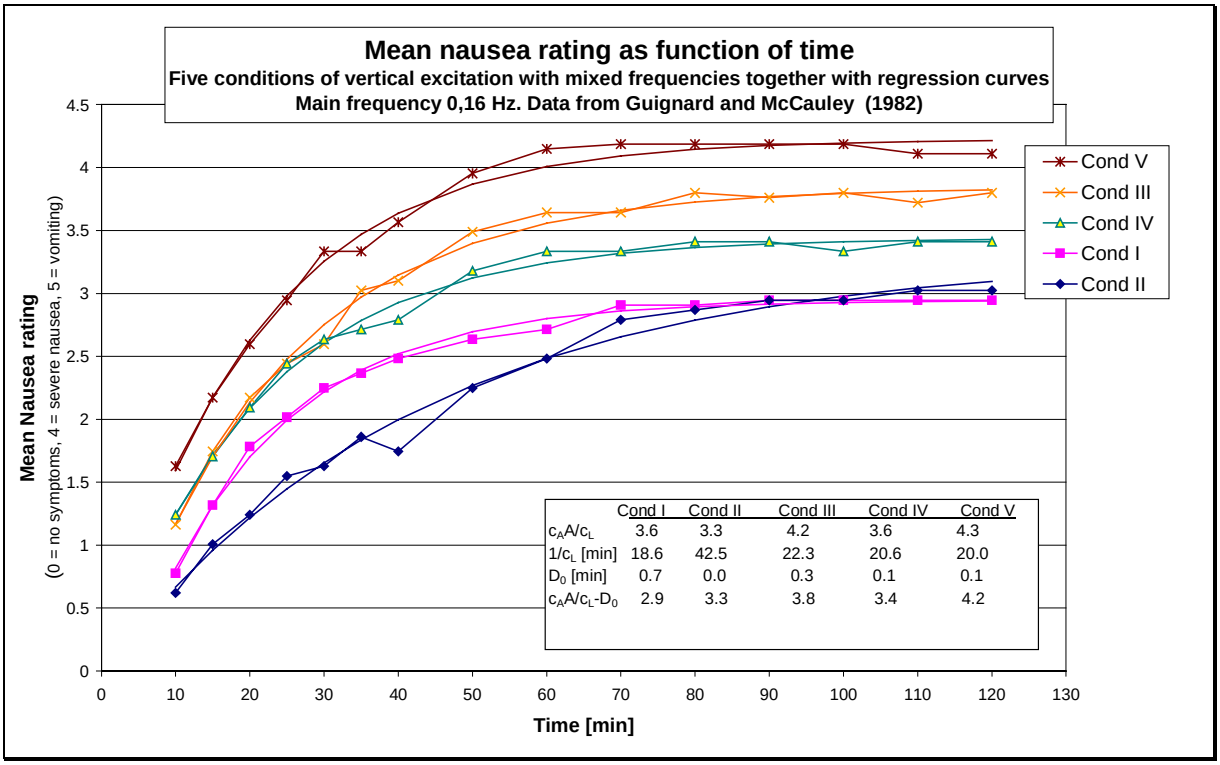


Figure 69 Net dose model - curve fitting to experiment by Guignard & McCauley (1982).

8.3 Variable amplitude

Travel in ships, trains, buses and cars often produce variable levels of motions in particular due to periods of low speed or stops, where passengers are exposed only to small motion levels and thus recover from previous (degree of) nausea. Therefore, a numerical procedure is proposed, according to the formula.

$$MSDV(t_{N+1}) = MSDV(t_N) \cdot e^{-c_L \cdot \Delta t} + \Delta MSDV(t_{N+1}) \qquad [8.15]$$

where $MSDV$ = motion sickness dose values and $\Delta MSDV$ is calculated from the instantaneous value of the motion during the interval Δt.

Figure 72 shows an example from the tilting train test in June 1995, described i Chapter 6 and Förstberg (1996, 2000b) with the time constant ($1/c_L$) of the leakage set to 21.6 min (time for half value = 15 min). After 2000 – 2500 s (about 30 – 40 min) the $MSDV$ levels are stabilised. Tested times for half value were 60, 30, 15 and 7,5 min where a regression analysis gave best results with the 15-min values.

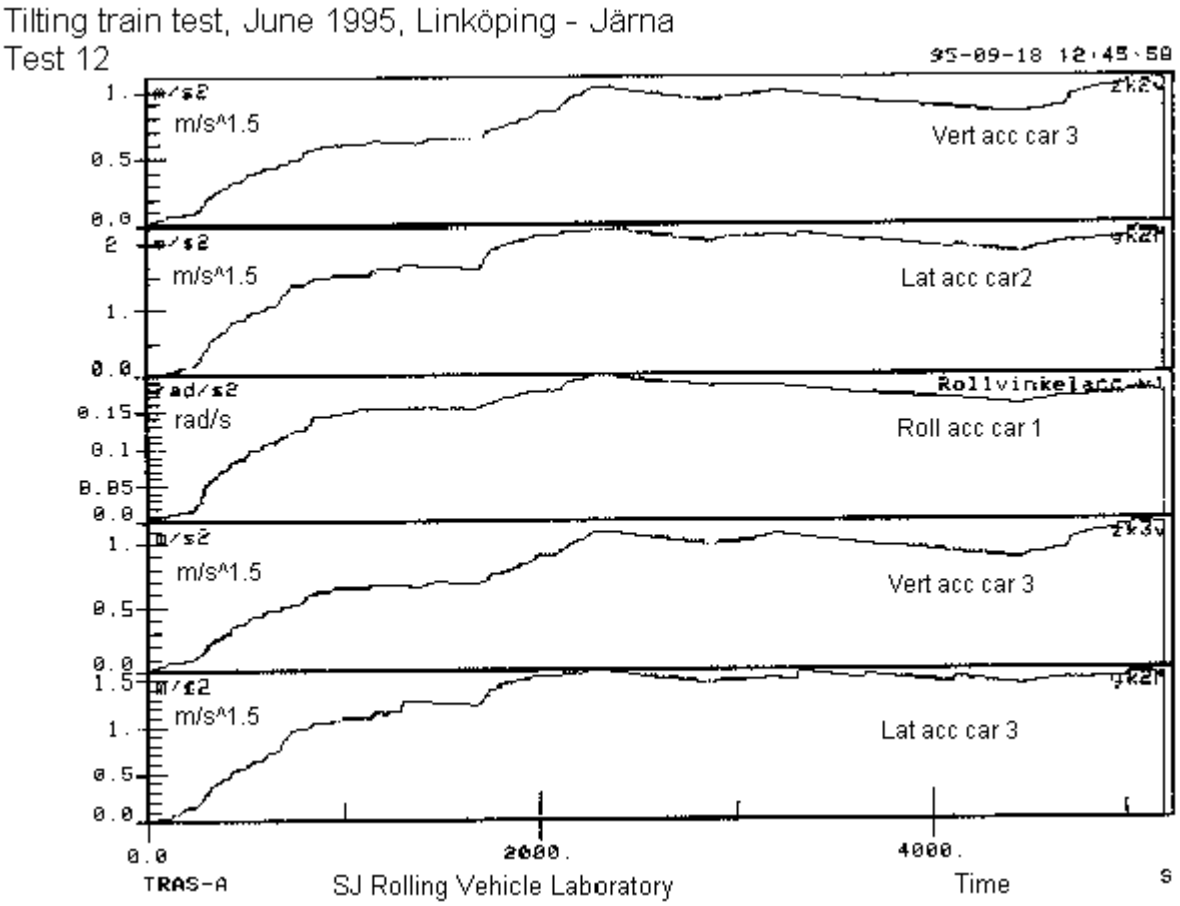


Figure 70 *Motion doses (lateral, vertical and roll acceleration) from tilting train test in June 1995 between Linköping and Järna with a leakage time constant of 21.6 min (15 min half-value leakage time) when integrating the momentary motion doses.*

Conclusions

The potential advantage of the model is the ability to cope with varying amplitudes of provoking inputs. The net dose model seems to have the potential to explain both the individual time developments to provoking stimuli and for a group as a whole. However, the model needs to be refined in order to situations when there are large differences between the individual threshold doses.

9 Regression analysis of test results – possible models for nausea

9.1 Introduction

A desirable model for explanation of nausea ratings (*NR*) from the motion environment, in a vehicle, should use the co-ordinate system of the body for the passenger. Such a system is defined in ISO 2631-1 (ISO 1997), with the so-called basicentric axes. For the upper part of the body (torso) with the head pointing straight forward, the following is defined; x- axis is pointing forward, y-axis pointing left, z-axis is pointing upward along the spine towards the head. However, it is difficult to measure in this co-ordinate system, as passengers are moving around, standing, seated or lying down. The head of the passenger is also free to move in different directions. A suitable compromise is to use the vehicle body as a reference system, as in ISO 2631-4 (ISO 1999). Another possible system is one with a reference to the horizontal plane, as in the simulator experiment. This might be the case if the above systems are not sufficient to explain the nausea provocation from the motion quantities.

In a train environment, some motions are less likely to be provocative for motion sickness, such as longitudinal acceleration and pitch motion. The magnitudes of pitch motions or the frequency contents of longitudinal acceleration and deceleration are too low to be of any importance in a nausea model.

A possible model should contain the following motion quantities (not consideration time influence):

$$NR = \beta_0 + \beta_1 \cdot (\text{vertical acc})^{\alpha 1} + \beta_2 \cdot (\text{lateral acc})^{\alpha 2} + \beta_3 \cdot (\text{roll})^{\alpha 3} + \beta_4 \cdot (\text{yaw})^{\alpha 4} + \varepsilon \quad [9.1]$$

where β_i are regression coefficients, α_i are exponents and ε is an error term (the co-ordinate system is not yet defined).

A model might also contain variables such as self-estimated sensitivity, rested/not rested or other human factor related quantities that may influence the resulting nausea (Guedry 1991a). A possible model might be (not considering time influence):

$$NR = \beta_0 + \sum \beta_i \cdot (\text{motion quantity})_i + \beta_5 \cdot (\text{sensitivity}) +$$

$$+ \beta_6 \cdot (\text{other human factors; adaptation, rested, food consumption, etc}) + \varepsilon \quad [9.2]$$

Yaw motion may be of interest in curves with small radii but since this motion was not applied in the simulator experiment, it cannot be considered in the regression models. Vertical vibrations below 0.5 Hz were not added to the used test environments and therefore only the low frequency vertical accelerations, which were generated from the combined effects of horizontal accelerations and roll motions, can be considered.

9.2 Models from simulator tests

Response variables for estimating the regression models are the population means (expected values) for *NR26*. These are estimated from the ordinal multinomial distribution that was based on all individual subjects' *NR26* responses for all turns. By this technique, it is possible to estimated the population mean for *NR26* for the *first turn*, when the subject was "naive" to the motion environment[44]. However, there may be different numbers of conditions in the analysis; 10 implies that the 7 conditions in part I (H100R0 – H0R75) together with conditions in part IIA (LRV, LRA and SC) have been used and 11 implies that the condition "no vibration" (NV) is also taken into consideration.

9.2.1 Correlation

Motions were monitored and recorded during test runs. The following motion quantities were recorded: vertical and lateral acceleration inside the cabin and roll velocity. By time differentiation, lateral jerk and roll acceleration were generated. Horizontal acceleration was estimated from condition 1 (H100R0) with no roll motion. Evaluation was done by filtering the quantities with various low-pass filters[45] including band-pass 0.08 – 0.35 Hz (the simplified motion dose filter w_f). R.m.s.-values were calculated for these quantities over the 60 s total motion sequences for all different test conditions.

A correlation analysis between r.m.s. – values for the various motion quantities and the expected means for *NR26*, shows some interesting characteristics, see Table 62. The motion quantities are in all those cases band-pass filtered with 0.08 – 0.35 Hz (approx. w_f-filter)

Vertical acceleration has the highest correlation to *NR26* followed by lateral acceleration in the horizontal plane. The lateral acceleration and lateral jerk in the cabin are both negatively correlated with *NR26*. Roll velocity and roll acceleration are both positively correlated but have the lowest *r*-values of all included motion quantities. Notice also the perfect correlation between lateral acceleration in the cabin and lateral jerk as well as between roll velocity and roll acceleration with this filtering[46].

Table 62 Correlation between r.m.s.–values for motion quantities and population mean for nausea ratings (NR26).

Frequency filtering BP 0.08 – 0.35	*Vertical acc.*	*Lateral acc. (cabin)*	*Lateral jerk (cabin)*	*Horizontal (lateral) acc.*	*Roll velocity*	*Roll Acc.*	*Expected. NR26 (all turns)*
Vertical acc	1						
Lateral acc. (cabin)	-0.680	1					
Lateral jerk	-0.663	0.998	1				
Horizontal acc.	0.551	-0.275	-0.232	1			
Roll velocity	0.732	-0.782	-0.794	-0.078	1		
Roll acc.	0.734	-0.784	-0.796	-0.077	1.000	1	
NR26 (all turns)	0.771	-0.468	-0.443	0.736	0.394	0.393	1

Remark: Filtering BP 0.08 – 0.35 Hz. 11 test conditions for correlation with *NR26*

[44] See Appendix A7 and Appendix A6 in Förstberg (2000a).

[45] LP 0.25 Hz, LP 0.35 Hz, LP 0.5 Hz, LP 0.7 Hz, LP 1.0 Hz and LP 2.0 Hz. Filter were 2-pole as the definition of band-limiting filters in ISO – 2631-1 (ISO 1997).

[46] R.m.s. – calculation involves either an integration with respect to time or an integration over an area in the frequency-plane. With small filter band widths the r.m.s. - values are strongly correlated between lateral jerk and lateral acceleration or between roll acceleration and roll velocity.

Figure 71 shows the corresponding correlation values for different low pass filtering frequencies together with the BP 0.08 – 0.35 Hz. Vertical acceleration is most correlated with *NR26* filtered with the BP-filter then followed by the horizontal (lateral) acceleration. Roll velocity and roll acceleration are equally strongly correlated with *NR26* up to 1 Hz, then roll acceleration decreases in magnitude of correlation. Lateral acceleration and lateral jerk have almost the same correlation up to 0.7 Hz. With higher frequency filtering (2 Hz), the lateral acceleration (cabin) is changing from negative to positive correlation. The main frequency content of the horizontal acceleration is up to about 0.5 Hz, therefore LP-filtering above 0.5 Hz has no effect in this case.

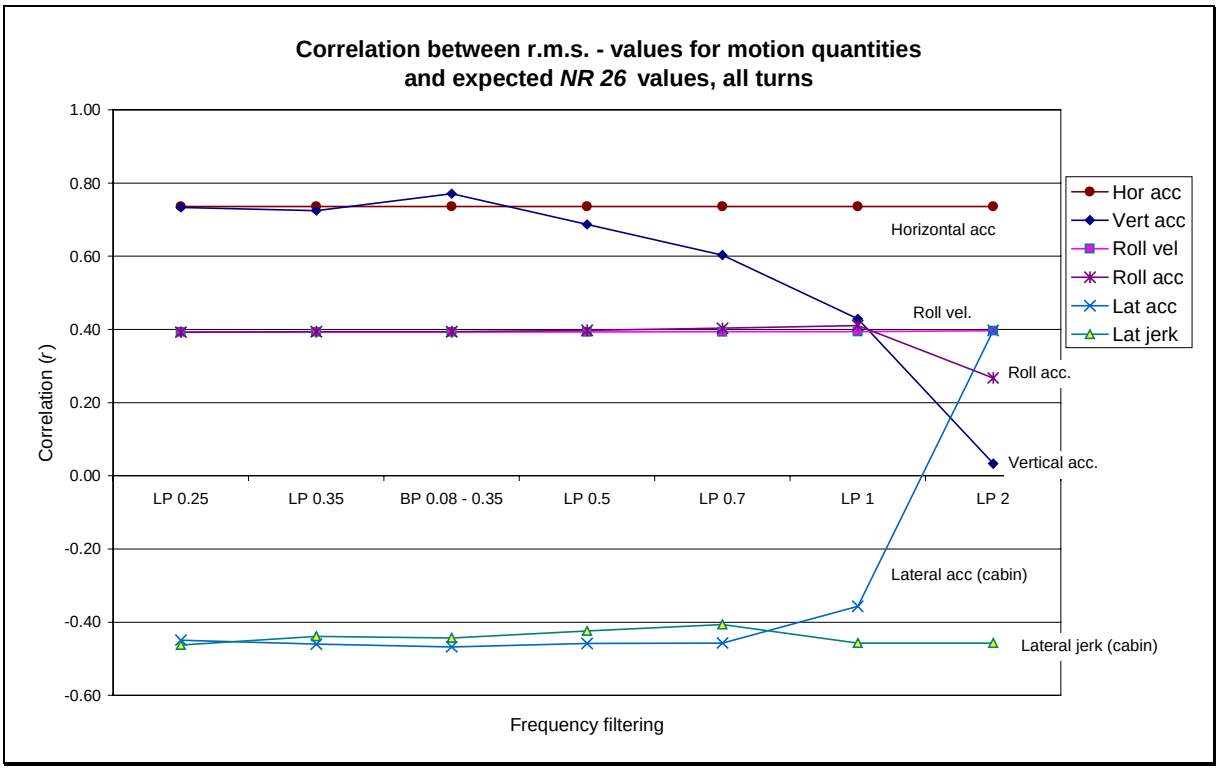


Figure 71 *Correlation between expected values for NR26 and r.m.s. - values for the different motion quantities filtered at different frequencies. (11 conditions, all turns).*

9.2.2 Regression models

The possible models originate from experiments in the simulator and can only be valid in environments having a constant motion environment as in the simulator experiment. The most obvious candidates for a regression model for explaining *NR26* are vertical acceleration, horizontal (lateral) acceleration, roll acceleration or roll velocity and, maybe, perceived lateral acceleration or lateral jerk.

Figure 72 shows the influence between vertical, horizontal and roll accelerations on nausea ratings, indicating possible linear regression models with one variable. Note that horizontal acceleration is divided by 10. From the figure, the vertical and horizontal accelerations show quite strong relation with nausea ratings. Roll acceleration alone is a poor predictor of nausea, in these tests.

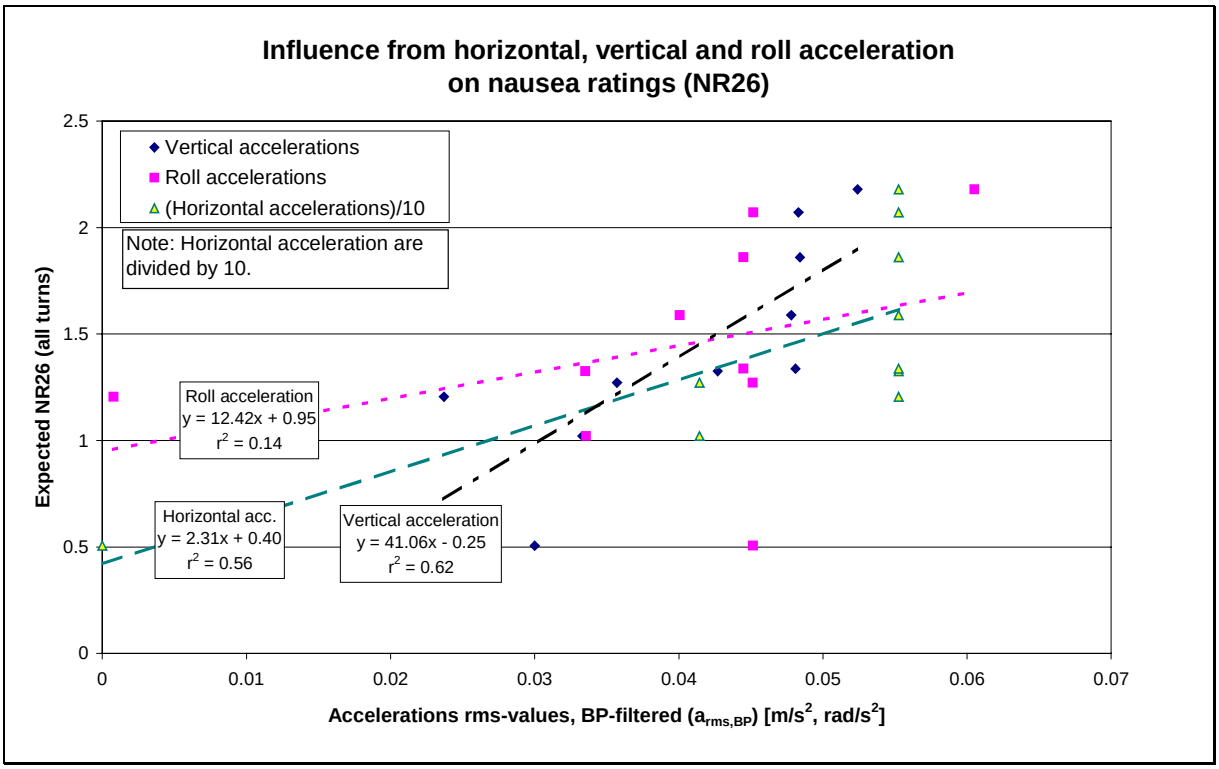


Figure 72 *Influence from vertical, horizontal and roll acceleration on NR26. Notify that the horizontal acceleration r.m.s. – values is divided by 10 (N = 10 conditions).*

Table 63 shows some possible regression models for prediction of *NR26* from r.m.s. - values from BP 0.08 – 0.35 Hz filtered motion quantities. Models with roll velocity instead of roll acceleration as an explanation variable, will give almost the same determination coefficients and are therefore not shown. Horizontal and roll accelerations together are better predictor (explanation) variables than vertical acceleration alone. Possible quadratic relations between nausea ratings and horizontal or roll acceleration are possible, but difficult to determine because of either few levels of input variation or large spread of responses. However, some of the possible regression models, in Table 63, incorporate squared variables with high coefficients of determination.

Table 63 *Regression models for expected NR26 (all turns) evaluated from r.m.s. – values of the motion quantities filtered with BP 0.08 – 0.35 Hz.*

BP: 0.08 – 0.35 Hz			*Model 1 Vertical*	*Model 2 Hor.*	*Model 3 Hor. + Roll*	*Model 4 Hor. + roll +lat jerk*	*Model 5 Hor. + roll²*	*Model 6 Hor.² + roll²*
Constant		β_0	-0.25	0.42	-0.30	-1.37	-0.15	-0.021
Vertical acc.	[m/s²]	β_1	41.1	-	-	-	-	-
Roll acc	[rad/s²]	β_2	-	-	16.0	28.1	-	-
Hor. acc	[m/s²]	β_3	-	2.16	2.35	2.77	2.28	-
Lat. jerk	[m/s³]	β_4	-	-	-	1.84	-	-
(Roll acc)²	[rad/s²]²	β_5	-	-	-	-	293	282
(Hor. acc)²	[m/s²]²	β_6	-	-	-	-	-	3.88
Determ. coeff.		r^2	0.62	0.56	0.80	0.85	0.85	0.86
Vertical acc.		p	0.007	-	-	-	-	-
Roll acc		p	-	-	0.025	0.031	0.007	0.007
Hor acc		p	-	0.012	0.002	0.002	<0.001	<0.001
Lateral jerk		p	-	-	-	0.208	-	-

Remark: *N* = 10 test conditions. Roll velocity can be substituted with roll acceleration with a change of the regression coefficient.

Some observations from Table 63

Best models of the above tested are Model 3, 5 and 6. These models combined horizontal acceleration with roll acceleration and having r^2 – values from 0.80 to 0.86 and highly significant explanation variables.

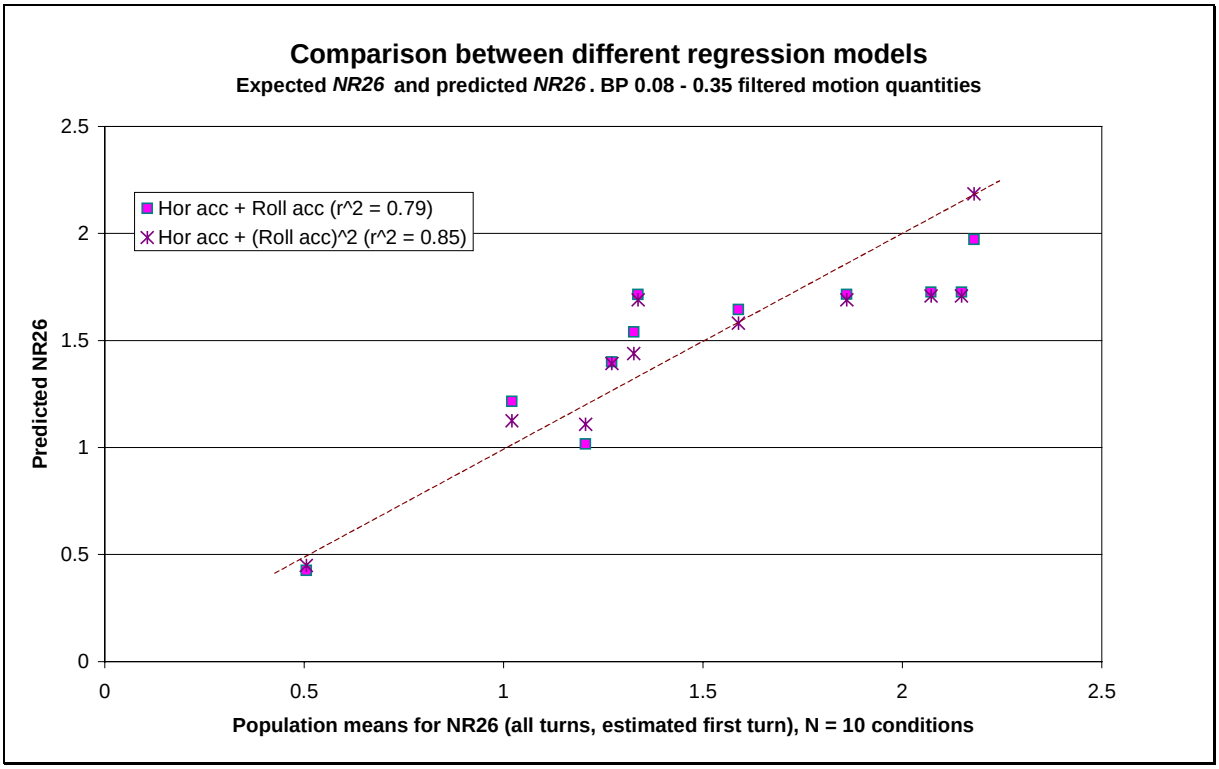


Figure 73 *Comparison between regression models: Horizontal (lateral) acceleration and roll acceleration. (N = 10 conditions.)*

Figure 73 shows a comparison between *NR26* (population means, all turns) and predicted *NR26* with model 3 and 5. The motion quantities were BP 0.08 – 0.35 Hz. The quadratic relation shows the highest degree of determination but both of them give good predictions.

Frequency dependency

The model 3 and 5 in Table 63 were tested with against the r.m.s. – values of different low pass filters horizontal and roll acceleration. The coefficient of determination (r^2) for Model 3 increased from 0.794 for LP 0.25 Hz to 0.833 for LP 2 Hz. For Model 5, the coefficient r^2 increased from 0.853 for LP 0.25 Hz up to 0.864 for LP 1 Hz and then diminish to 0.853 for LP 2 Hz. The differences are very small. Additional explanation variables like lateral acceleration (cabin) or lateral jerk (cabin) for LP 2 Hz, do not improve the regression models. Therefore, the band pass filtering BP 0.08 – 0.35 or w_f –filter are chosen for the proposed models.

9.2.3 Proposed models

Motion dose models

The motion dose (*MSDV*)[47] can be calculated from an acceleration quantity if the motion exposure is continuous and of approximately constant magnitude by taking the r.m.s. – value for a shorter period (ISO 1997).

$$MSDV = a_{rms,wf} \cdot \sqrt{t} \qquad [m/s^{1.5}] \qquad [9.3]$$

where $a_{rms,wf}$ is the r.m.s. – value of acceleration (vertical), filtered with weighting filter w_f. This method can be extended to either other translations or angular accelerations (Turner & Griffin 1999c).

According the hypothesis (Griffin 1990, ISO 1997), the vomiting incidence

(*VI*) = 1/3 * $MSDV_z$ and illness rating (*IR*) = 1/50 * $MSDV_z$

In the case of the simulator experiment: $t = 26 \cdot 60 = 1560$ s and then $\sqrt{t} \approx 39.5$ [$s^{0.5}$].

Maximal r.m.s. - value for vertical acceleration is in condition 4 (H100R100), $a_{Z,\ rms,\ BP} \approx 0.05$ giving a $MSDV_Z \approx 2$, which corresponds to a vomiting incidence (VI) of about 0.7% and an illness rating (IR_{ORG}) of about 0.04. For condition 4, the illness ratings ($IR26_{MOD}$) and nausea ratings (*NR26*) are about 1.0 and 2.2, respectively. Vertical acceleration, as from the model 1 above is not in this case a good predictor of the experienced illness and nausea. Therefore, the influences from lateral acceleration and roll velocity/roll acceleration are essential in the used test environments.

Possible models, according to the motion dose method can be designed, under the conditions of a constant and continuous environment like that in the experiment. For example from model 3 can be written as follows:

$$NR = \beta_0 + (\beta_1 \cdot a_{1,rms,wf} + \beta_2 \cdot a_{RA,rms,wf}) \cdot \sqrt{t} \qquad [9.4]$$

where $a_{yH,\ rms,\ wf}$ and $a_{RA,\ r.m.s.,\ wf}$ are examples on r.m.s – values for w_f (BP 0.08 – 0.35) filtered horizontal and roll acceleration.

The constants β_i can be calculated from the models in Table 63 by dividing them with time factor $\sqrt{t} = \sqrt{26 \cdot 60} \approx 39.5$ [$s^{0.5}$]. The constraint is that the motion has to be continuous and constant

[47] *MSDV* Motion Sickness Dose Value

over time. The r.m.s. - values have to be calculated over a period of time that is representative for the motion environment in question.

A possible model using the horizontal acceleration only (Model 2), according to Table 69 could be designed as follows:

$$NR = 0.42 + 2.16/39.5 \cdot a_{yH,rms,wf} \cdot \sqrt{t} = 0.42 + 0.055 \cdot a_{yH,rms,wf} \cdot \sqrt{t} \quad [9.5]$$

Possible regression models, under the conditions of constant motion environment (constant and continuous motions):

Model 3: $$NR = -0.30 + (0.060 \cdot a_{yH,rms,wf} + 0.40 \cdot a_{RA,rms,wf}) \cdot \sqrt{t} \quad [9.6]$$

Model 5: $$NR = -0.15 + (0.058 \cdot a_{yH,rms,wf} + 7.44 \cdot a^2_{RA,rms,wf}) \cdot \sqrt{t} \quad [9.7]$$

Model 6: $$NR = -0.02 + (0.098 \cdot a^2_{yH,rms,wf} + 7.14 \cdot a^2_{RA,rms,wf}) \cdot \sqrt{t} \quad [9.8]$$

Possible models using roll velocity (*RV*) instead of roll acceleration, would be (these models have the same coefficient of determination as above models):

Model 3A: $$NR = -0.30 + (0.060 \cdot a_{yH,rms,wf} + 0.48 \cdot a_{RV,rms,wf}) \cdot \sqrt{t} \quad [9.8]$$

Model 5A: $$NR = -0.14 + (0.058 \cdot a_{yH,rms,wf} + 10.8 \cdot a^2_{RV,rms,wf}) \cdot \sqrt{t} \quad [9.9]$$

Model 6A: $$NR = -0.02 + (0.098 \cdot a^2_{yH,rms,wf} + 10.35 \cdot a^2_{RV,rms,wf}) \cdot \sqrt{t} \quad [9.10]$$

Possible models using horizontal jerk ($\dot{a}_{yH}$) instead of horizontal (lateral) acceleration, would be (these models have the same coefficient of determination as above models):

Model 3B: $$NR = -0.30 + (0.066 \cdot \dot{a}_{yH,rms,wf} + 0.40 \cdot a_{RA,rms,wf}) \cdot \sqrt{t} \quad [9.11]$$

Model 5B: $$NR = -0.15 + (0.064 \cdot \dot{a}_{yH,rms,wf} + 7.44 \cdot a^2_{RA,rms,wf}) \cdot \sqrt{t} \quad [9.12]$$

Model 6B: $$NR = -0.02 + (0.098 \cdot \dot{a}^2_{yH,rms,wf} + 7.14 \cdot a^2_{RA,rms,wf}) \cdot \sqrt{t} \quad [9.13]$$

Remark: Used indices are: *Z* vertical acceleration, *yH* horizontal (lateral) acceleration, *RA* roll acceleration, *RV* roll velocity, BP filtering 0.08 – 0.35 Hz

All the models above anticipate continuous and almost constant motion environment over time.

Net dose models

Another way of designing regression models is to use the net dose model, see Eq. [8.6]:

$$NR = \beta_0 + \beta_1 \cdot D_N(t) = \beta_0 + \beta_1 \cdot \frac{c_A \cdot A}{c_L} \cdot (1 - e^{-c_L \cdot t}) \quad [9.14]$$

where A is substituted to any of the above models.

If the motion environment is varied with respect to time, an iteration technique is possible, see equation [8.15]

$$NR = \beta_0 + \beta_1 \cdot D_N(t_n) = \beta_0 + \beta_1 \cdot (D_N(t_{n-1}) \cdot e^{-c_L \cdot \Delta t} + c_A \cdot A \cdot \Delta t) \quad [9.15]$$

where A is substituted to any of the above models. The r.m.s. – values have to be evaluated over a sufficiently long period of time Δt.

A possible model according to (Model 5) Eq. 9.7 with constant environment and with a time constant of 12 min (720 s) would be:

$$NR = (2.28 \cdot a_{yH,rms} + 293 \cdot a_{RA,rms}^2) \cdot (1 - e^{t/720}) \quad [9.16]$$

The development of nausea rating (*NR*) according to [9.16] is shown in Figure 74.

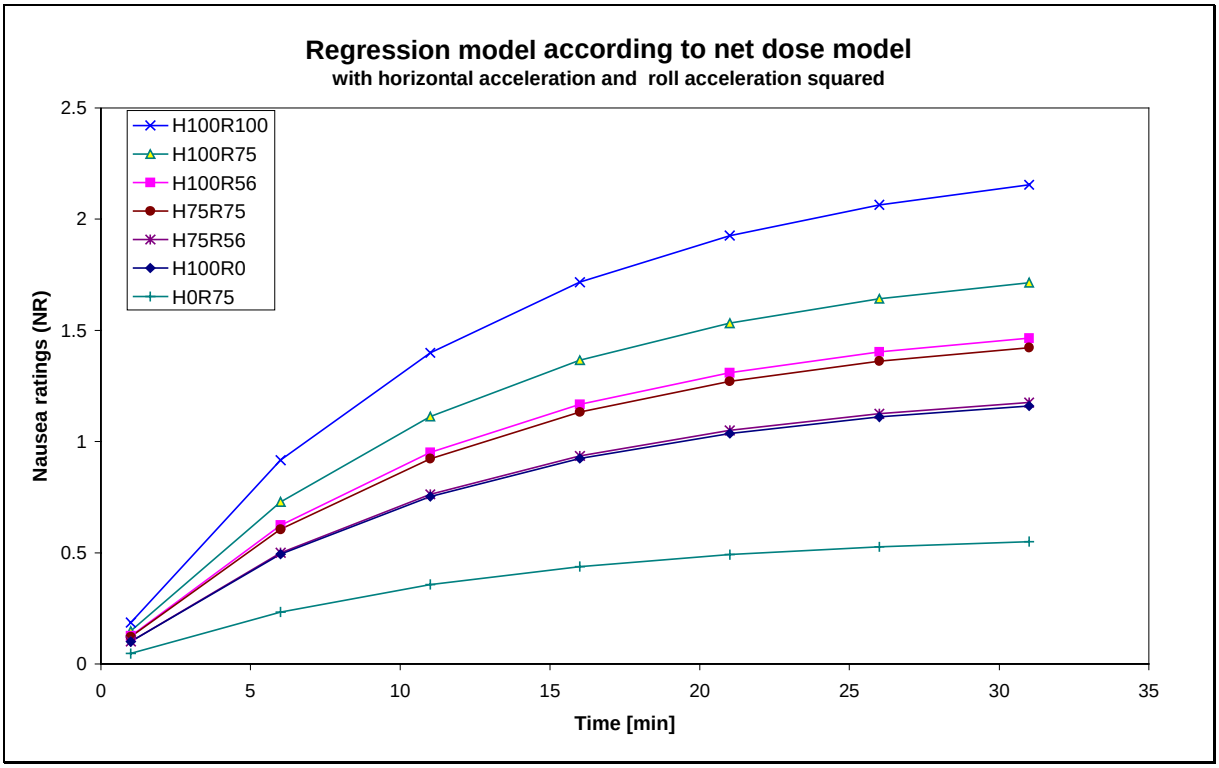


Figure 74 *Development of nausea ratings according to the net dose model based on the Model 5.*

Influence of sensitivity

The influence of sensitivity can be evaluated from the individual responses where the sensitivity can be entered as an explanation variable in the regression analysis. A possible regression model based on all subjects taking part on their first turn (70, both part I and part II) is shown below. All variables are significant ($p < 0.05$) .The same constraints are applied as above.

Model 3C: $NR = (0.05 + 0.066 \cdot a_{yH,rms} + 0.44 \cdot a_{RA,rms} + 0.012 \cdot Sens) \cdot \sqrt{t}$ $r^2 = 0.28$ [9.17]

Remark: Used indices are: *yH* horizontal acceleration, *RA* roll acceleration. Sensitivity *Sens* estimated on a seven-degree scale from 1 (very low sensitivity) to 7 (very high sensitivity)

The coefficient of determination is of course much lower than before because not average nausea ratings are used but individual nausea ratings.

9.3 Conclusions

Proposed models with the explanation variables, horizontal acceleration and roll acceleration show good agreement with expected *NR26* (all turns), estimated for the first turn. The coefficient of determination is high, greater or equal to 0.80 for the proposed models. Additionally, the self-estimated sensitivity is shown as a significant explanation variable. The frequency dependency seems to be very weak with these models. Therefore, the w_f or BP 0.08 – 0.25 filtering is chosen for the regressions models.

10 Discussion and conclusions

10.1 General aspects

One of the spoken or unspoken objectives of the present project was to find a general model for low-frequency lateral and roll motion influence on comfort, ability to work and read, motion sickness symptoms and nausea for the ordinary passengers travelling in tilting trains. These low-frequency inputs are generated from the railway line's horizontal alignment and cant, and are interacting with the vehicle and the tilt system. Different vehicle characteristics (suspension, tilt system, tilt control strategies) modify these responses while travelling, even on the same track. All low-frequency motion quantities and inputs have to be characterised with a few measures to fit into a regression model.

In addition, the vertical alignment, especially with high speed trains and large gradients may give substantial vertical acceleration inputs, what may also cause nausea.

Objective of the train experiments

The main objective of the train experiments, was to test if different tilt control strategies had any influence on average ride comfort, discomfort and motion sickness. Tilting train experiments were carried out with students in two series of tests with different tilt control alternatives. The answer to the last issue (motion sickness) was affirmative and roll acceleration motion dose was identified as one of the major provocative inputs. Therefore, a study in a simulator was necessary as a next step towards an understanding of the influence of roll and lateral acceleration.

Objective of the simulator experiment

The main objective of the simulator experiments was to study the combined influences of roll, lateral (cabin) and/or horizontal (lateral) acceleration on ride comfort/discomfort and nausea.. Sufficient levels of roll velocity and horizontal jerk could be reached but the horizontal acceleration was low in comparison with tilting train environments. A choice was made to use "train like" motion inputs instead of traditional harmonic (sinusoidal) inputs. The motion was then less predictable than a pure harmonic, since it contained different motion sequences and periods of no motion. To enhance the train likeness, train vibrations were added together with train interior noise. Further reduction of possible interference with other variables than motion was achieved by the elimination of visual inputs.

Relevance and validity

One question is how representative the simulator experiments are for describing the motion encountered in a tilting train environment and for predicting discomfort and nausea in *real life*. Some motion quantities such as lateral acceleration perceived by passengers and horizontal jerk as well as roll velocity were of the same order of magnitudes as in tilting trains but the lateral acceleration in the horizontal plane was not. Therefore, some results in the simulator study should be seen as qualitative rather than giving exactly quantitative relations.

Another question, discussed by Yardley (1992), is that a laboratory test generally consists of a brief exposure to a highly provocative motion for nausea and sickness, not found in reality except

in roller coasters and amusement parks. It measures an immediate sensibility. In longer exposures to levels that are normally encountered during travelling, adaptation during the journey and between journeys may change this sensitivity. However, there are no predictive links between vestibular sensibility and sensitivity to motion sickness (Yardley 1992).

The simulator tests employed an intensive and provocative motion environment in comparison with the trains experiments. The purpose of the high and intensive motion levels was to shorten test time. As the responses from different motion conditions spanned from very low nausea ratings (*NR*) to high *NR*, a good compromise was probably reached. However, the intense tests may have changed the order of influence from one motion quantity to another. The subjects showed a significant adaptation process from one test run to the next, at least for the first 2 – 4 turns.

10.2 Ride comfort

Comfort is mostly defined as a state of well-being. However, questionnaires about ride comfort is often formulated so that subjects should rate their average ride comfort according to a subjective scale from very bad to very good. We do not explicitly ask about their well-being but we assume that they have an intuitive picture of comfort as a state of well-being. This may lead to a discrepancy between the researcher's concept of ride comfort and the comfort rating by the subjects. However, on the other hand it may be more true to their own estimation of comfort. Therefore, an assumed relation between ride comfort and different motion parameters may include other variables besides motion. The subjects are probably rating the ride quality, i.e. besides vibration and motion they are rating ambient variables like temperature, seat quality, noise, interior standard and colours instead of just rating the dynamic environment. The lack of a suitable terminology that can be accepted by both subjects and researchers is a problem when making estimates of comfort.

In the tilting train test the difference in estimated average ride comfort between the three main tilt conditions (A, F and G) are very small and insignificant (Förstberg 1996). Also a non-tilting condition (C) with train speed according to Cat B[48], displays an average ride comfort around 4 (good), the same as tilt condition A. However, in an extreme case like the non-tilting condition (C1) with train speed according to Cat S, the rated average comfort was reduced to 2 (bad) (Förstberg 1997b). Variations in motion environment may not have as large impact on human responses as rated comfort, as it is often believed to have. Other variables may influence the comfort rating of the subjects more than the motion aspects.

The difficulties in measuring comfort disturbances have been analysed by Kufver (1997b). Both the push-button technique and discomfort rating after announcing the evaluation zones in beforehand have their draw5rbacks. A development of better measuring and evaluation techniques is desirable. Weisser (1999) has developed the equations for comfort disturbances based on the works of Harborough (1986b) and Förstberg (1994a).

The estimation of comfort disturbances from large lateral acceleration (side forces in cabin) from the subjects, divided with five, shows very high similarity with the calculated P_{CT} from the test sequences. The roll influence on these two concepts is about the same.

[48] Cat A corresponds to maximum lateral acceleration in track plane (a_{yj}) to 0.65 m/s^2, Cat B to 1.0 m/s^2 (approx. +10% speed in curves) and Cat S to 1.6 m/s^2 (approx. +25% speed in curves).

10.3 Development of motion sickness

The mechanisms of motion sickness provocation are not entirely known. The most popular hypothesis is the sensory conflict hypothesis (Benson 1988, Oman 1982, Oman 1990, Oman 1998, Reason 1978, Reason & Brand 1975, Yardley 1992). The hypothesis simply states: if there is a conflict between information from eyes, vestibular system and proprioceptive system or these signals are in conflict with the internal model, there is a risk of motion sickness. It seems clear that the vestibular organs are a necessary part of the reaction (Money 1991). The visual field is of great importance, either to enhance motion sickness or to reduce the provocation depending on the situation. Different subjects probably react in different ways depending on the persons reliance on the visual field. Therefore, external visual information and reference were effectively blocked by the cabins walls in the simulator experiment.

Vertical accelerations alone within a frequency range of 0.1 to 0.3 Hz have proved to be provocative for motion sickness (Griffin 1990, Griffin 1991, Guignard & McCauley 1982, Lawther & Griffin 1987, McCauley et al. 1976). Lawther & Griffin (1987) suggested the concept of a cumulative motion dose for frequency weighted vertical accelerations for the evaluation and prediction of motion sickness at sea.

From Oman's (1982, 1990) control theory approach for the sensory conflict hypothesis, a model for estimation of vertical sensory conflict has been proposed (Bles et al. 1998, Bos & Bles 1997, Bos & Bles 1998). This model also indicates that the most sensitive range for provocation from vertical accelerations is 0.1 – 0.3 Hz.

Correlation analysis between nausea ratings and r.m.s. – values for the different test conditions, in the simulator experiment, agrees that for vertical accelerations the most provocative range is 0.08 – 0.35 Hz, corresponding to the standardised w_f weighting filter (ISO 1997).

10.4 Tests in tilting train

In earlier investigations of motion sickness (McCauley 1976, Lawther and Griffin 1987, Griffin 1990) the incidence of motion sickness (vomiting) increased by a factor approximately proportional to the square root of time. The McCauley study utilised a relativity high and uniform acceleration level, but the present study utilised fairly low and intermittent provocation levels with frequent pauses, for example when passing a station at low speed or on longer stretches of straight track. Therefore, the subjects were possibly able to recover at the lower provocation levels. Golding et al (1995) have shown that subjects report recovery times of 5 - 10 min (time constants 3 –5 min) of total rest after a 30 min test run with horizontal acceleration. These times are shorter than times found in the simulator tests.

In the tilting train experiments, the main variables changed in the different tilt conditions were tilt compensation ratios and limitation in either tilt velocity or tilt acceleration. Some tests were conducted with reduced speed and no tilt to get a conventional train condition. The concept of *symptoms of motion sickness incidence*[49] (*SMSI*) was found to be the best evaluation technique of motion sickness. The regression analysis showed that roll acceleration motion dose is the main cause of motion sickness. From the performed tests and evaluations, it is difficult to separate their combined influence on roll velocity and roll acceleration but it seems that roll acceleration motion dose has the greatest influence on *SMSI*.

[49] *SMS* equal to at least one of the following symptoms *dizziness*, *nausea* or *I do not feel well.*
SMSI = Symptoms of motion sickness incidence.

The effects of curve radius have not been investigated explicitly. Normally, yaw acceleration and yaw velocity are small in comparison with roll acceleration and roll velocity. However, on smaller radius curves, the combined effects from yaw and roll motion may become a problem.

The reference tilt condition A employed an approximate 70% tilt compensation ratio, i.e. reducing the lateral acceleration at the track level with 70%. Conditions F and G both employed an approximate 55 % ratio of tilt compensation, with the difference that condition F had a limitation on tilt acceleration and G had a limitation on tilt velocity. Both the condition F and G lowered the *SMSI* from 14 - 15% to 8 – 10%. Despite the fact that roll acceleration motion dose correlates well with *SMSI*, the condition G indicates a lower *SMSI* than condition F, although not statistically significant. A limitation of the tilt acceleration together with that the tilt motion is started at the beginning of the transition curves, will have the consequence that the tilt signal is time delayed. In order to minimise the time delay, the tilt motions must reach a higher magnitude of tilt velocity. A higher tilt velocity might give a higher *SMSI*. One the other hand, there were differences between the different cars in the train formation. Cars in the rear end show lower *SMSI* than those in the front (Förstberg 1996). This might have an effect of the delaying of tilt angle control signal for the cars in the rear end by an additional low-pass filter. By this the low-pass filtering of the tilt acceleration was limited and shaped with soft corners centred around the corners "kinks" of the transition curves. Limitation in tilt acceleration might well be a positive factor, if it is possible to start the tilt motion before the transition curves starts.

There were about 10-percentage units difference in *SMSI* between females and males. One way of explaining this difference besides difference in sensitivity is males have large threshold values D_0 than females have. Another explanation is the reporting level is different. Otherwise, the correlation between the subjects' reported subjective sensitivity of motion sickness and the reported *SMSI* seems quite good. For females, there were differences between travelling backwards or forwards. The visual field is probably interfering with the subjects horizontal references (Magnusson & Örnhagen 1994). The activity (working, reading or talking) reported by the subjects does not seem to correlate with *SMSI*, although some of the subjects reported that if they had been reading for a while they had to stop this activity because of nausea.

Motion-dose values (*MSDV*) calculated from PSD-spectra on a quite curve-intense part of the test section will give an overestimation of magnitudes but in principle, the result is in accordance with motion doses calculated from time histories. PSD-spectra might offer a way of better understanding the differences between the tested conditions, since it is possible to detect in what frequency bands they differ.

10.5 Tests in simulator

Influence from horizontal motion

The studies done by Golding and co-authors (Golding et al. 1997, Golding & Markey 1996, Golding et al. 1995) showed that horizontal (longitudinal and possibly lateral) accelerations are about twice as nauseogenic than vertical acceleration. The frequency influence of lateral / longitudinal accelerations seem to have a maximal nauseogenicity around 0.1 – 0.3 Hz, i.e. the same frequency range as vertical accelerations (Golding et al. 1997, Golding et al. 1999, Lobb 1999).

A study from Vogel, Kohlhaas, & von Baumgarten (1982) showed that sitting in an ambulance car while doing several brisk brakings (0.7*g* – 0.95*g*; 6.9 – 9.3 m/s^2) is about twice as provocative as lying down. In the first case, the acceleration is in the head's x-axis and in the other in the head's z-axis. There is also a risk for pitch motions when the braking is administrated. This may also have influenced the subjects.

Another suggestion (Andersson 1999/ personal communication), is that jerk (rate of acceleration per time unit) should be one of the primary sources of provocations, instead of just the maximum level of horizontal(lateral) acceleration.

In the present study, females were about twice as sensitive than males in the condition with only horizontal accelerations (H100R0). The above mentioned studies show that horizontal accelerations are substantially provocative for motion sickness. The difference between lateral and vertical provocations was not tested.

Lateral acceleration (cabin) as perceived by the subjects show a negative correlation with nausea ratings (*NR*). An increased roll motion compensates the horizontal acceleration more, resulting in a decreased lateral acceleration (cabin) but higher *NR*.

Influence from roll motion

One of McCauley's et al. (1976) studies investigated the influence from roll or pitch motion combined with a strong vertical motion but they found no statistical evidence that roll or pitch had any influence on *MSI*. The pitch-only motion did provoke an *MSI* of 9% with a frequency of 0.345 Hz with r.m.s.-value of 33.3 ° /s^2 (0.58 rad/s^2). They used fairly high levels of vertical accelerations resulting in a motion sickness incidence (*MSI*) vomiting in a 2 h test of 30 - 50% from the vertical accelerations.

Coriolis simulation means constant angular velocity of the body about the z-axis (yaw) and a head rotation about an axis other than the axis of rotation of the body (roll or pitch). Woodman & Griffin (1997) found in a study on Coriolis simulation no significant difference in illness (nausea) levels between conditions when the rotation axis (yaw) was placed along the body centre or 0.75 m away. The subjects were doing pitch motions every 30 s. They also found no significant differences between genders.

Howarth (1999) showed that the frequency influence from roll motions seems to have the same nauseogenicity from 0.025 Hz up to 0.4 Hz and the nausea ratings may be approximately proportional to the roll angle.

In present study, condition 7 (H0R75) with roll motion only, showed the smallest recorded *NR*. There were small differences in *NR* between the genders. Rotation axis was at chest height of the subjects. The subjects had to make head movements at least when to pick up and lay down the questionnaires at 5-min intervals. For this condition, there were also small differences in nausea ratings between the genders.

Influence form combined motions (angular and translational)

In the train experiments, it was shown that roll motion was probably the main cause of *SMS*[50]. Vertical motion doses were almost identical between the three test conditions and the lateral (car body) motion doses were negatively correlated with *SMSI* (Förstberg 1996, Förstberg et al. 1998a, Förstberg et al. 1998b).

[50] *SMS* = Symptoms of motion sickness. *SMSI* = Symptoms of motion sickness incidence.

In the simulator experiments, both horizontal and roll motion gave contributions to nausea ratings, in particular combined roll and horizontal motions were quite nauseogenic. It is also clear that it is the combination of motion dose from roll acceleration together with motion dose of horizontal (lateral) acceleration and not the lateral acceleration at the cabin floor that is responsible for the provocation of nausea. The roll only condition (H0R75, condition 7) gave small response for nausea ratings. The perceived lateral acceleration (cabin) for condition 7 was much higher than perceived lateral acceleration in condition 3 and 4 (H100R75 and H100R100) but the latter conditions provoked much higher nausea ratings. In this case, it seems to be a small conflict in the vestibular system between the sensed motion from roll and perceived lateral acceleration.

In three experiments, performed at TNO, Soesterberg (Netherlands) with the Ship Motion Simulator (Wertheim et al. 1998, Wertheim et al. 1995), it was shown that small vertical motions combined together with small pitch and roll motions can provoke much more motion sickness than claimed by the classic models. These motions by themselves have very low provocation potential of motion sickness. They suggest that in models on motion sickness, pitch and roll should be combined in a non-linear fashion with vertical motion. These models will remain rather crude if they do not include a description of the vestibular contribution to motion sickness (Wertheim et al. 1998, Wertheim et al. 1995).

The combined motion from lateral accelerations (horizontal plane) and roll motions will generate a subjective variable vertical g-vector both in size and direction. According to Bles et al. (1998) a conflict between the sensed and subjective *g*-vector is the main provocative force behind motion sickness. They wrote:

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

This may well be the case in the present simulator test. Bos and Bles (1997, 1998) have found that vertical accelerations generate large differences between the *sensed*[51] and *subjective*[52] vertical for frequencies around 0.2 Hz, which corresponds very well with the findings of McCauley (1976). Probably the same situation exists for lateral (horizontal) accelerations. Nevertheless, if roll and horizontal motions are combined, the combination probably generates large differences between the sensed and the subjective vertical and therefore they are highly provocative.

The tests in Part II contained tests with *limited roll acceleration* (LRA), *limited roll velocity* (LRV) and *smoothed ends* (SE). These conditions seem to be less provocative than the corresponding condition 3 (H100R75). Lower provocation levels of decreased roll acceleration and/or roll velocity agree with the findings from the train experiments.

Kufver (1999b) has studied the different track aspects of conditions LRA and SE and their resulting effects on motion and comfort (P_{CT}). These designs do not show any significant advantage over the traditional design with linear type of transitions curves (clothoids), from a pure P_{CT} point of view.

To implement LRA and LRV design into the tilt system (no changes to the horizontal alignment), the tilt control needs a beforehand knowledge of the curve in order to start the tilt motion in time. This can be implemented in middle and the rear part of the tilt train set. Alternatively, the transition curves may be design for less roll acceleration and/or roll velocity.

[51] Integrated information from eyes, vestibular system and proprioceptive system.
[52] From previous experience and internal model.

Influence from visual fields

The field of vision is probably of great importance for modifying the nauseogenicity of motions (Money 1970). Since the subjects were able to look out of the windows, they were able to view a horizon in order to stabilise their reference perception. Rolnick and Bles (1989) showed that an artificial horizon (fast rotation laser point) or a visual reference through windows can reduce motion sickness symptoms and performance decrement while working in a closed tilting room.

In a study using a distant (¬1 0 m) static visual scene was much less nauseogenic than a near (¬1 m) visual scene or an internal scene, moving with the subject (Howarth, Martino, & Griffin 1999). Used motion was a lateral (horizontal) acceleration 0.25 Hz, 1.0 m/s^2 peak (0.7 m/s^2 r.m.s.). One of their conclusions was to provide cars passenger with a view of the road ahead. The difference between the condition with the 10 m external scene and the two conditions with 1 m external scene and internal scene were relatively large and clear.

The importance of an external view is shown in a study of 3256 coach passengers, where a good external view forwards significantly lowered the rate of motion sickness, especially for females (Turner & Griffin 1999c).

This may be lead to the observation that the relatively high influence from horizontal acceleration on nausea found in the simulator experiments would be less nauseogenic, if there was an external scene provided at a sufficient distance from the subjects. Therefore, the regression coefficient may be high in comparison with a tilting train environment where it is possible to have an external view.

Regression models

The regression models show a strong influence from horizontal acceleration and a weaker from the roll acceleration. The roll only condition 7 (H0R75) have a nausea rating (*NR26*, population mean, all turns) that is about 25% of condition 3 (H100R75). However, for females this proportion is as low as 10% and for males as high as 35% (estimated marginal means, all turns). The conclusion seems that both genders have about the same sensitivity for roll motion (condition H0R75, Woodman & Griffin 1997) but the difference in sensitivity is for horizontal acceleration, i.e. females are in much more sensitive for horizontal acceleration. A good view ahead for coach passengers, lowers this sensitivity (Turner & Griffin 1999c).

Roll acceleration is exchangeable with roll velocity and horizontal acceleration with horizontal jerk with the used r.m.s. evaluations. Since both roll velocity and horizontal jerk were of the about the same order of magnitudes in the simulator experiments as in a tilting train environment, they might be better explanation variables. All explanation variables have been treated separately (linear combination) but a common *conflict variable* might be better to explain the variation of *NR* according to the motion conditions. Further research has to investigate this idea.

Response variables

Used response variable in the regression models has been the expected *NR26* calculated from an estimated ordinal multinomial distribution for the nausea ratings. The advantage is that the individual nausea ratings are distributed according to this distribution and it is easy to calculate the population means (expected values). It is also possible to use all ratings recorded from all turns, but estimate the outcome as for the first turn. The regression models are based on these estimated population means. Comparison with expected values and observed means for the first turn shows that condition 1 (H100R0) and condition 4 (H100R100) are underestimated. The provocation ability for these conditions seems to decrease as the subjects take part in more turns. Another possibility for a response variable is the estimated marginal means for *NR26*, which is cal-

culated together with analysis of variance (ANOVA). The ANOVA assumes that *NR26* is normally distributed. The estimated marginal means are in average half the magnitudes of the expected *NR26*, because of the adaptation of subjects after some turns.

Frequency dependency

The frequency influence on the regression models is very weak. Only the vertical accelerations showed in the correlation analysis a peak in correlation coefficient (*r)* at BP filtering 0.08 – 0.35 Hz, i.e. the approximate w_f-filter. However, the regression model with roll acceleration in the tilting train test showed best coefficient of determination (r^2) with this BP – filtering.

10.6 Conclusions

In the tilting train tests, the concept of *symptoms of motion sickness incidence* (*SMSI*) has been used with good results. *Symptoms of motion sickness* (*SMS*) have been estimated by healthy subjects in a high-speed train utilising different strategies for active tilting of the car body to reduce lateral acceleration during curving. The subjects have found the average ride comfort in all test conditions to be good. By using a lower ratio of tilt compensation (55%) instead of the normal (70%), a reduction of up to 25 - 40 % in the number of test subjects reporting *SMS* was found. Inadequate compensation levels may create ride discomfort due to high lateral acceleration levels and a high rate of change of lateral acceleration. The female subjects reported two to three times as high *SMSI* as the males or about 10-percentage units.

The absolute levels of *SMSI* found may not be directly transferable to a normal population of train passengers, because of the selection of subjects (sensitivity, age etc.). However, it is likely that lower compensation and limited tilt velocity also are favourable in a everyday population of passengers. *SMSI* values, evaluated over a suitable length of time or track, seem to be approximately proportional to motion dose of roll acceleration ($MSDV_{ral}$).

The test design developed in the train and simulator experiments, seems to be quite adequate for the purpose of estimating the human responses from a number of motion quantities as well as human factors. The repeated designs should be considered only when a few number of test conditions are used and with low provocation level, so problems of adaptation are minimised.

In the simulator tests, the evaluation variable *nausea rating* (*NR*) was used instead of *SMSI*. The main reason for this is the much higher rate of symptoms of motion sickness. This made the *SMSI* scale inadequate. The main conclusions are:

- Roll motions presented alone, for the magnitudes and frequencies used in this study, are not very nauseogenic. This seems to be in accordance with the sensory conflict hypothesis. Only small differences between gender in nausea ratings were found.
- Horizontal (lateral) accelerations alone seem to be medium provocative. Horizontal motions seem to provoke females more than males. The relative sensibility for horizontal acceleration alone is decreasing, as subjects are more adapted to test conditions after some turns.
- Combinations of high roll and high horizontal (lateral) accelerations, as those presented in this study, seem to be highly provocative. High compensation ratios are not necessarily nauseogenic, if the provocation level is low. The condition 5 (H75R56), with low roll and low horizontal acceleration and with compensation rate of 75%, show low nausea ratings.
- Ride comfort, comfort disturbances as well as the ability to work /read are affected by the degree of nausea. Both high horizontal acceleration and high roll motion have negative effects on these factors.

- Regression models with the explanation variables r.m.s. w_f-filtered horizontal acceleration and r.m.s. w_f-filtered roll acceleration were found to have high coefficients of determination and high significance in the simulator tests. These models are well suitable for prediction of nausea for conditions that are similar to the tests. A regression analysis, from the tilting train tests, shows that motion dose for roll acceleration is a good predictor for *SMSI*.
- Adaptation to the motion conditions was effective and after two or three turns the average nausea ratings were reduced with 30 – 50%. The adaptation process was much stronger than in the tilting train test where subjects took part in three constitutive days. Only on the last day the *SMSI* was somewhat decreased. This is in spite of that the train test run took about 3 hours whereas the simulator test took 31 min.

10.7 Suggestions for future research

Since the simulator study only investigated parts of the environment that can be found in a train environment, it is essential to carry on the studies in trains. The regression models from the simulator experiments employed the explanation variables horizontal accelerations and roll accelerations. Future research in this field has to focus on information needed for a prediction model for nausea in a tilting environment. This model has to estimate effects from both lateral and vertical accelerations as well as effects from roll and yaw motion.

One of the questions the present simulator study was not able to explain is whether it is motion dose from horizontal jerk or horizontal acceleration as well as roll acceleration or roll velocity that is the primary causes of provocation.

The motion dose model is based on a dose concept of the square root of an integrated squared motion quantities over time, i.e. it is corresponding to the r.m.s-values times the square root of time. Is there any alternative way of estimating the prediction variables, e.g. by taking account to the maximum values or 75% quartile of the motion quantities instead for r.m.s - values? Another interesting issue is whether it is possible to identify a *sensory conflict signal* for both translational and angular motions. The work of Bos and Bles (1997, 1998) may show if this way.

The frequency dependence, for different motion quantities, is not fully investigated together with the influence of visual field in tilting trains. This includes travelling backwards or forwards or using larger windows for a better outside views. These are questions to put forward in future research.

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Appendix A Definitions, terminology and abbreviations

Definitions, terminology and abbreviation are given in different parts:
A1 Test terminology and variables
A2 Track and vehicle quantities
A3 Statistical terminology
A4 Abbreviations and other definitions
A5 Notations
A6 Tilt system
A7 An example of estimation of data on ordinal multinomial distribution

A.1 Test terminology and variables

Condition — See test condition for simulator tests and tilt condition for test with tilting trains.

Illness Rating *(IR, IR_{OLD})* — A four-grade scale proposed by Lawther and Griffin for judging the well-being of a person. The grades were: 0, *I felt all right*; 1, *I felt slightly unwell*; 2, *I felt quite ill*; 3, *I felt absolutely dreadful* (Griffin 1990, Lawther & Griffin 1987).

Illness Rating (IR_{MOD}) — The original *IR* scale has been adopted but changed into a *modified* five-grade scale with the following wording:

0	Jag mår bra	I feel all right
1	Jag mår inte riktigt bra	I do not feel quite well
2	Jag mår ganska illa	I feel rather unwell
3	Jag mår dåligt (illa)	I feel bad (miserable)
4*	Jag mår mycket dåligt (illa)	I feel very bad (miserable)

Remark: * Not used in the present simulator test but used in the train tests

The original predicted *IR* can be calculated according to the formula: $IR_{OLD} = 1/50\ MSDV_Z$. Since the wording and number of grades as been changed, this formula is not longer true. A possible relation may be: $IR_{MOD} \approx 3/200\ MSDV_Z$

*IR*26 — *IR26* can be either the subjects *IR* at 26 min or the mean value of the subjects' *IR26*. The context where it stands, defines the use.

IRmean — *IRmean* is a mean value over *IR*21, *IR*26 and *IR*31.

Latin square — A Latin square of the order n is a matrix of n x n, where each of the n symbols occurs only once in each row and column. An example of a Latin square of order 4 is:

A B C D
B A D C
C D A B
D C B A

A Latin Square of order 7 can be constructed as follows:

1 2 3 4 5 6 7
2 3 4 5 6 7 1
3 4 5 6 7 1 2
4 5 6 7 1 2 3
5 6 7 1 2 3 4
6 7 1 2 3 4 5
7 1 2 3 4 5 6

General rule for construction of a Latin square of order n. An element (i, j) in the matrices can be computed as i + j (*addition modulo n*, i.e. if the number i + j is ≥ n it is replaced with i + j – n). To avoid that event (k+*1*) always follows the event (k), a random permutation of the columns can be performed (Thompson & Martinsson 1994).

Motion sequence — Horizontal (lateral) and roll motion used in the simulator. Three basic motions sequences were used added together up a 60 s long total motion sequence.

Motion dose — See *MSDV*.

Motion sickness — The state of being dizzy or nauseated because of travelling in a moving vehicle.

MSDV

$$MSDV = \left[\int_0^T a_{wf}^2(t)dt\right]^{0.5} = a_{rms,wf} \cdot \sqrt{T} \qquad [\mathrm{m/s^{1.5}}]$$

MSDV stands for *Motion Sickness Dose Value*, a_{wf} is frequency weighted vertical acceleration, T is integration time, 20 min < T < 6 h. The weighting curve (w_f) is defined in ISO (1997), BSI (1987) and in Griffin (1990). The corresponding r.m.s.-value of the weighted acceleration ($a_{rms,wf}$) can be calculated, if the acceleration signal is "stationary and continuous" in time.

$MSDV_z$ *Motion Sickness Dose Value* (vertical axis).

MSI — *Motion Sickness Incidence* (Vomiting Incidence, *VI*). The percentage of subjects vomiting in a particular circumstance.

Nausea — Sickness feeling.

Nausea rating *(NR)* — *Nausea Rating*. The subjects' rated their nausea on the grades defined below. This definition is modified from Golding et al. (1997, 1996, 1995). The subjects were told to notify the test leader if they reached *NR* = 3 or higher, so they could interrupt the test run and leave the cabin. Most subjects continued up to *NR* = 4.

Grades of nausea

0	Inga symtom	No symptoms
1	Lätta symtom men inget illamående	Light symptoms but no nausea
2	Lätt illamående	Light nausea
3	Medel illamående	Moderate nausea
4	Kraftigt illamående	Strong nausea
5	Kräkning	Vomiting (Not used)

Remark * mot used in the present tests.

*NR*26, *NRmean* — *NR26* can be either be the subjects *NR* at 26 min or the mean value of the subjects' *NR*26. The context where it stands, defines the use. *NRmean* is a mean value over *NR*21, *NR*26 and *NR*31.

*NP, NP*26 — *Nausea percentage*. The percentage of subjects having *NR* > 0. *NP*26 is *NP* at 26 min.

p-deletion test — A test where the subjects are marking as many small case "p" in a matrix of random letters. In the simulator test a (40 x 50) matrix was used with 2 p's per row. The number of marked p and number of search rows of p's was used for evaluation.

p-test — See p-deletion test.

SMS, SMSI — *Symptoms of motion sickness, Symptoms of motion sickness incidence*. An evaluation variable used in the *train experiment*, defined as (if *IR0* = 0):

SMS = 1 if dizziness + nausea + *IR* > 0 and *IR0* = 0

SMS = 0 if dizziness + nausea + *IR* = 0 and *IR0* = 0

SMS is undefined if *IR0* > 0 and then omitted from calculation of *SMSI*.

In the *simulator experiment*, *SMS* can be defined as:

SMS = 1, if *NR* + *IR* > 0, else *SMS* = 0.

$SMSI = \frac{1}{N}\sum_{i=1}^{N} SMS_i$ where i is the subject no. i and N is the number of subjects in the group.

Subject — A person who participated in the experiments.

Test conditions (train experiment), see tilt conditions

Test conditions — A certain combination of lateral and roll motions in the simulator tests. Conditions numbers range from 1 to 11. For mnemotechnical purposes these abbreviations are used for the different conditions:

Condition	*Mnemonics*	*Explanation*
Condition 1	H100R0	Horizontal (lat) acc. 100%, roll angle 0%
Condition 2	H100R56	Horizontal acc. 100%, roll angle 56%
Condition 3	H100R75	Horizontal acc. 100%, roll angle 75%
Condition 4	H100R100	Horizontal acc. 100%, roll angle 100%
Condition 5	H75R56	Horizontal acc. 75%, roll angle 56%
Condition 6	H75R75	Horizontal acc. 75%, roll angle 75%
Condition 7	H0R75	Horizontal acc. 0%, roll angle 75%
Condition 8	LRA	Limited roll acceleration
Condition 9	LRV	Limited roll velocity
Condition 10	SE	Smoothed ends on transition curves
		(Horizontal acceleration has the same shape as roll motion in condition 8 (LRA))
Condition 11	NV	No vibration

With HX means X% of maximum horizontal (lateral) acceleration and RX means X% of maximum roll angle.

Test design — The principles of experimental test design are as follows: differential treatments are administrated to different group of subjects and performance on some response measure is observed and recorded following the administration of the treatments.

Test group — A number of subjects administrated to the same conditions. In the trains experiment seated in the same car.

Test parts — The simulator experiments was divided into two parts. Part I contained the test numbers 1 to 7 and was conducted in June 1998. Test parts II was divided into two parts labelled part IIA and part IIB. Test part IIa contains the test numbers 3, 8, 9 and 10 and test part IIB the test numbers 3, 11,12 and 13. These test parts were conducted in August 1998.

Test parts (train) — The test run is divided into four approximately equal parts Linköping – Katrineholm, Katrineholm - Järna, Järna – Katrineholm and Katrineholm – Linköping.

Test run (simulator) — A subject's test on a certain turn or trial in the simulator. Duration was 31 min of motion in the simulator.

Test run (train) — An approximately three-hour train ride from Linköping to Järna and return. It is divided into four test parts.

Test sequence — The test sequence describes how the test run was performed, i.e. in what order different actions was undertaken.

Test subject — See subject.

Tilt conditions — A set of different alternative parameters for controlling the tilt system and speed of the train, as used in the experiments.

A (reference condition: 70% tilt compensation, Limitation of tilt velocity = 4 °/s (0.070 rad/s).

F: 55% tilt compensation. Limitation of tilt velocity = 4 °/s (0.070 rad/s). Limitation of tilt acceleration = 4 °/s^2 (0.070 rad/s^2) and no dead zone around tilt angle = 0.

G: 55% tilt compensation. Limitation of tilt velocity = 2.3 °/s (0.040 rad/s). The limitation of tilt velocity, in normally cases, should not limit the necessary tilt motion in transition curve. However, it should limit unnecessary tilt motion due to long-wave horizontal irregularities.

Normal limitation of tilt accelerations are about 10 °/s^2 (0.17 rad/s^2) due to car-body inertia and characteristics of the suspension system.

Turn (trial) — The number of a subject's test run. Turn no. 2 means both the second test run for a specific subjects and the group of subjects that made test runs for the second time.

VI — Vomiting incidence, see *MSI*.

A.2 Track and vehicle quantities

Bogie — The part of the vehicle, where the wheelsets, suspension and parts of the tilt system are located.

Car — The train is divided in different car (coaches or vehicles).

Car body — The main part of the vehicle, where passengers compartments and/or cargo are located. The car body rests upon the bogies.

Car body tilt — See tilt.

Cant — Cant (D) is the height difference between the upper surfaces of the two rails in wheel-on-rail systems, at the same longitudinal position. In curves, the outer rail is set higher than the inner rail to minimise the effect of centrifugal force. The cant is positive if the outer rail is higher than the inner rail. Cant can also be called superelevation (Source: UIC). Cant is normally measured in mm but can given as an angle. [m, mm, rad, °]

Cant deficiency — Cant deficiency (I) is the difference between the existing degree of superelevation and the degree required to fully eliminate the effect of centrifugal force at maximum allowable speed. Reduced superelevation may be necessary for technical reasons (switching) or for avoidance of excessive superelevation for slow trains, such as freight trains (Source: UIC). [m, mm]

Cant deficiency can also be measured as an angle. [rad, °]

Cat A train — A normal non-tilting train with a maximum permitted cant deficiency of 100 mm, according to Swedish regulations.

Cat B train — A non-tilting train with a maximum permitted cant deficiency of 155 mm, corresponding to a curving speed in order of 10% higher than Cat A train, according to Swedish regulations.

Cat S train — A tilting train with a maximum permitted cant deficiency of 245 mm, corresponding to a curving speed in order of 25% higher than Cat A train, according to Swedish regulations.

Compensation ratio — Tilt compensation ratio (k_c) is to what degree the lateral acceleration in the track plane (a_{yt}) is reduced in the car body (a_{yc}).

$k_c = 1 - (a_{yc} / a_{yt})$ [-]

It can also be expressed as the degree of compensation

$k_c = [1 - (a_{yc} / a_{yt})]\ 100$ [%]

Comfort — The subjective state of well-being. The comfort experience is influenced by physical factors (dynamic, ambient and spatial), as well as social and situational factors (Alm 1989).

Effective roll factor — The quotient between the lateral acceleration in cabin and lateral acceleration in the track plane: $f_r = (a_{yc} / a_{yt}) = 1 + s$, where f_r = effective roll factor and s = roll coefficient.

Jerk, jolt — Jerk is the rate of change in acceleration. In a train environment, jerk is associated with the change of lateral acceleration in transition curves.

	Jolt is a sudden motion caused by passing a turn-out or track alignment faults, causing comfort disturbances to the passengers. Both jerks and jolts are usually filtered by a low-pass filter (typically 0.3 - 2 Hz) before evaluation. Jerk is measured in [m/s^3] and jolt in peak to peak acceleration [m/s^2] over a certain period of time (normally 2 s).
Lateral acceleration	Acceleration perpendicular to the direction of motion, caused by centrifugal forces as the vehicle moves through a curve, or by defects in track configuration. The impact of lateral acceleration on passengers can be reduced or even eliminated by proper cant in curves. The component of lateral acceleration acting parallel to the car body (a_{yc}) floor can be called *free lateral acceleration*. It has an impact on passenger comfort, and, in curves, the free lateral acceleration can be reduced by superelevation of the track and by an active car body tilt mechanism (Source: UIC).
Nominal	Parts of the signal that depends on train speed, designed track alignment and cant. The rest of the signal is then called dynamic.
Quasi-static	The quasi-static level of a signal corresponds to the average level during stationary conditions (such as running at constant speed on a curve with constant radius and cant).
Ride comfort	Sometimes also passenger comfort, i.e. the human response to dynamic motion quantities, such as vibrations.
Ride (dis-)comfort	The technical evaluation of ride discomfort. This can be done according to different standards as Wz (Sperling and Betzhold 1956), ISO 2631-1 (ISO 1997), CEN prENV 12299 (CEN 1996). Evacuation of ride comfort is done by weighting the accelerations on the floor of vehicles (minimum requirement) or additional on interfaces between passengers and seats.
Ride index	Evaluation of ride (dis-)comfort according to Wz or the British Ride Index.
Ride quality	Human evaluation of the average comfort of the ride on the scale very poor to very good. However, many refers this as passenger comfort or ride comfort. (Numerical value used to quantify ride comfort. Forces and acceleration generated in the bogie and in the coach (with a distinction made between horizontal and vertical elements) are added and weighted. Source: UIC.)
Roll coefficient	See effective roll factor.
Stations	Jn = Järna, K = Katrineholm, Lp = Linköping, Nr = Norrköping, Gn = Gnesta, H = Hallsberg, Sk = Skövde.
Superelevation	See cant.
Superelevation ramp	A superelevation ramp is a section of the track where the cant changes gradually. (According to many standards of many railways companies, a superelevation ramp should normally coincide with a transition curve.)

Tilt	The concept of inclining the car body (roll) in order to reduce the experienced lateral acceleration in the car body, while travelling through a curve. See also Appendix A.4.	
Tilt angle	The angle between the car body plane and track plane (θ_c).	[rad, °]
Tilt velocity	Time derivative of tilt angle ($\dot{\theta}_c$).	[rad, °]
Tilt acceleration	Time derivative of tilt angle velocity ($\ddot{\theta}_c$).	[rad, °]
Tilt compensation	See compensation ratio.	
Tilt condition	A set of different alternative parameters for controlling the tilt system and speed of the train, as used in the tilting train experiments, see also tilt conditions in A1.	
Track irregularity	The difference between the actual track position and the designed position. The mismatch between actual and designed position could involve horizontal alignment, gauge, vertical alignment and/or cant.	
Track plane	The track plane is a function of the longitudinal distance. The instantaneous direction of the track centre plane defines the x-axis with the track plane, while the y-direction within the track plane is a tangent to the designed positions of the top surfaces of the two rails.	
Transition curve	A transition curve is a track element where the curvature changes gradually.	
Vehicle	A conveyance that transports people or objects	
x, y, z directions	When evaluation the ride comfort, the directions refer to the car body (vehicle body); the x and y- directions are longitudinal and lateral directions parallel to the floor, while the z-direction is perpendicular to the floor	

A.3 Statistical terminology

ANOVA — *ANalysis Of VAriance*. A structured method of analysis of the variation of the tested variables in an experiment in order to judge if the variation is significant. See for example (Keppel 1991) for a reference book.

ANOVA implemented in SPSS — The SPSS General Linear Model (GLM) General Factorial procedure provides *regression analysis* and *analysis of variance* for one dependent variable by one or more factors and/or variables. The factor variables divide the population into groups. It can test null hypotheses about the effects of other variables on the means of various groupings of a single dependent variable. It can investigate interactions between factors as well as the effects of individual factors, some of which may be random. In addition, the effects of covariates and covariate interactions with factors can be included. For regression analysis, the independent (predictor) variables are specified as covariates.

Both balanced and unbalanced models can be tested. A design is balanced if each cell in the model contains the same number of cases. In addition to testing hypotheses, GLM General Factorial produces estimates of parameters.

Commonly used a priori contrasts are available to perform hypothesis testing. Additionally, after an overall F test has shown significance, you can use post hoc tests to evaluate differences among specific means. Estimated marginal means give estimates of predicted mean values for the cells in the model, and profile plots (interaction plots) of these means allow you to easily visualise some of the relationships[1].

Balanced design — A test design, where all groups are testing all conditions and also minimises the influence from one condition to another. A typical (counter-) balanced, or Latin Square design is shown in the example below. Conditions: A, B, C and D. Test groups: 1 - 4 (Campbell & Stanley 1966).

	Test1	Test 2	Test 3	Test 4
Group 1	A	B	C	D
Group 2	B	D	A	C
Group 3	C	A	D	B
Group 4	D	C	B	A

Binomial distribution — The frequency in n independent trials with a probability in each trail = p. Expected value = $n \cdot p$.Variance = $n \cdot p \cdot (1-p)$.

Confidence interval — A confidence interval for a parameter x with a confidence degree of y%, is an interval wherein the true parameter x_{true}, of the true population, is located y times out of 100.

[1] Text from helpfile from Statistical Package for Social Sciences (SPSS)

Coefficient of determination (r^2) A measure of goodness of (linear) fit of a regression model. It is 1 for total fit and 0 for no linear association between the dependent and independent variables.

Correlation A measure of linear association between two variables. Values of the correlation coefficient range from -1 to 1. The sign of the coefficient indicates the direction of the relationship, and its absolute value indicates the strength, with larger absolute values indicating stronger relationships.

Spearman rank correlation coefficient ρ. A non-parametric version of the *Pearson correlation coefficient*, based on the ranks of the data rather than the actual values. It is appropriate for ordinal data, or for interval data that do not satisfy the normality assumption. Values of the coefficient range from -1 to +1. The sign of the coefficient indicates the direction of the relationship, and its absolute value indicates the strength, with larger absolute values indicating stronger relationships[2].

Chi-square (χ^2) test In the χ^2 test the observed numbers is compared with the expected numbers under a null hypothesis (H_0). The test statistic is:

$$\chi^2 = \sum_i \frac{(O_i - E_i)^2}{E_i}$$

where O_i = the observed number of cases in the ith category, $1 \leq i \leq k$
E_i = the expected number of cases in the ith category, $1 \leq i \leq k$
k = the number of categories

Degrees of freedom $df = k - 1$. Find in a χ^2 Table the probability p (that H_0 is true) from the observed value χ^2 and df. If that probability p is less than or equal to the significance level α ($p \leq \alpha$), reject H_0 and accept H_1 (Siegel & Castellan 1988).

Covariate Covariates are quantitative explanation variables, used together with dependent variables to define a linear (regression) model[2].

Estimated marginal mean *Estimated marginal means* are calculated on the assumption that the proposed model is linear. It takes all entered values into consideration and creates a linear model. Therefore, it is a better estimation of the "true" mean than the observed mean. If the model is perfectly balanced, the *observed mean* and the *estimated marginal mean* is the same. Estimated marginal means are calculated at the mean value at the covariates[2].

For example. If the factor gender is important for same response variable and there are different percentages of females in different conditions, when the normal (observed) mean will be coloured by the factor gender. However the estimated marginal means will give the mean of the response variable at the same percentage of females (mean percentage of females in all conditions).

Expected value See population mean and multinomial distribution.

GLM General linear model, see ANOVA.

[2] Text from helpfile from Statistical Package for Social Sciences (SPSS)

GLZ — Generalised Linear Model (Dobson 1990, McCullagh & Nelder 1989, Wiklund 2000), see also Förstberg (2000a, section A4) for short introduction (source: help file from Statistica program). An example of calculation of population means (expected values) is shown in section A.7.

Hypothesis testing — H_0 is called the null hypothesis and is a hypothesis of "no effect". It is formulated in the express purpose of being rejected. If it is rejected, the alternative hypothesis (H_1) is supported. The alternative hypothesis is the operational statement of the experimenter's research hypothesis. The significance level α is the probability, when in fact the hypothesis H_0 is true, to reject H_0 and accept H_1 (Siegel & Castellan 1988).

Kruskal-Wallis test — The Kruskal-Wallis one-way analysis of variance by ranks is an extremely useful test for deciding whether k independent samples are from different populations (Siegel & Castellan 1988). For a definition of the test, see above reference.

Likelihood function — is proportional to the probability of obtaining the given sample observation, regarded as a function of the unknown parameters μ_1, μ_2, $..\mu_2$, ϕ (Aitkin, Anderson, Francis, & Hinde 1989).

Multinomial distribution. — An extended case of the binomial distribution with n levels. Each level i has a probability p_i and $\sum_i p_i = 1$, $0 \le i \le n - 1$.

Population means (expected value) = $\sum i \cdot p_i$, $0 \le i \le n - 1$.

Observed mean — The mean of the samples: $s = 1/N \sum_i x_i$

Ordinal — This term means that there is an order between the different levels of the variable: $x_i < x_{i+1}$.

Examples of ordinal variables are IR and NR.

Examples of non-ordinal variables are x_0 = blue, x_1 = yellow, x_2 = green, x_3 = red.

Population mean — The mean of a population (distribution f(x) or for a discrete distribution (f(i)).

$$pm = \int x \cdot f(x)dx = \sum_i i \cdot f(i)$$

Regression coefficients — The coefficients β_i (i= 0, 1, 2, …, n) in a regression model.

$$Y = \beta_0 + \sum(\beta_i \cdot x_i) + \varepsilon$$

Significance level — The probability of rejecting the null hypothesis (H_0) when H_0 is in fact true.

Statistical power — The power is the probability to reject the test hypothesis H_0 when the alternative H_1 is true, i.e. the probability find a significant effect of the experiment. The power of an experiment is determined by the interplay from three factors, namely, significance level α, the magnitude or size of the treatment effects, and the sample size n.

Test design — See A.1.

t-test — A test of hypothesis of any difference of means between two populations. It based upon the assumption that the both population

have normal distributions and it is using the Students t-distribution (Hays 1988).

H_o: $\mu_1 - \mu_2 = k$

then the test is

$t = \frac{(\bar{y}_1 - \bar{y}_2) - k}{\text{est.}\,\sigma_{diff}}$ where $(\bar{y}_1 - \bar{y}_2)$ is the difference in observed mean between two sets of samples and

$$\text{est.}\,\sigma_{diff.} = \sqrt{\left(\frac{(N_1 - 1)s_1^2 + (N_2 - 1)s_2^2}{N_1 + N_2 - 2}\right) \cdot \left(\frac{N_1 + N_2}{N_1 N_2}\right)}.$$

Tamhane — Post hoc test using conservative pairwise comparisons based on a t-test. This test is appropriate when the variances are unequal[3].

Tukey — Post hoc test using the studentized range statistic to make all of the pairwise comparisons between groups. Sets the experimentwise error rate at the error rate for the collection for all pairwise comparisons[1].

Variable transformation — To stabilise the variation of a variable. The standard deviation should be the same for a particular variable for different categories with different means. For example, square root transformation sqrt(y_i) or sqrt(1+y_i) are useful for Poisson's distributions (Montgomery 1991).

Wald statistics — The Wald statistics use that the square quantity of estimated regression coefficient divided with standard deviation of the coefficient is Student's t- distributed (Wiklund 2000).

Wald = $\left(\frac{\beta}{SD(\beta)}\right)^2$, where SD is standard deviation β is estimated regression coefficient

[3] Text from helpfile from Statistical Package for Social Sciences (SPSS)

A.4 Abbreviations and definitions

A.4.1 Organisations etc

Adtranz	*Adtranz Sweden. DaimlerChrysler Rail Systems*, A global supplier of railway equipment. In this report, Adtranz is the Swedish train manufacturer, *Adtranz Sweden*, Västerås.
Banverket (BV)	*Swedish National Rail Administration*, Borlänge.
BR	Former *British Rail*, London.
BRR	Former *British Rail Research*, Derby.
BSI	*British Standards Institution*, London.
CEN	*European Committee for Standardization*, Brussels.
DB (DBAG)	*Deutsche Bahn* AG. German Railways, Frankfurt/Berlin.
DIS	*Draft International Standard*. A draft standard issued by ISO and valid for two years.
ETR	*Elettrotreni rapidi*, Italian high speed electric train.
FIAT Ferroviaria	An Italian manufacture of railway equipment, Savigliano.
FS	*Ferrovie dello Stato S.p.A.*, Italian State Railways, Firence.
ISO	*International Organization for Standardization*, Geneva.
Jernbaneverket	*National Rail Administration* in Norway, Oslo.
JR (JNR)	*Japan Railways Group*, former *Japanese National Railways*.
KFB	*Kommunikationsforskningsberedningen* (Swedish Transport and Communications Research Board), Stockholm.
KTH	*Kungliga Tekniska högskolan* (Royal Institute of Technology), Stockholm.
LiU	*Linköping University*, Linköping.
NSB	*NSB BA*, former *Norwegian State Railways*, Oslo.
RTRI	*Railway Technical Research Institute*, Tokyo.
SBB	*Schweizerischen Bundesbahnen* (Federal Railways of Switzerland), Bern.
SJ	*Statens Järnvägar* (Swedish State Railways), Stockholm.
SNCF	*Société Nationale des Chemins de Fer Français*. French National Railways, Paris.
TGV	*Train à Grande Vitesse*. French high speed train.
TGV Duplex	Two level TGV train.
UH	*University Hospital*, Linköping.
VTI	*Swedish National Road and Transport Research Institute*, Linköping.

A.4.2 Miscellaneous

acc. Acceleration.

BP Band pass filter.

CNS Central nervous system.

Conf. See confidence (statistic).

Coriolis cross-coupled stimulus After 60 s of whole-body rotation, head movements in pitch or roll will produce a sensation of moving the head in the perpendicular direction.

Dead zone If the response $y = 0$ if the source signal x $|x| \leq a$ then a is called a dead zone.

Graybiel scale A scale for judgement of the severity of motion sickness proposed by Graybiel et al (1968).

H, Hor. Horizontal. The horizontal plane is parallel to the horizon.

Lat. Lateral

L_{eq} *Equivalent continuous sound level.* L_{eq} is the A-weighted energy mean of the noise level averaged over the measurement period. It is defined as:

$$L_{eq} = 10 \cdot \log_{10} \frac{1}{T} \int_0^T \left(\frac{p_A(t)}{p_o} \right)^2 dt$$

where T s the total measurement time

$p_A(t)$ is the A-weighted instantaneous acoustic pressure

p_o is the reference acoustic pressure (20 μPa)

LP Low-pass filter.

MSI Motion sickness incidence. [%]
MSI normally means vomiting incidence (VI) within 2 h.

md motion dose, see $MSDV_Z$.

$MSDV_Z$ Motion Dose Sickness Value (in vertical direction). Defined by $MSDV_Z = \left[\int a_{z,wf}^2 dt \right]^{1/2}$, where $a_{z,wf}$ is w_f weighted vertical acceleration.

Predicated $VI = K_m \cdot MSDV_z$. Valid up to VI < 70% and T > 20 min and T < 6 h. $K_m \approx$ 1/3 for an un-adopted adult population of mixed genders (ISO 1997).

Otoliths Organs sensitive for static and dynamic linear accelerations, found in the inner ear. See also the vestibular system.

P Probability

P_{CT} Passenger dissatisfaction on transition curves (Harborough 1986b).

P_{DE} Passenger dissatisfaction on discrete events (Harborough 1986b).

P_{disc} Probability of a comfort disturbance

Pitch Rotation about the lateral (y) axis. [rad], [°]

Posture system	Through information from the vestibular, visual and proprioceptive system, the posture system is able to control the posture and movements of the body. (See also the vestibular system).
Proprioceptive	Information of the posture of the body received from sensory cells located system in muscles and joints.
r.m.s.	Root mean square. A measure of signal power. r.m.s. = $\frac{1}{T}\left[\int_0^T a^2 dt\right]^{1/2}$
Roll	Rotation about the longitudinal (x) axis (φ). [rad], [°] Reference plane is the horizontal plane. The roll angle of the car body in indicated as φ_c.
Semicircular canals	Organs sensitive to dynamic angular acceleration, found in the inner ear. See also the vestibular system.
Sqrt	Square-root
Vel.	Velocity
Vert, vert.	Vertical
VI	Vomiting incidence, see also MSI. [%]
Vestibular system	The vestibular system consists of the peripheral and central vestibular systems. The peripheral vestibular system consists of the two *otoliths* sensitive to linear static and dynamic accelerations and the three *semicircular canals* sensitive to dynamic angular motion in three axes. These organs are located in the inner ear together with the auditory part.
VOR	*Vestibulo - Ocular Reflex*. The interaction between the vestibular system and eyes, where vestibular information directs the eyes by means of a reflex. Enables stable vision in spite of movements of the head.
w_f, w_b, w_k, w_d	Weighting filters. See Appendix D, Figure D-3.
Yaw	Rotation about the vertical (z) axis. [rad], [°]
($\dot{x}$), ($\ddot{x}$), ($\dddot{x}$)	First, second and third time derivative of (x).

A.5 Notations

A	Amplitude. Amplitude of provocation signal in net dose model.	
a	Acceleration.	[m/s^2]
a_y	Lateral acceleration.	[m/s^2]
a_{yc}	Lateral acceleration i car body plane.	[m/s^2]
a_{yH}	Horizontal (lateral) acceleration.	[m/s^2]
a_{yt}	Lateral acceleration in track plane.	[m/s^2]
a_z	Vertical acceleration.	[m/s^2]
c_A	Proportional constant according to A in the net dose model.	
c_L	Proportional constant leakage to net dose in the net dose model.	
D_L	Leakage of accumulated net dose.	
D_N	Accumulated net dose.	
D_p	Perceived dose.	
df	degrees of freedom.	
f	Frequency.	[Hz]
f_n	Relative frequency.	
f_r	Effective roll factor $f_r = a_{yc} / a_{yt}$	[-]
g	Gravitational acceleration (9.81).	[m/s^2]
ge	Gender (= 0 for male and = 1 for females).	
H_0	Null hypothesis.	
H_1	Alternative hypothesis.	
k_c	Tilt compensation.	[-]
K_m	Constant in the formula $MSI = K_m * MSDV_Z$; $K_m \approx$ 1/3 ,according to (Griffin 1990, ISO 1997, Lawther & Griffin 1987).	
L	Length.	[m]
md	Motion dose, see MSDV	
$MSDV$	Motion Sickness Dose Value = motion dose	[m/s$^{1.5}$, rad/s$^{1.5}$]
N, n	Number of observations.	
p	Probability of hypothesis H_0 to be true. If $H_0 < \alpha$, then H_0 is rejected and the alternative hypothesis H_1 is accepted.	
p_x	Number of marked p's at x min. Used x are p (pre-test), 0, 30 and a (after test).	
p_{rowx}	Number of rows with marked p's at x min.	
pm	Population mean (expected value) calculated from a distribution (f(x) or f(i)).	
r	Correlation coefficient.	
r^2	Coefficient of determination.	
s, SD	Standard deviation of a sample.	
s	roll coefficient $s = f_r - 1 = a_{yc} / a_{yt} - 1$	
T, t	Time.	[s]
t	Parameter from Students t-distribution.	
tr	Turn. The specific number of a subject's participation in a test run.	

v	Velocity.	[m/s]
V	Speed.	[km/h]
$\overline{X}$, m	Mean of a sample.	
α	Significance level.	
α, β	Regression coefficients.	
φ, phi	Roll angle.	[rad, °]
μ	Mean of a population.	
ω	Angular frequency.	[rad/s]
χ^2	Chi-square test.	

A.5.1 Indices

		(Example)
a	acceleration	
c	car body	(a_{yc})
c	circular curve	(L_c)
H	Horizontal	(a_{yH})
l	leakage	(c_l)
$part$	test part	
r	resulting	
r	roll	($MSDV_{ra}$)
t	track	(a_{yt})
t	transition curve	(L_t)
v	velocity	
x	longitudinal	(a_x)
y	lateral	(a_y)
z	vertical	(a_z)

A.6 Tilt system

Tilt angle, tilt velocity, tilt acceleration is the corresponding angle / velocity / acceleration with which the tilt system rotates the car body with respect to the track plane.

Roll angle, roll velocity and roll acceleration is the corresponding angle / velocity / acceleration with which the car body rotates with respect to the horizontal plane.

For definition of angles and directions of acceleration, see Figure A-1.

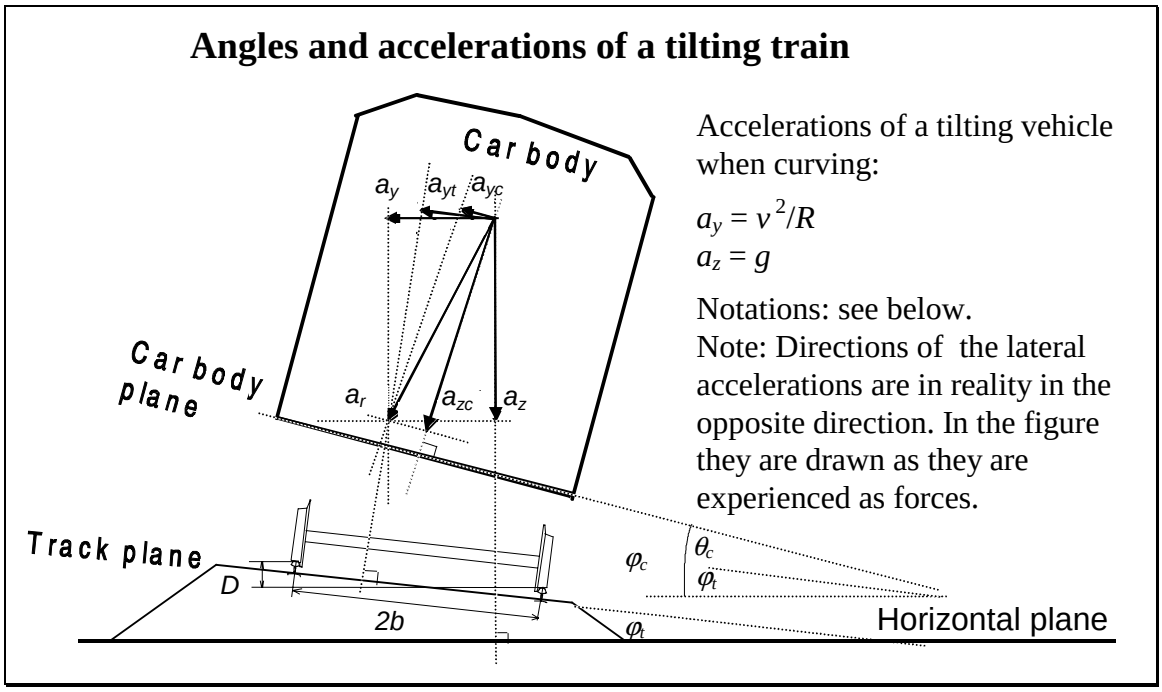

Figure A-1 Definition of angles and accelerations. Track cant is φ_t. Tilt angle of the car body is θ_c. Total roll angle is $\varphi_c = \varphi_t + \theta_c$ to the horizontal plane. Vertical acceleration perpendicular to the horizontal plane is a_z,, lateral acceleration parallel to the horizontal plane is a_y and the resulting acceleration is a_r. Lateral acceleration in the car body plane is a_{yc}.

Notations with reference to Figure A-1.

A.6.1 Angles

φ	=	roll angle (referring to the horizontal plane).	[°, rad]
φ_t	=	angle between the horizontal plane and the track plane.	[°, rad]
φ_c	=	angle between the horizontal plane and the car body plane.	[°, rad]
$\dot{\varphi}$	=	roll angle velocity.	[°/s, rad/s]
θ	=	tilt angle (referring to the track plane).	[°, rad]
θ_c	=	car body tilt angle.	[°, rad]
$\dot{\theta}_c$	=	car body tilt velocity (tilting velocity).	[°/s, rad/s]

A.6.2 Track and vehicle parameters

$2b$	=	the lateral distance between the two wheel-rail contact patches, $2b$ = 1 500 mm for standard gauge track (1 435 mm).	[m]
D	=	cant (superelevation) of the track (measured at the distance of 2b).	[m], [mm]
I	=	cant deficiency, the difference of the D needed to get a zero lateral acceleration in track plane (a_{yt} = 0) and the actual cant D	[m], [mm]
R	=	horizontal curve radius.	[m]
v	=	speed.	[m/s]
V	=	train speed	[km/h]

A.6.3 Accelerations

g	=	gravitational acceleration, g = 9.81.	[m/s^2]
a_H	=	lateral acceleration parallel to the horizontal plane, $a_H = v^2 / R$.	[m/s^2]
a_{yt}	=	lateral acceleration parallel to the track plane, $a_{yt} = (v^2 / R) \cos(\varphi_t) - g \sin(\varphi_t) \approx v^2 / R - g \cdot D / 2b$.	[m/s^2]
a_{yc}	=	lateral acceleration parallel to the car body plane, $a_{yc} = (v^2 / R) \cdot \cos(\varphi_c) - g \cdot \sin(\varphi_c)$.	[m/s^2]
a_z	=	vertical acceleration perpendicular to the horizontal plane, $a_z = g$	[m/s^2]
a_{zc}	=	vertical acceleration perpendicular to the car body plane.	[m/s^2]
a_{zc}	=	$v^2 / R \cdot \sin(\varphi_c) + g \cdot \cos(\varphi_c)$	
a_r	=	resulting acceleration ($a_r = \sqrt{a_y^2 + a_z^2}$).	[m/s^2]

The tilt compensation ratio (k_c) is to what degree the lateral acceleration in the track plane (a_{yt}) in circular curves under quasi-static conditions is compensated by the tilt, i.e. $a_{yc} = a_{yt} \cdot (1-k_c)$. The resulting lateral acceleration is the lateral acceleration (a_{yc}) felt by passengers.

A.6.4 The car body tilt system

A car body tilt system normally consists of the following basic principal parts. Example taken from X2 tilt system (Persson 1989):

1. A sensor for lateral acceleration in the leading bogie of the train. The signal is low-pass filtered before being transmitted onwards to the tilting computer located in each car.
2. The tilt system's computer calculates a lead value from the lateral acceleration measured in the leading bogie, the position of the car in the train to delay the tilt movement to the right moment, desired tilt compensation, other tilt control parameters and the train speed.
3. An actuator (pneumatic, hydraulic or electric) tilting the car body in relation to the bogie.
4. A controller comparing the actual car body tilt value with the lead value.

Some parameters of the tilt system are possible to vary in order to change the characteristics of the system. Table A-1 shows some possible variations of parameters in the tilting system.

Table A-1 Possible variation of parameters in the tilt system. Example of normal values are from X2000 original settings.

Parameter	*Amplitude of variation*	*Normal value*	*Units*
Compensation of car body tilt	0 - 100	70	[%]
Car body tilt velocity	0 - 4	4	[°/s]
Car body tilt acceleration	0 - 10	10[i]	[°/s^2]

Remark: i The car body tilt acceleration is not limited by the tilt control system, however the suspension system together with inertia of the car body limits the tilt acceleration to an estimated value of 10 - 15 °/s^2.

A.6.5 Track formulas

Formulas for approximate relations calculated from track parameters are shown below (Kufver 1997a; Kufver 1997b).

$$f_r = \frac{a_{yc}}{a_{yt}}$$ Definition of effective roll factor [-]

$$a_{yt} \approx \left(\frac{v^2}{R} - \frac{g \cdot D}{2b} \right)$$ Lateral acceleration in the track plane [m/s^2]

or

$$a_{yt} \approx \frac{I \cdot g}{2b}$$ [m/s^2]

$$a_{yc} \approx f_r \cdot \left(\frac{v^2}{R} - \frac{g \cdot D}{2b} \right)$$ Lateral acceleration in the car body plane [m/s^2]

or

$$a_{yc} \approx f_r \cdot \frac{I \cdot g}{2b}$$ [m/s^2]

$$\dot{a}_{yc} = \frac{da_{yc}}{dt} \approx f_r \cdot \frac{I \cdot g}{2b} \cdot \frac{v}{Lt} = f_r \cdot \frac{I \cdot g \cdot V}{3.6 \cdot 2b \cdot L_t}$$ Lateral jerk (car body plane) [m/s^3]

$$\varphi_t \approx \frac{D}{2b}$$ Roll angle caused by cant [rad]

$$\varphi_{fr} = \theta_c \approx (1 - f_r) \cdot \frac{I}{2b}$$ Roll angle caused by car body rolling [rad]

$$\varphi_c = \varphi_D + \varphi_{fr} \approx \frac{D + (1 - f_r) \cdot I}{2b}$$ Total roll angle caused by cant and car body rolling [rad]

$$\dot{\varphi}_c \approx \frac{D + (1 - f_r) \cdot I}{2b} \cdot \frac{V}{3.6 \cdot L_t}$$ Roll velocity [rad]

$$\dot{\varphi}_c \approx \frac{D + (1 - f_r) \cdot I}{2b} \cdot \frac{V}{3.6 \cdot L_t} \cdot 180/\pi$$ Roll velocity [°/s]

where:

$2b$ =	Distance between the contact patches between wheel and rail	[mm]
f_r =	Effective roll factor	[-]
g =	Gravitational acceleration	[m/s^2]
c =	Car body (vehicle body)	
D =	Cant	[mm]
I =	Cant deficiency	[mm]
L_c =	Length of circular curve	[m]
L_t =	Length of transition curve	[m]
R =	Radius	[m]
a_{yt} =	Lateral acceleration in the track plane	[m/s^2]
a_{yc} =	Lateral acceleration in the car body (vehicle) plane	[m/s^2]
$\dot{a}_{yc}$ =	Lateral jerk in the car body (vehicle) plane	[m/s^3]
v =	Speed	[m/s]
V =	Speed	[km/h]
φ =	Roll angle	[rad], [°]
$\dot{\varphi}$ =	Roll velocity	[rad], [°/s]

A.7 Estimating of data of the ordinal multinomial distribution

(Source: Document from Dr Mats Wiklund (VTI), (Wiklund 2000). See also McCullagh & Nelder (1989) and Dobson (1990).

Example below is an evaluation of nausea rating NR26 with the 20 subjects that have taken part in all seven conditions. Statistical evaluation is performed with program *Statistica* and the *GLZ* (generalised linear model). The tables below are example of output from program.

Dependent variable is *NR26*, ordinal with levels 0, 1, 2, 3, 4. Explanation (independent) variables are subjects (20 groups), condition (7 types) and turn (7 times). Table A-2 show the intercepts for the ordinal levels, the explanation variables subjects, conditions and turn. There are 5 – 1 = 4 intercepts, since the ordinal variable has 5 levels. Turn is entered as a continuous variables and have therefore no degrees of freedom. All variables are statistical significant.

Table A-2 NR26 - Test of all effects. Distribution: ORDINAL MULTINOMIAL Link function: LOGIT

	Degr. of Freedom	Wald Stat.	p
Intercept	4	74.3	.000000
SUBJECT	19	44.9	.0007
CONDITION	6	27.1	.0001
TURN		22.8	.0009

Table A-3 shows a goodness of fit and there is no overspread, on the contrary, it is less. The deviance is less than number of degrees of freedom.

Table A-3 NR26 - Statistics of goodness of fit. Distribution : ORDINAL MULTINOMIAL Link function: LOGIT

	Df	Stat.	Stat/Df
Deviance	525	224.9	.43
Scaled Deviance	525	224.9	.43
Pearson Chi^2	525	415.2	.79
Scaled P. Chi^2	525	415.2	.79
Loglikelihood		-112.4	

The table A-4 shows estimating of parameters. Subject, condition and turn are entered as explanation variables. To calculate a probability, one have to start with calculating a linear predictor η

Example 1. To calculate the probability that subject no. 19 has a nausea rating *NR26* of ≤ 2, in condition 4 and turn 2, one have to used the intercept for level 3 and add the parameter for subject 19, condition 4 and turn 2.

The linear predictor is then:

$$\eta = +5.25277 - 3.69235 - 1.84665 - 0.45751 = -0.74375$$

The cumulative probability is then

$$\frac{e^{\eta}}{1+e^{\eta}} = 0.32$$

Notify that cumulative probability for $NR26 \leq 4$ is always 1. The parameter for condition 7 = - sum of parameters for the condition 1 – 6. The same is valid for turn and subjects.

Example 2.
For condition 4, turn 1 the following is valid (subject is entered as 0):

$\eta(NR = 0)$ = 1.206 - 1.847- -2.014 = -2.655	cumulative probability F(0) = 0.066
$\eta(NR \leq 1)$ = 3.484 - 1.847- -2.014 = -0.377	cumulative probability F(1) = 0.407
$\eta(NR \leq 2)$ = 5.253- 1.847- -2.014 = 1.392	cumulative probability F(2) = 0.801
$\eta(NR \leq 3)$ = 6.030- 1.847- -2.014 = 2.170	cumulative probability F(3)= 0.898
$\eta(NR \leq 4)$	cumulative probability F(4) = 1

This gives a population mean (expected value) for condition 4 in turn 1 as
$pm = \sum_i (i\ (F(i) - F(i-1))) = 1.82$

Since the standard error for intercepts are very high, reflecting a great uncertainty of the exact value, it is better to omit the variable subjects in most cases, see Table A-5 and A-6. In these cases the intercepts the standard error is small and strongly significant.

Table A-7 shows the linear predictor η for the different conditions and for turn 1. For condition 1, turn 1 and for $NR26 = 0$ the following is valid: η= 0.19124 + 0.41112 – 1.200 = -0.598.

Table A-8 shows the cumulative distribution based on Table A-7 and Table A-9 shows the population means (expected value) for the distribution in Table A-8.

Table A-4 NR26 - Parameter estimates. Distribution: ORDINAL MULTINOMIAL. Link function: LOGIT

	Level of			Standard	Wald	
	Effect	Column	Estimate	Error	Stat.	p
Intercept 1		1.000	1.20590	167.014	.00005	.994239
Intercept 2		2.000	3.48361	167.014	.00044	.983359
Intercept 3		3.000	5.25277	167.015	.00099	.974910
Intercept 4		4.000	6.03025	167.015	.00130	.971198
SUBJECT	1	5.000	2.19728	167.020	.00017	.989503
SUBJECT	2	6.000	1.77286	167.019	.00011	.991531
SUBJECT	3	7.000	-.98297	167.016	.00003	.995304
SUBJECT	4	8.000	-4.57995	167.016	.00075	.978123
SUBJECT	5	9.000	-2.79481	167.016	.00028	.986649
SUBJECT	6	10.000	-1.52752	167.016	.00008	.992703
SUBJECT	7	11.000	2.02580	167.021	.00015	.990323
SUBJECT	9	12.000	19.80000	3173.267	.00004	.995022
SUBJECT	10	13.000	1.43267	167.018	.00007	.993156
SUBJECT	11	14.000	-.99885	167.016	.00004	.995228
SUBJECT	17	15.000	-2.74505	167.016	.00027	.986887
SUBJECT	18	16.000	-1.77646	167.016	.00011	.991513
SUBJECT	19	17.000	-3.69235	167.016	.00049	.982362
SUBJECT	20	18.000	-.45812	167.016	.00001	.997811
SUBJECT	21	19.000	-2.68907	167.016	.00026	.987154
SUBJECT	23	20.000	-2.04385	167.016	.00015	.990236
SUBJECT	26	21.000	-.98490	167.016	.00003	.995295
SUBJECT	28	22.000	.31605	167.017	.00000	.998490
SUBJECT	29	23.000	-.61162	167.016	.00001	.997078
CONDITION	1	24.000	.55812	.525	1.13109	.287542
CONDITION	2	25.000	-.22083	.482	.20976	.646954
CONDITION	3	26.000	-1.57993	.464	11.58197	.000666
CONDITION	4	27.000	-1.84665	.513	12.97543	.000316
CONDITION	5	28.000	1.38522	.578	5.73377	.016642
CONDITION	6	29.000	-.27392	.476	.33132	.564883
TURN	1	30.000	-2.01379	.476	17.93125	.000023
TURN	2	31.000	-.45751	.471	.94258	.331615
TURN	3	32.000	.53081	.530	1.00393	.316361
TURN	4	33.000	.45612	.514	.78817	.374655
TURN	5	34.000	1.04328	.604	2.98375	.084104
TURN	6	35.000	-.49721	.508	.95973	.327256
Scale			1.00000	0.000		

Table A-5 NR26 - Test of all effects. Distribution: ORDINAL MULTINOMIAL Link function: LOGIT

	Degr. of	Wald	
	Freedom	Stat.	p
Intercept	4.000	88.4	0.000000
CONDITION	6.000	16.20	0.013
TURN	6.000	11.89	0.064

Table A-6 NR26 - Parameter estimates. Distribution: ORDINAL MULTINOMIAL Link function: LOGIT

	Level of Effect	Column	Estimate	Standard Error	Wald Stat.	p
Intercept 1		1.000	.19124	.187386	1.04154	.307463
Intercept 2		2.000	1.66355	.239015	48.44172	.000000
Intercept 3		3.000	2.90632	.349934	68.97869	.000000
Intercept 4		4.000	3.47707	.432557	64.61609	.000000
CONDITION	1.000	5.000	.41102	.445893	.84971	.356633
CONDITION	2.000	6.000	-.21060	.410796	.26283	.608181
CONDITION	3.000	7.000	-1.00592	.398910	6.35889	.011679
CONDITION	4.000	8.000	-1.07134	.416554	6.61469	.010114
CONDITION	5.000	9.000	.83662	.488544	2.93255	.086810
CONDITION	6.000	10.000	.02972	.417970	.00506	.943304
TURN	1.000	11.000	-1.20054	.403981	8.83141	.002961
TURN	2.000	12.000	-.31519	.407305	.59883	.439024
TURN	3.000	13.000	.48180	.449044	1.15120	.283299
TURN	4.000	14.000	.15438	.428499	.12981	.718632
TURN	5.000	15.000	.70554	.495065	2.03104	.154115
TURN	6.000	16.000	-.19026	.430884	.19497	.658809
Scale			1.00000	0.000000		

Table A-7 Estimation of linear predictor η from Table A-6, valid for turn 1

Test condition	*NR = 0*	*NR ≤1*	*NR ≤2*	*NR ≤3*
1 (H100R0)	-0.598	0.874	2.117	2.688
2 (H100R56)	-1.220	0.252	1.495	2.066
3 (H100R75)	-2.015	-0.543	0.700	1.271
4 (H100R100)	-2.081	-0.608	0.634	1.205
5 (H75R56)	-0.173	1.300	2.542	3.113
6 (H7575)	-0.980	0.493	1.736	2.306
7 (H0R75)	0.001	1.474	2.716	3.287

Table A-8 Estimation of cumulative distribution from Table A-6, valid for turn 1

Test condition	*NR = 0*	*NR ≤1*	*NR ≤2*	*NR ≤3*	*NR ≤4*
1 (H100R0)	0.355	0.706	0.893	0.936	1
2 (H100R56)	0.228	0.563	0.817	0.888	1
3 (H100R75)	0.118	0.368	0.668	0.781	1
4 (H100R100)	0.111	0.352	0.653	0.769	1
5 (H75R56)	0.457	0.786	0.927	0.957	1
6 (H7575)	0.273	0.621	0.850	0.909	1
7 (H0R75)	0.500	0.814	0.938	0.964	1

Table A-9 *Population means (expected values) calculated from Table A-8, valid for all test condition for subjects taking part in all turns and showing theier estimated response for the first turn.*

Test condition	*Expected value*
1 (H100R0)	1.111
2 (H100R56)	1.505
3 (H100R75)	2.066
4 (H100R100)	2.114
5 (H75R56)	0.873
6 (H7575)	1.347
7 (H0R75)	0.784

Appendix B Description of the research project at the start (1994)

Slightly modified from (Förstberg 1994b).

B.1 Introduction

Comfort involves a sense of subjective well-being and the absence of discomfort, stress or pain. Richards (1980). Discomfort means that the passenger is dissatisfied with the train ride. There are three different kinds of input: physical, social and situational. In vehicle design and comparing ride comfort or ride quality for different vehicles, the physical inputs are most important. These factors are listed in Table B-1.

Table B-1 Physical characteristics of vehicle environments relevant for comfort (Richards 1980).

Dynamic Factors	Ambient Factors	Spatial Factors
Vertical Acceleration	Pressure	Workspace
Lateral Acceleration	Temperature	Seat Width
Longitudinal Acceleration	Humidity	Leg room
Roll Rate	Ventilation	Seat Adjustment
Pitch Rate	Smoke	Seat Shape
Yaw rate	Odors	Seat Firmness
Shocks, Jolts	Air Quality	
Ascents, Descents	Noise (?)	
Change in Speed		

In a sense comfort is multidimensional in that it is the result of joint presence of all physical factors and discomfort arise when one of these factors is outside a specified range. The concept of vehicle ride quality appears to focus upon the vehicle but is actually a concept dependent upon the human passenger. It is a subjective judgement Richards (1980). Normally ride comfort means comfort depending on variations of the physical dynamic factors such as accelerations, rate of change of accelerations (jerks) and angular motions.

The human perception of ride comfort is complicated. Many factors are integrated. The human perception of ride comfort in a steam vintage tour is very different from a business journey. The technical evaluation of ride comfort is only a prediction under certain assumptions of what human evaluation of ride comfort could be.

Therefore, in a technical sense, ride comfort is a function of accelerations, jerks and roll motions of the vehicle. These factors are in turn functions of track and vehicle variables, speed, seats and other variables. This is shown in Table B-2.

Table B-2 Relations between different variables and ride comfort

Inputs (variables)		*Technical evaluation / Human evaluation*	
Track/Vehicle interaction	Dynamic physical quantities	Ride Comfort (Wz, ISO, CEN)	Ride quality
Vehicle (v_i) Track (t_i) Other variables (o_i) as speed, etc.	accelerations, jerks (a_j, da_j / dt), roll, yaw φ_j $a_j, \varphi_j = \mathbf{f}(v_i, t_i, o_i)$	Ride comfort = $\mathbf{g}(a_j, \varphi_j)$	Probability functions

Remark: **f** and **g** are functions

B.2 Proposed research

It is of vital importance to establish a valid hypothesis about the influence of low frequency motions on comfort disturbances. Based on such knowledge it will be possible to modify vehicle and track design that will minimise comfort disturbances.

The research project is divided into different stages with different aims and proposed activities. The aims and activities for a later stage are naturally dependent on the results and experience of earlier stages.

Stage 1
Aims:

- Establish hypotheses of causes of comfort disturbances due to low frequency motions.

Methods:

- A literature survey of comfort criteria and methods of determination of ride comfort. What kind of motions are important for comfort disturbances such as ride comfort, comfort disturbance due to low frequency accelerations and motion sickness.
- Contact and visit other research institutes and railway companies for discussion of comfort disturbances.

Stage 2.
Aims:

- Establish methods for description and evaluation of comfort disturbances.
- Establish methods for testing different hypotheses.
- Determine the influence of different vibration and motion components (such as low frequency lateral accelerations, jerks and roll motions) for comfort disturbances.
- Establish possible criteria for the evaluation of comfort disturbances caused by low frequency motions.

Methods:

- Evaluate the low frequency motions and vibrations in high speed and conventional trains.
- Develop an evaluation technique for measuring comfort disturbances.
- Make experiments in a moving vehicle (car driving) simulator to rank different hypothesis of causes of comfort disturbances. (See proposed actions in simulator below).
- Evaluation of covariance between expressed discomfort by test persons and measured vibration and motion components.

Stage 3.
Aim:

- Check the validity of comfort criteria in high speed train environment

Methods:

- Test the most relevant hypothesis in a train with test persons for evaluation of possible criteria. (See proposed test in a train below).
- Evaluation of covariance between expressed discomfort by test persons and measured vibration and motion components.
- Evaluation of Griffin concept of motion dose for prediction of motion sickness.

Possible stage 4.
If this stage will be included, it will be influenced considerably by the results and experience of earlier stages. Possible activities are:

- Investigate how different parameters for track and vehicle influence the comfort disturbances.
- Suggest different actions to improve ride comfort and minimise the number of comfort disturbances and passenger dissatisfaction.

B.2.1 Proposed tests in simulator

The VTI driving simulator is a half car built upon a platform which can rotate in roll and move on rails to achieve horizontal acceleration. In a simulator, it is not possible to achieve a steady state horizontal acceleration (for example in a curve) except through simulating it by applying a roll angle. Therefore, it is feasible to simulate curves as a vibration at a low frequency (0.2 Hz) to provoke comfort disturbances.

It is proposed to test and rank the validity of different hypotheses for comfort disturbances (motion sickness). Are comfort disturbances strongly influenced by

- Low frequency lateral acceleration,
- Roll speed or
- A combination of both lateral acceleration and roll motion?

B.2.2 Proposed tests on a train

The results and the experience from the simulator will possibly be used to alter and redefine the tests proposed to be conducted on the train. Parameters that may easily be varied are speed through the curves and the tilt angle. Therefore, lateral acceleration and roll velocity can be varied to test the hypotheses that comfort disturbances are influenced by

- Low frequency lateral acceleration only (no compensation),
- Roll velocity only (full compensation),
- A combination of lateral acceleration and roll motion (partly compensation),
- Fixed roll angle with variable lateral acceleration or
- Low frequency vertical accelerations.

The proposed tests will test the validity of the results from the simulator and find a possible criterion.

Appendix C Motion sickness prediction models

C.1 Model by McCauley et al.

By the 1970 a number of experiments were performed by the American Navy (McCauley, Royal, & Wylie 1976, O'Hanlon & McCauley 1973), which was summed up to a mathematical model for prediction of motion sickness incidence (MSI) from the variables frequency and r.m.s.-values of vertical acceleration. According to McCauley et al roll or pitch motions did not significantly contribute to the prediction of MSI.

The complete model (McCauley et al. 1976) is based of standardised normal distribution function for two variables $\Phi(a,t)$ with harmonic vertical oscillation with r.m.s. amplitude a and a fixed frequency f over the time t.

$MSI = 100 \cdot \Phi(a,t)$

where

$$\Phi(a,t) = \frac{1}{2\pi\sigma_a\sigma_t\sqrt{1-\rho^2}} \int_{-\infty}^{\log_{10} a} \int_{-\infty}^{\log_{10} t} \exp\left\{ \frac{-1}{2(1-\rho^2)} \left[\left(\frac{x-\mu_a(f)}{\sigma_a} \right)^2 - 2\rho \left(\frac{x-\mu_a(f)}{\sigma_a} \right) \left(\frac{y-\mu_t}{\sigma_t} \right) + \left(\frac{y-\mu_t}{\sigma_t} \right)^2 \right] \right\} dydx$$

with the frequency function

$\mu_a(f) = k_1 + k_2 \log_{10} f + k_3 (\log_{10} f)^2$

This can be simplified according to McCauley & Kennedy (1976) to:

MSI = 100 P_A P_T

where P_A, the asymptotic proportion, is given by

$$P_A = \Phi\left[\frac{\log A - (k_1 + k_2(\log F - k_3)^2)}{k_4} \right]$$

and $\Phi(z) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{z} \exp(-x^2/2)dx$ (the standardised normal distribution function)

where A = acceleration (r.m.s. g) and F = frequency (Hz)

and P_T, the time dependent proportion, is given by

$$P_T = \Phi\left[\frac{\log T - (k_5 - k_6 P_A)}{k_7} \right]$$

where T = exposure time (min)

P_A = asymptotic proportion (defined above)

and the constants are as follows:

k_1 = -0.87; k_2 = 2.74; k_3 = -0.80; k_4 = -0.46; k_5 = 2.18; k_6 = 1.44 and k_7 = 0.51

This model is complicated where amplitude and frequency are interacting with time but if P_A is a constant (A and F constant) then

$MSI = k \cdot \Phi \cdot (\log T)$

C.2 Model by Lawther and Griffin

The motion dose model by Lawther and Griffin (1986) and Lawther (1988) is based on both observations from observations on ships and earlier data from Alexander, Cotzin, Klee, & Wendt (1947) and McCauley et al. (1976), see Figure C-1. They split the problem of prediction in two parts; first a weighting filter for vertical acceleration (w_f) and second a square-root time response, the motion dose.

$$VI(\%) = K_m \cdot \left[\int_0^T a_{wf}{}^2(t)dt \right]^{1/2} = K_m \cdot a_{wf,rms} \sqrt{T}$$

where K_m = 1/3 for a population of mixed adults of both genders and unadopted to motion sickness. a_{wf} is acceleration filtered with w_f.

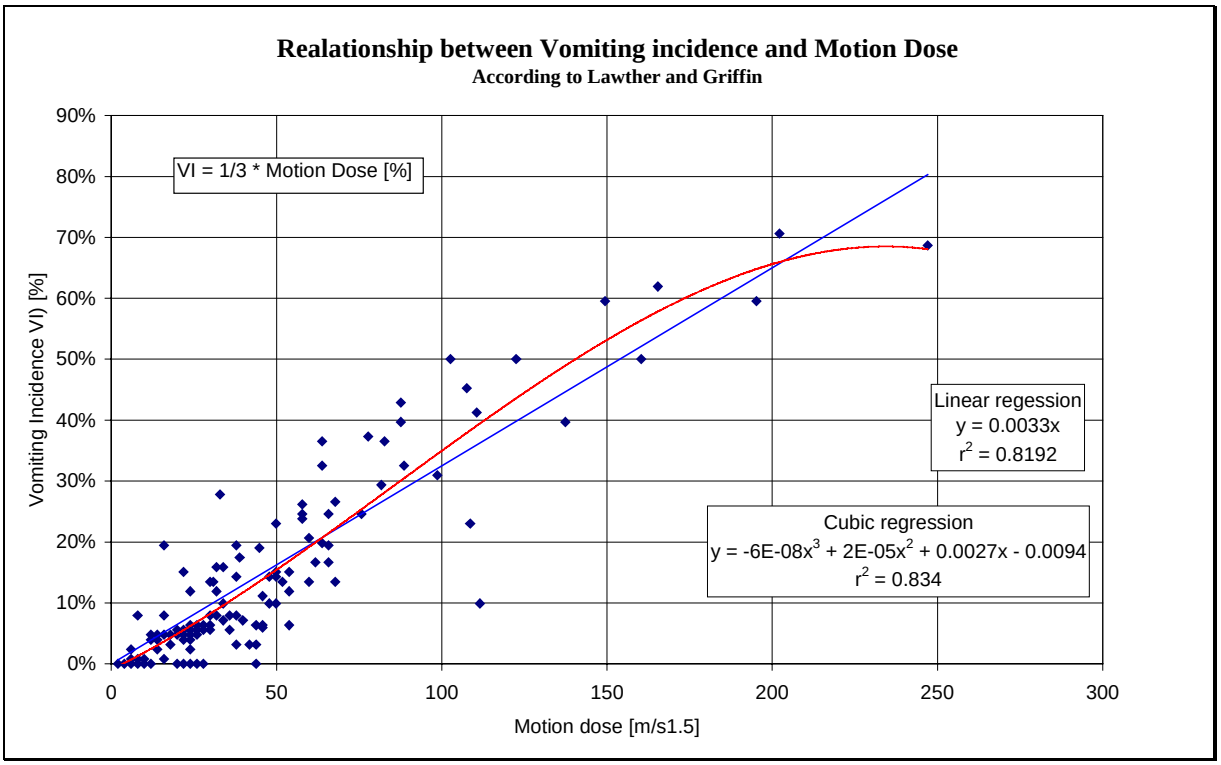

Figure C-1 Relation between the vertical motion dose and VI calculated from the laboratory experiments by Alexander et al (1947), McCauley et al (1976) and the sea trials by Lawther and Griffin (1986). Modified from Griffin (1990).

Differences between the two models in time development can be shown as in Figure C-2 according to (Lawther 1988, Lawther & Griffin 1987).

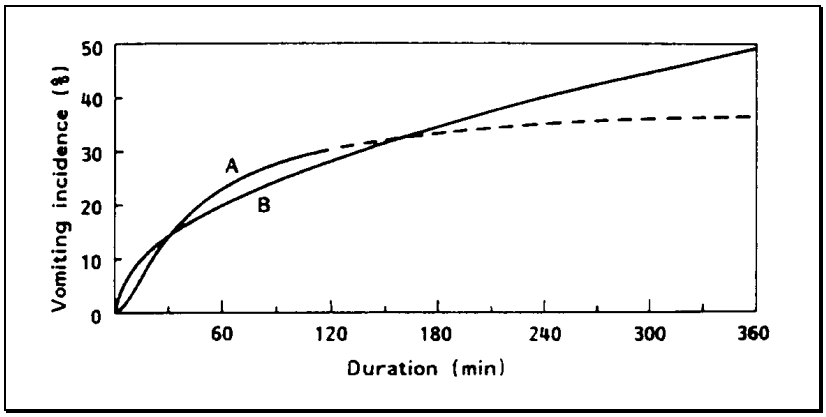

Figure C-2 MSI predictions for exposures of 1 m/s^2 r.m.s. at 0.2 Hz using the models of(A) McCauley et al (1976) and (B) Lawther and Griffin (1987).

C.3 Model by Oman

An heuristic mathematical model for the dynamics of the sensory conflict and evaluation of motion sickness has been presented in two papers by Oman (Oman 1982, Oman 1990) The model is partly based on the optimal estimator model from (Borah, Young, & Curry 1979, Borah, Young, & Curry 1989). Oman makes an analogue to an *observer* control of vehicle orientation, see Figure C-3. The vehicle has to be controlled despite noisy orientation sensors and exogenous forces. A state feedback, with an *observer* for estimating states which are not measured, is probably required for controlling the vehicle.

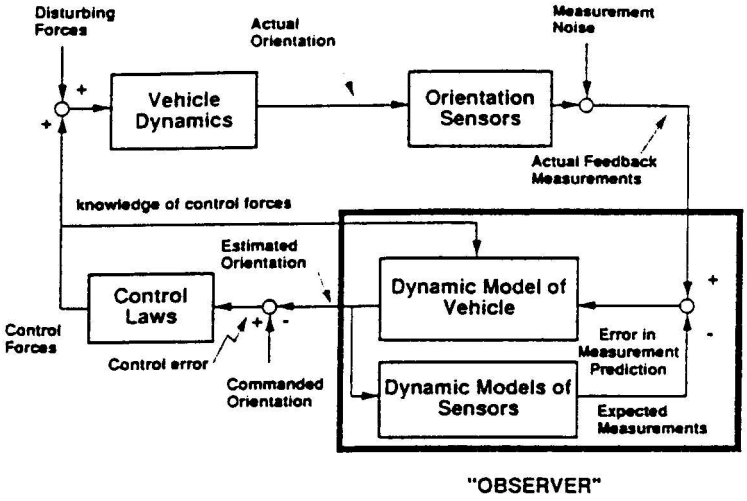

Figure C-3 Engineering use of an observer to control vehicle orientation. Solid arrows represent multi-dimensional vector quantities. From Oman (1990).

Figure C-4 shows a mathematical model for sensory conflict and movement control based on observer theory. The structure resembles and parallels the structure in Figure C-3.

The central neural system (CNS) must infer the body's orientation and control the body's movement using a limited set of noisy sensory signals. Incoming sensory inputs are compared with estimated signals and the difference is used for maintaining a correct spatial orientation estimate as shown in Figure C-4. The estimated orientation is used for controlling the body and its movements and is detected through the sensory organs and compared once again.

The *internal CNS dynamic models* are the differential equations describing the dynamics of body and sense organs. Based on knowledge of the muscle commands, the internal model equations are used to compute an *estimated orientation* state vector, which determines new muscle commands based on *control strategy* rules.

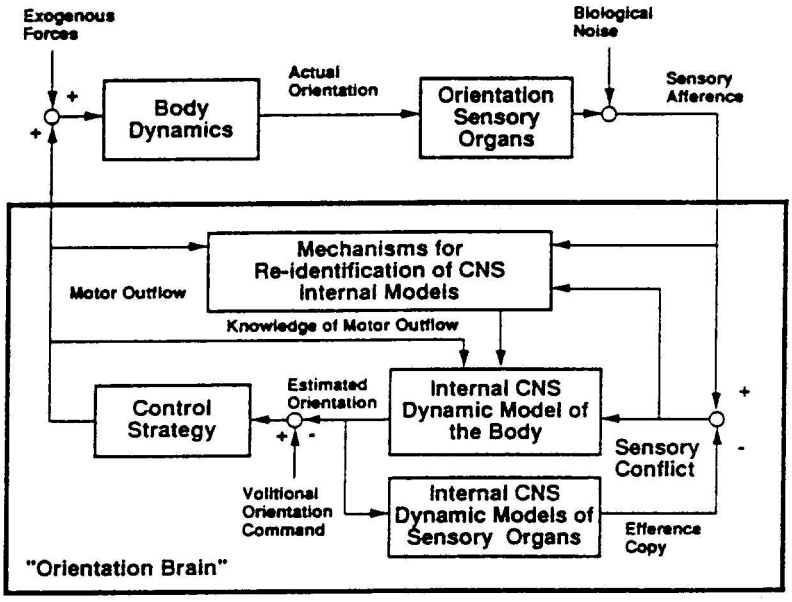

Figure C-4 A mathematical model for the sensory conflict and movement control based on observer theory from Oman (1982, 1990).

Simultaneously, the CNS model for the sense organs to compute the responses from the organs uses the estimated state. Normally, the expected signals almost cancel the input signals from the sensory organs, but when they do not, the difference (the sensory conflict vector) is used to steer the model prediction towards reality and indirectly to trigger corrective muscle commands. These functions represent a critical functional role in daily life. "*Clearly, we need not postulate that the sensory conflict signals exist just to make people sick*" (Oman 1990).

A model for estimation of the severity of motion sickness is found in Figure C-5. The sensory conflict signals from Figure C-4 are rectified, frequency weighted and added together. The resulting signal may be referred as the *neural mismatch signal* to correspond to Reason's model (Reason 1978).

The neural mismatch signals act through two parallel pathways with *fast* and *slow* dynamics. The signals from the two pathways are added together and after passing through a threshold and power law, an estimate of nausea magnitude is made. In this model, susceptibility to motion sickness is determined not only by the degree of sensory conflict produced but also by the gains of the fast and slow pathway, time constants and nausea threshold (Oman 1990).

The conclusion by Oman (1990) is that this model captures many of the known properties of motion sickness in at least a semi-quantitative fashion. However, the model has certain limitations. The model is linear and describes the CNS as an observer, but some of the sensory information is probably evaluated in a non-linear way. Also, the present model cannot predict the adaptation process.

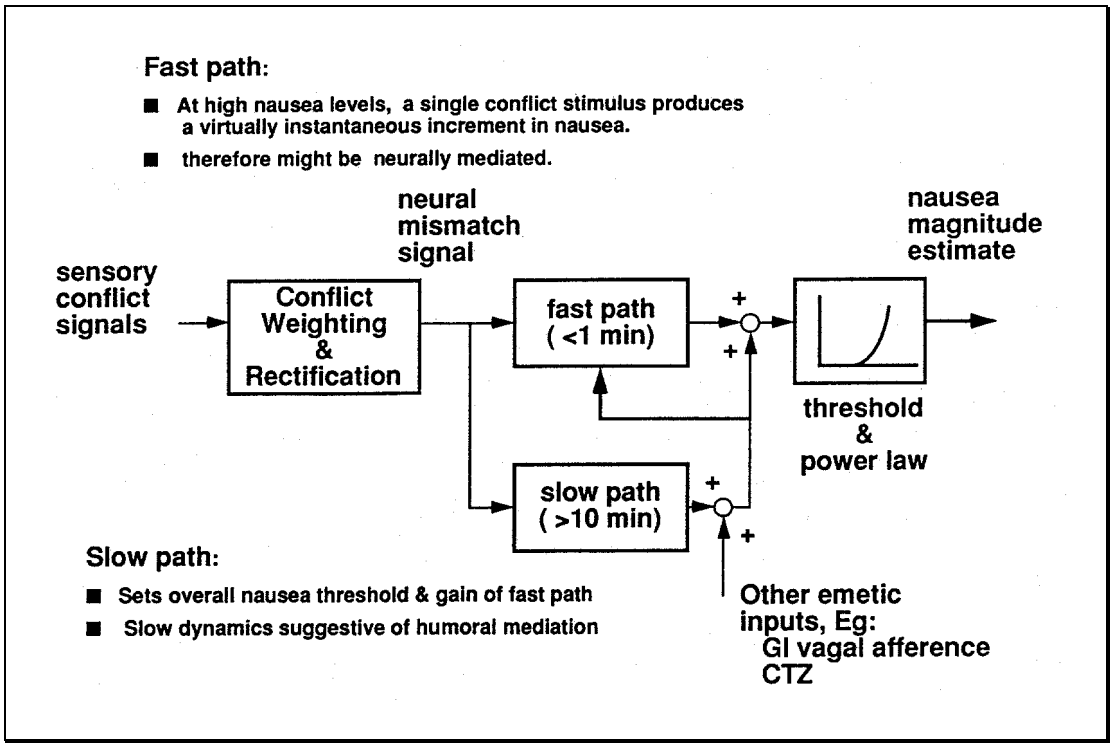

Figure C-5 Schematic figure of revised model for nausea path symptom dynamics. From Oman (1990). (CTZ = chemical trigger zone, GI = gastrointestinal).

Appendix D Ride comfort and comfort disturbances

D.1 Ride comfort

Average ride comfort has traditionally in Sweden been measured with the German W_Z (Wertungsziffer). There is also a close British version called Ride Index (RI). Internationally, the ISO standard 2631 has been introduced and adopted by some of the railway companies. The former ORE and now ERRI has done much research on comfort with weighting curves, measuring points and evaluation techniques (B153 and B207). This work has been the one of the preambles to the proposed CEN standard CEN preENV 12299. In this standard, the BRR work on comfort disturbances is integrated.

D.1.1 Ride comfort indexes

Wz

Ride comfort index and vehicle ride index by Helberg & Sperling (1941) and Sperling & Betzhold (1956).

Wz Ride Comfort		Wz Vehicle ride	
1	just noticeable	1	very good
2	clearly noticeable	2	good
2.5	more pronounced but not unpleasant	3	satisfactory
3	strong, irregular, but still tolerable	4	acceptable for running
3.25	very irregular	4.5	not acceptable for running
3.5	extremely irregular, unpleasant, annoying; prolonged exposure intolerable	5	dangerous
4	extreme unpleasant; prolonged exposure harmful		

Sources: Oborne(1976) and Esveld (1989)

Wz

Wz was originally defined as $Wz = 2.7 \cdot (a^3 f^3 F(f))^{0.1}$ (Helberg & Sperling (1941) or later expressed as (Sperling & Betzhold (1956)

$$Wz = \left[\frac{1}{T} \int_0^T (B(f) \cdot a(t))^2 dt \right]^{0.15}$$

where $F(f)$ and $B(f)$ are empirical frequency weighting functions for discrete frequencies (sinusoidal accelerations). Accelerations a and $a(t)$ are peak amplitudes measured on the floor [cm/s^2]. The formulas below shows the frequency weightings for vertical $B_V(f)$ and lateral $B_L(f)$. The weighting curves are shown in Figure D-4.

Weighting functions for Wz ($B(f)$):

Vertical comfort

$$B_V(f) = 0.588 \cdot \left[\frac{1.911 \cdot f^2 + (0.25 \cdot f^2)^2}{(1 - 0.2777 \cdot f^2)^2 + (1.563 \cdot f - 0.0368 \cdot f^3)^2} \right]^{0.5}$$

Lateral comfort $B_L(f) = 1.25\ B_V(f)$

Source: Esveld (1989).

Calculation of Wz from time histories:

$$Wz = \left[\frac{(100\sqrt{2})^2}{T} \int_0^T a_B^2(t)dt \right]^{0.15} = 4.42 \cdot (a_{rms,B})^{0.3}$$

where a_B is acceleration weighted with the appropriate B(f) filter [m/s^2]. $a_{rms,B}$ is the corresponding weighted acceleration r.m.s. –value over the time period T.

Ride Index (*RI*)

Ride index	Ride comfort
1	very good
1.5	almost very good
2	good
2.5	almost good
3	satisfactory
3.5	just satisfactory
4	tolerable
4.5	intolerable
5	dangerous

Definitions

Vertical Ride index

$RI_Z = 7.5\ (a_{rms})^{0.3}\ (f_c / 5.9)^{1/3}$ $\quad f_c \leq 5.9$ Hz

$RI_Z = 7.5\ (a_{rms})^{0.3}\ (5.9/f_c)$ $\quad f_c > 5.9$ Hz

Lateral Ride index

$RI_Y = 8.1\ (a_{rms})^{0.3}\ (f_c / 5.9)^{1/3}$ $\quad f_c \leq 5.9$ Hz

$RI_Y = 8.1\ (a_{rms})^{0.3}\ (5.9/f_c)$ $\quad f_c > 5.9$ Hz

Where a_{rms} is the octave-band r.m.s. acceleration in g and f_c is the octave-band centre frequency.

Source: Garg & Dukkipati (1984). Notify the close resemblance with the Sperling's Wz. Comparison with weighting curves Ride index – Wz in Figure D-4.

ISO standard 2631-1

Guidance

Less than 0.0315 m/s^2	not uncomfortable
0.0315 to 0.63 m/s^2	a little uncomfortable
0.5 to 1 m/s^2	fairly uncomfortable
0.8 to 1.6 m/s^2	uncomfortable
1.25 to 2.5 m/s^2	very uncomfortable
Greater than 2 m/s^2	extremely uncomfortable

(ISO 1997)

Definitions:

The standard used r.m.s. –values of frequency-weighted accelerations. Used weighting curves are w_d for horizontal (lateral and longitudinal) accelerations and w_k or w_b for vertical accelerations. For railway applications the weighting curve w_b is considered appropriate for vertical acceleration. The weighting curves are displayed in Figure D-3.

$$\text{Comfort value}_{ISO} = \left[\frac{1}{T}\int_0^T (a_{wi}(t))^2 dt\right]^{0.5} \quad [\text{m/s}^2]$$

there a_{wi} is frequency-weighted acceleration with w_i ; i = k, b, d. Measuring points are located on the floor of the vehicle, seat and backrest.

CEN ENV 12299:1999 Ride comfort according to CEN prestandard. This is a statistical method taking in account the distribution of sampled running r.m.s.-values of weighted accelerations (CEN 1996a, CEN 1999).

Guidance:

$N < 1$	Very comfortable
$1 \leq N < 2$	Comfortable
$2 \leq N < 4$	Medium
$4 \leq N < 5$	Uncomfortable
$5 \leq N$	Very uncomfortable

Definitions

Simplified method

$$N_{MV} = 6 \cdot \sqrt{(a_{XP95}^{W_d})^2 + (a_{YP95}^{W_d})^2 + (a_{ZP95}^{W_b})^2}$$

Seated passengers

$$N_{VA} = 4 \cdot (a_{ZP95}^{W_b}) + 2 \cdot \sqrt{(a_{YA95}^{W_d})^2 + (a_{ZA95}^{W_b})^2} + 4 \cdot (a_{XD95}^{W_c})$$

Standing passengers

$$N_{VD} = 3 \cdot \sqrt{16 \cdot (a_{XP50}^{W_d})^2 + (a_{YP50}^{W_d})^2 + (a_{ZP50}^{W_b})^2} + 5 \cdot (a_{YP95}^{W_d})$$

where

a = measured accelerations (x-, y- or z- direction) [m/s^2]

Superscript W_i for weighting filter

i = b, vertical (z)

i = d, horizontal (x, y)

i = c, horizontal (x), seat backrest

Subscript

$X, Y, Z,$	direction of accelerometer sensitivity (x, y or z)
P	mounted on the floor
A	mounted on seat interface (y and z – directions) with a *seat pan*. Subjects has to
D	mounted on backrest interface (x-direction)
$50, 95$	50 or 95% percentile of the distribution of weighted r.m..s.-values sampled each sequential 5 s during a 5 min test

D.2 Comfort disturbances caused by low-frequency motions.

British Rail Research (BRR) carried out during the 1980:ies a great number of tests with both non-tilting train HST (High Speed Train) and with a tilting train APT (Advanced Passenger Train) (Harborough 1986a, Harborough 1986b). See chapter D4 for a short summation of the experiment. The test subjects were equipped with push-buttons and marked whenever they thought the comfort was not good. Below definition are from CEN (1996a).

P_{CT} Comfort index on Curve Transition,

$$P_{CT} = \text{Max}(A \cdot \ddot{y} + B \cdot \dddot{y} - C; 0) + D \cdot \dot{\varphi} \quad [\%]$$

where

$\ddot{y}$ = maximal absolute lateral acceleration in car body from the transition curve entry to its end + 1,6 s, [% g]

$\dddot{y}$ = maximal absolute lateral jerk on the transitions curve, calculated as max ($\ddot{y}(t+1)$-$\ddot{y}(t)$) (signal low pass filtered with 2 Hz), [% g/s]

$\dot{\varphi}$ = maximal absolute roll velocity on transition curve [° /s]

See Figure D-1 for explanation of the different quantities.

A, B, C, D, E are constants defined as

	A	B	C	D	E
Standing	2.80	2.03	11.1	0.185	2.283
Seated	0.88	0.95	5.9	0.120	1.626

P_{DE} Comfort index on Discrete Events.

$$P_{DE} = a \cdot \ddot{y}_p + b \cdot \ddot{y}_m - c \quad [\%]$$

where

$\ddot{y}_m$ = Absolute value of mean value of lateral acceleration, measured in a time window of 2 s and low pass filtered with 2 Hz. [% g]

$\ddot{y}_p$ = peak to peak value of lateral acceleration under the same time window as above and low pass filter with 2 Hz. [% g]

See Figure D-2 for explanation of different quantities.

a, b, c are constants defined in as

	a	b	c
Standing	1.63	2.65	37.0
Seated	0.83	1.28	21.7

The low pass filter for 2 Hz corresponds to the lateral weighting filter (w_d) but with the difference that it has a flat response from 0 to 1 Hz where after it follows the w_d weighting curve.

D Definition of acceleration quantities

Definition of maximal absolute of lateral acceleration ($\ddot{y}$) and maximal absolute jerk ($\dddot{y}$) in the formula for P_{CT}:

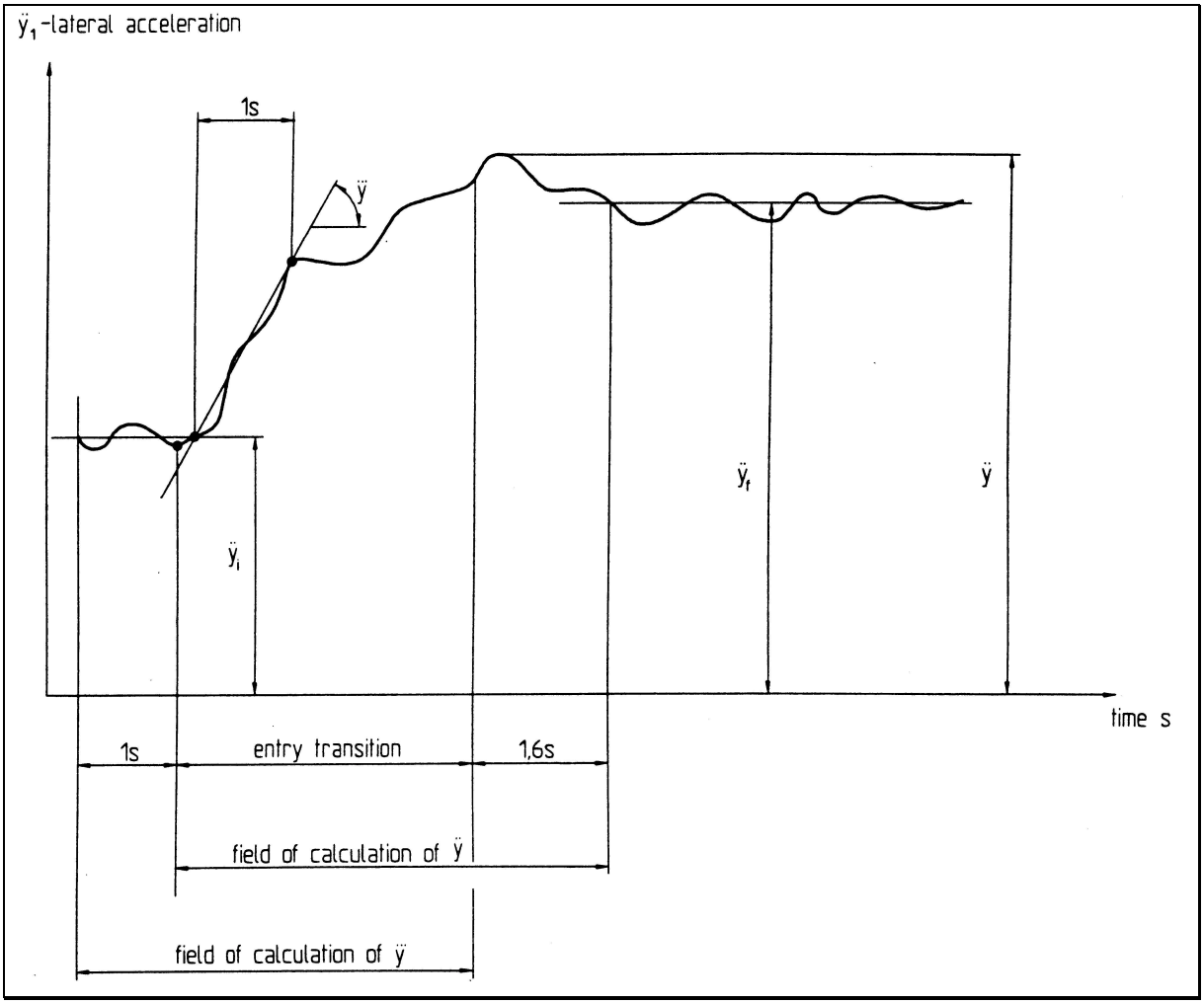

Figure D-1 Determination of the quantities $\ddot{y}$ and $\dddot{y}$ for the calculation of P_{CT} (CEN 1996a).

Definition of peak to peak value ($\ddot{y}_p$) and absolute value of mean value ($\ddot{y}_m$) of lateral acceleration $\ddot{y}(t)$ in the formula for P_{DE}.

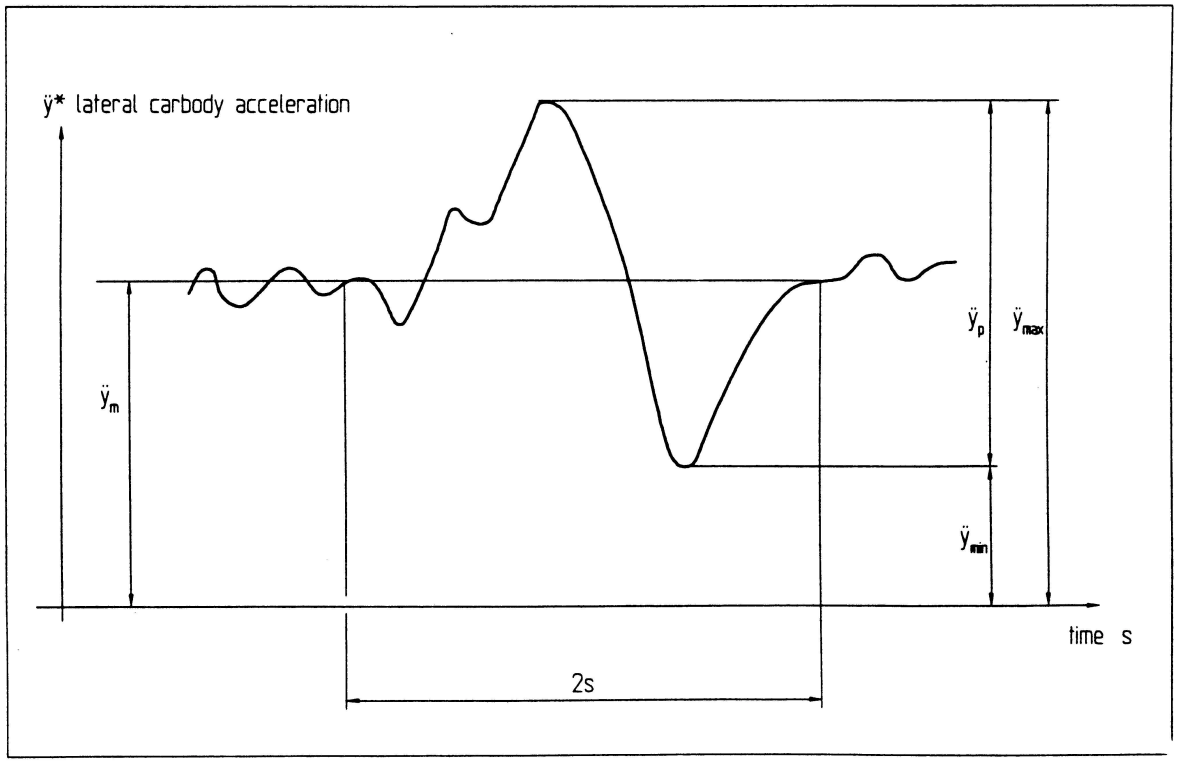

Figure D-2 Determination of the quantities $\ddot{y}_p$ and $\ddot{y}_m$ for calculation of P_{DE} (CEN 1996a).

D.3 Weighting curves

Weighting curves defined according to ISO 2631-1 and BS 6841, see Figure D-3

w_b Weighting curve for vertical accelerations for comfort and health according to BS 6841:1987 (BSI 1987). w_b is used for comfort evaluation according to the CEN standard (CEN 1996b). w_b is not the primary weighting curve for vertical acceleration according to ISO 2631-1 but is acceptable for railway applications (ISO 1997).

w_d Weighting curve for lateral and longitudinal accelerations for comfort and health according to ISO 2631-1 (ISO 1997).

w_k Weighting curve for vertical accelerations for comfort and health according to ISO 2631-1(ISO 1997).

w_f Weighting curve for vertical accelerations for evaluation of motion sickness according to ISO 2631-1 (ISO 1997).

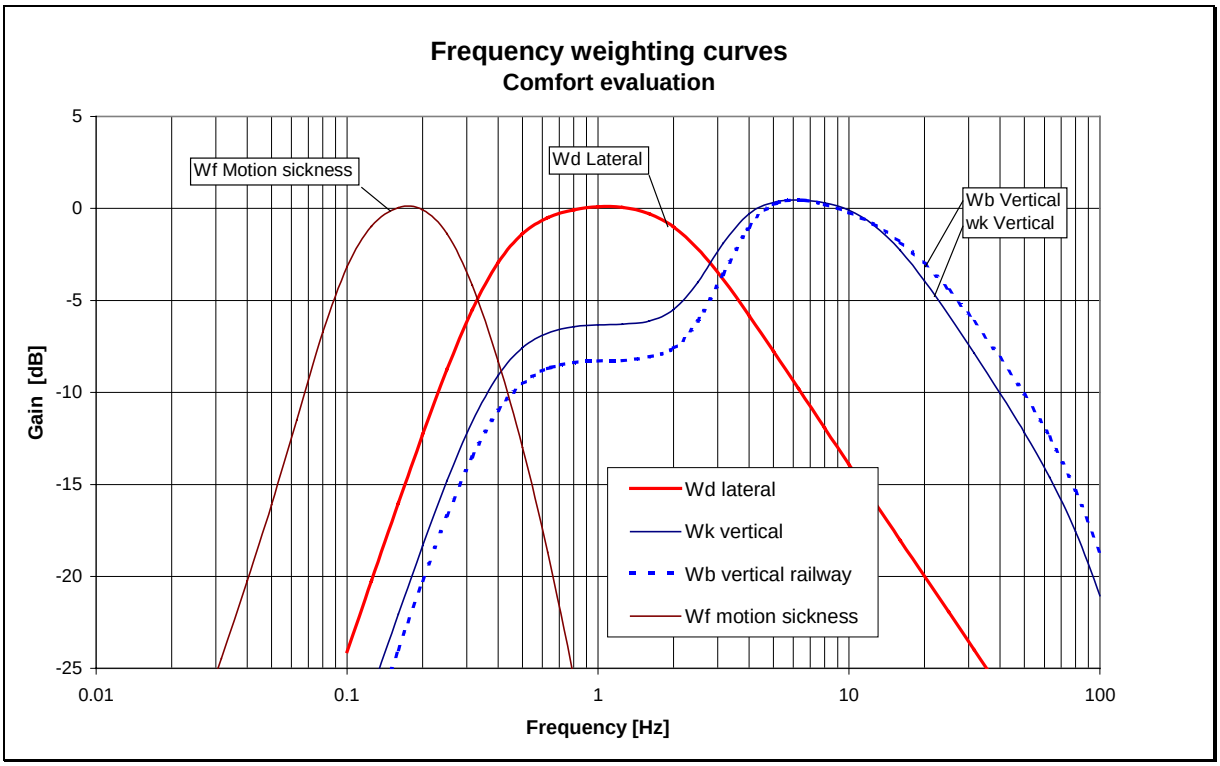

Figure D-3 Weighting curves w_k, w_d, w_f (ISO 2631-1 1997) and w_b (BS 6841:1987 1987).

Weighting curves for Wz and Ride index are shown in Figure D-4.

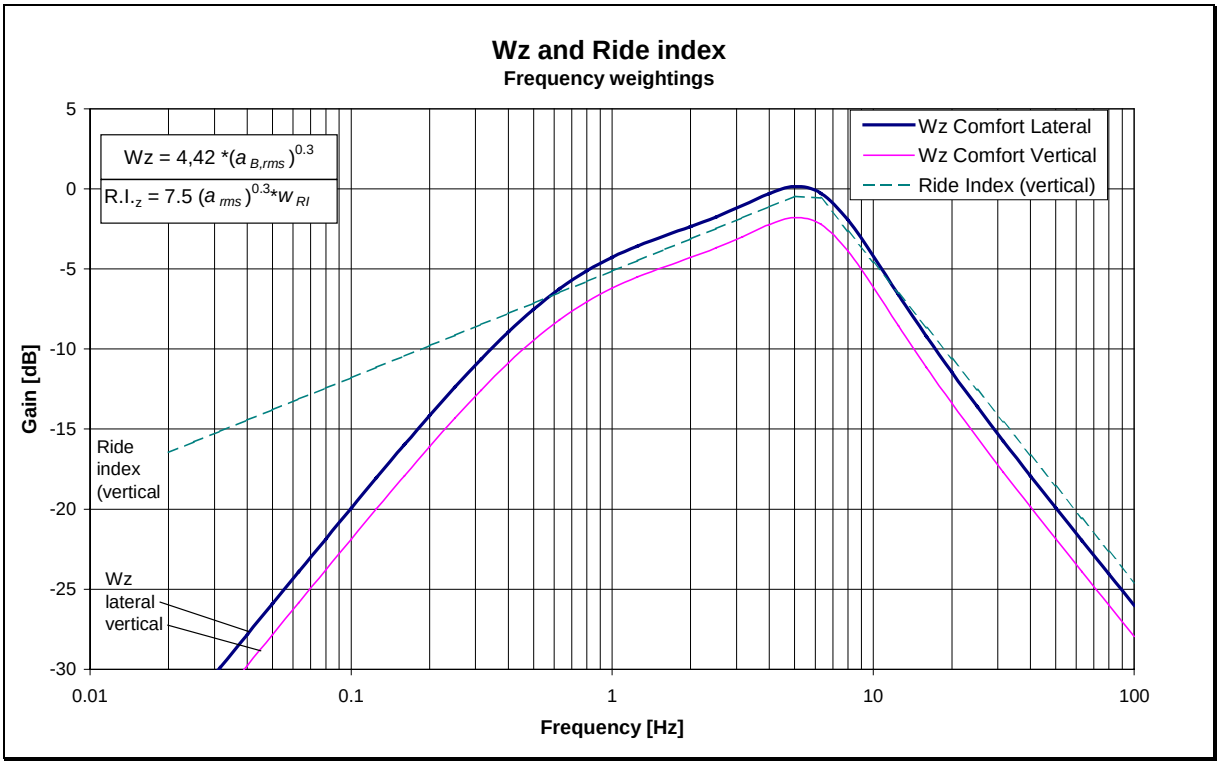

Figure D-4 Weighting curves for Wz and Ride Index (Esveld 1989, Garg & Dukkipati 1984, Sperling & Betzhold 1956).

D.4 Background experiments

D.4.1 Test with comfort disturbances with *SJ* experimental tilting train *X15*, 1979

A test concerning comfort disturbances was conducted in 1979 with the experimental tilting train *X15* for the following purposes (Andersson & Nilstam 1984, Förstberg 1994a):

- Evaluate ride comfort at high speed and high uncompensated lateral acceleration
- Evaluate and try to determine limit values for mean lateral acceleration, rate of change of lateral acceleration (jerk) and roll angle velocity, valid for certain levels of comfort disturbances
- Determine the risk of motion sickness
- Provide basic knowledge about comfort disturbances and information for possible future tests.

Two groups of 10 test persons from SJ were engaged in the tests. Twenty-two test runs were done on the Järna - Nyköping line with test persons seated or standing. Five test runs were carried out between Gävle and Sundsvall with the test persons alternating between, seated, seated reading, standing and walking.

The test persons were instructed: *To press the button once on every occasion you register shakings and jerks etc., as according to your comfort standard is at the limit of a good train ride. Press twice if you register extra strong disturbances.*

Recommendations (results)

	Limit values	
▪ Mean lateral acceleration (over 1 s)	0.9 - 1.0	[m/s^2]
▪ Lateral jerk (low pass filtered 0.3 Hz)	0.4	[m/s^3]
▪ Compensation in tilt system	65 - 70	[%]

- Long-wave irregularities in horizontal alignment should be minimised.

Limit values were determined with special attention to standing and walking passengers.

D.4.2 BRR test, 1983 – 1984

In the years 1983 and 1984 the British Railway Research (BRR) in Derby conducted several series of tests measuring passenger dissatisfaction (comfort disturbances) with the push button technique. Their instructions to the test persons were: *To press a button whenever you consider the lateral ride uncomfortable or very uncomfortable.* These tests are documented in *British Rail Research BRR TR DOS 017* and *DOS 018* (Chappel 1986, Harborough 1986a, Harborough 1986b).

In their analysis they distinguish between comfort disturbances from
- a sudden movement on a circular curve or on tangent track (discrete event) and
- from high rate of change of lateral acceleration (jerk) on a transition curve.

The passengers' dissatisfaction for *discrete event* (P_{DE}) are characterised by the peak-to-peak value of lateral acceleration ($\ddot{y}_p$) and the mean accelerations ($\ddot{y}_m$).

The passengers' dissatisfaction for a *transition curve* (P_{CT}) is characterised by the maximum acceleration ($\ddot{y}$) within or shortly after the transition curve end, the maximum lateral jerk ($\dddot{y}$) evaluated over a second and the maximum roll angle speed ($\dot{\phi}$).

One successful application of the British P_{CT} formula is given in Wichser &. Boesch (1982).

Appendix E Questionnaires for tilting train experiments

Examples of instructions and questionnaires that been used in the train tests, are shown below. However, all instructions and questionnaires were given in Swedish.

Questionnaire A Test subject #: . . . .
Test of Comfort

The aim of this test is to compare different conditions of comfort and obtaining suggestions to improve train ride comfort. It is important that you answer the questions from your own experience. Your answers will be treated as confidential. Answer by ticking one of the boxes or writing your answer on the dotted line.

Questions of background

1. *Are you* a Man ☐ or a Woman ☐? 2. *Age* . . . . 3. *Length* . . . . .
4. *Do you feel rested?* . . . . . .

5. *How many times have you used the following means of transport during the last year?*

	X2000	Ordinary train	Aeroplane
Never	☐	☐	☐
1-2 times	☐	☐	☐
3-6 times	☐	☐	☐
7-12 times	☐	☐	☐
more than 12 times	☐	☐	☐

6. *How many times have you felt motion sickness in the following means of transport during the last five years*

	Never	Sometimes	Several times
Car	☐	☐	☐
Coach	☐	☐	☐
Ship	☐	☐	☐
Aeroplane	☐	☐	☐
Ordinary train	☐	☐	☐
X2000	☐	☐	☐

7. *How do you feel just now in general?*

I feel all right	☐	yawnings	☐
I do not feel quite well	☐	headache	☐
I feel rather unwell	☐	drowsiness	☐
I feel bad	☐		
I feel very bad	☐		

8. *What is your own rating of your sensitivity to motion sickness?*
Try to grade your sensitivity in a scale from 1 to 7. 1 means that you are totally insensitive and 7 means that your are very sensitive

None						Very high
1	2	3	4	5	6	7

9. *Have you taken anything that can disturb your sensitivity to motions?*
(such as medicine etc.) : ☐ Yes
☐ No
If yes, what . . . . . .

10. *Complementary information.*
. . . . . .

Have you answered all the questions? Thanks in advance!

Questionnaire B Test subject #: . . . .

Questions to be answered after each test part

21. *Test stretch:* *Test number:* *Time:* . . . . . . *Car number* : . . . . . . 22. *Seat number?* . . . . . 23. *Window?:* ☐Yes ☐No 24. *Are you sitting forwards* ☐Yes ☐No	25. *Occupation. What have you spent most time doing on this journey?* Working ☐ Reading ☐ Looking out ☐ Talking ☐ Other, specify ☐ . . . . .
26 *How do you categorise the ride comfort during this test trip?* Very good ☐ Good ☐ Either good nor bad ☐ Bad ☐ Very bad ☐	27. *What is your opinion on your ability to work and read in the train:* very good ☐ good ☐ neither good nor poor ☐ poor ☐ very poor ☐
28. *If you think there are complaints about the ride comfort, what do you think is the cause* Shaking and jolts in lateral ☐ Shaking and jolts in vertical ☐ Large centrifugal forces in curves ☐ Jerky tilting motion ☐ Something else, specify ☐ . . . . . . No complaints ☐	29. *Have you felt anything of he following during this test trip?* Yawnings/Light sleepiness ☐ Headache ☐ Felt hot /cold sweating / pallor ☐ Increased salivation ☐ Drowsiness / tiredness ☐ Dizziness ☐ Feel sick ☐ Other (Specify) ☐ . . . . .
30. *How do you feel just now?* I feel all right ☐ I do not feel quite well ☐ I feel rather unwell ☐ I feel bad ☐ I feel very bad ☐	31. *If you were able to improve comfort in this train, what would you do?* Improve the seats ☐ Improve the light ☐ Lower the noise ☐ Lower the vibrations ☐ Improve the quality of the air ☐ Something else (see question no. 33) ☐ . . . . .

32. What is your opinion on reading or working on the train?

. . . . . .

. . . . . .

33. Do you have any suggestions on improvement of the comfort? Space is also available on the back of this paper. Do you have any other comments?

. . . . . .

. . . . . .

Thank you!

Appendix F Instructions and questionnaires (Simulator)

Examples of instructions and questionnaires that been used in the simulator tests, are shown below. However, all instructions and questionnaires were given in Swedish.

Instruction to test subjects

The objective with the test is to investigate comfort and discomfort (nausea) from typical motions in trains. You are going to ride in a special cabin with two seats, where you can read and work and also answer some questions each 5 minutes. The motions are combinations of motions side-ways and roll.

Occupation: You should read when you are not working on the questionnaires.

Questionnaire: The different pages in the questionnaire are filled out on request from the test leader. Answer as careful as possible. Marking of the letter *p* is done along the rows and you shall try to mark as many as possible during 1 min. Put a mark on the row where you were when the time is out.

You are going to estimate your possible nausea on the scale below; with light symptoms means tiredness, headache, pallor, sweating or light dizziness.

No symptoms
Light symptoms but no nausea
Light nausea
Moderate nausea
Strong nausea

Strong nausea: If you experience strong nausea, please let the test leader know that, so we can stop the motion and let you out. It is not our intention that you are going to feel so bad that you might vomit.

Emergency stop: Please, do not use it unnecessary. Tell the test leader, and he/she will stop the motion and you can get out, if you want. Stay in the seat until the test leader has opened the door. Only then you can leave the cabin.

Important:
When the test is over, please be seated until the test leader comes and opens the door. Remember to walk backwards down the steps and hold on with both hands.

You are taking part on your own will and will get paid. If you don't want to go on with the test or the test series, please let the test leader know, so we can get a substitute.

Examples from a questionnaire

Test in the simulator

The objective of this test is that we want a comparison between typical motions in a tilting trains. You are going to answer a number of questions and it is important that you answer according to your own standpoints. Your answers are naturally confidential. Answer with a tick in the appropriate answer box or write your answer on the marked line.

Name: . . . . . .

Date:

1. *Are you*
Man ☐ or
Woman ☐?

2. *Born year*: . . . . . .

Background information

3. *Do you feel rested?* ☐ Yes ☐No

4. *What and when did you last eat?*

	Big meal	Only a sandwich	Nothing
0-2 hours before test start	☐	☐	☐
more than 2 hours ago	☐	☐	☐

5. *How often have you travelled with the following transport modes during the last year?*

	X2000	Normal train	Aeroplane
0 times, (never)	☐	☐	☐
1-2 times	☐	☐	☐
3-6 times	☐	☐	☐
7-12 times	☐	☐	☐
more than 12 times	☐	☐	☐

6. *How often have you felt motion sickness in the following transport modes during the last five years?*

	No times	Some times	A number of times
Car	☐	☐	☐
Bus	☐	☐	☐
Ship	☐	☐	☐
Aeroplane	☐	☐	☐
Normal train	☐	☐	☐
X2000	☐	☐	☐

8. *How do you feel just now in general*
I feel fine ☐
I do not feel fine ☐ because of what: . . . . . .

9. *What is your own estimation of your sensitivity to motion sickness?*
Try to estimate your sensitivity on a scale from 1 to 7, where 1 means you are totally insensitive and 7 that your sensitivity is very high. Mark your sensitivity on the scale below:

None						Very high
1	2	3	4	5	6	7

10. *Have you taken anything that might influence your normal sensitivity to motions (like medicine, nausea pills etc.)*?
☐ Yes, if yes, what . . . . . .
☐ No

11. Do you consider yourself having a normal vestibular system?
☐ Yes,
☐ No, if no, what . . . . . .

12. *Other comments or information.*
. . . . . .

Have you answered all questions? Thanks in advance!

Mark every p that you find in a minute's time! **Pre-test, 0, 10, 20, 30, 40 min**
Please look along the rows.

y h q p w o z z n y s u d s e d y s r y m i b z p z u w f v d f n t y c n n a l
j x t i a m o w n n p g q l b a r r n d x h l f b d u y h y l t d t g x k p g u
f y z t u t k f s x k u a k z y r o b l d f a p c o d h d g l v c p b q r c l b
e s b a q j m a e i u l d c z g o t a f p c q b x q l w d u y a k z e p o z h b
x j r z o c b r z r u j m c e k f z y r g i f z k e y o t s n w w q p p j t g k
i u g x n u j j p u l u n z e w w r h f p i x m k l r z y l b s l s q b j j a c
h b i f b j c f u p j f o t g l r z n j l v b t z v l i i n x k r p u q l g i j
t o x n x n t c w g p k t w f n m c v f t k o d b z q d n f j m n s q b p l h g
s r e a w z t h y o u p l z h g u z h t c p r y o l a h t q b w y g l e g s u g
l t t g w r p u b j y o a p g j g b z u l k b d t i a i t t o l h l d c d m g t
a e i l s l o k e y k g p w v o y e s q o c w x o e b z k y s e i a i s b u n b
n s q i z a v w z m o v z l z u t h z l s x w p v w x o s d z w p t i w f u v h
z o x e i g e z t l f l m a p u h x k s t h x r r f n k j l w t t f w s s p u x
g g y f u c n c q s z b o k n n m z o a s p h z u w s p h i y d m a s e d r d h
y l b j m z x r z h l w b x k m n r q u o d b t q x e x t m f p t t p i i q n g
i q k h v c f z d l h h k w p w o a t f r z n v o w w q l m i a c p f c g j f a
r h p c n m f k b j s m w l l r i g f p y c q l i y q f c t x a k o j x m b e c
k h s e l i x b p l l l w v j s w r u q j z b r p i f z v f l s y s x s u e m m
g w b a p m t i i h x v j e v f y j s g j g g b s r f k q c d m y e f q u j p g
x l p x n x s r f s w i f c b a s a v c p h s i a a n f t o e b h z k g y m f f
x t v m x h p h w h f d n o x p b i n j q u i e y h v j i m s d r t w o x a e n
b t g d o e d w h e z b a t t q g p x i r g g w q n n k y c q b x z t o w p e e
h c x y v o g b y m d y b t u b v y e f r x a h x h h n t g f n j v t p k t u q
l v z k l z i r j r t q p w l h k z t g r k t l p a r z m g e l j q m c u g g j
d z n i u s z j c z v w k u h k s g n k m m j v v f k h x y g p p q v i d y j t
n n y c l o z e d w w v j c k i p i t a n f s f e j d v p g v t i b q r x o o y
o z c n j l x u j m s p l c z y r f c y j w m i c p t d n m m s e u k r x y f k
x n i o w y o y t b c q m q w c n m f f e c k n l h q l z l y p s v a p c a v l
u t k j t m s n u k z o p a k d d w v c i c d m h p j y l w v c j c k f b h y u
a n z f y m a v w g d x h z i p r q p q h u o e c z n i q g q t j j d d v n z k
r p k l h a b h t t r c x q k n t n n z q i t f r y a j g f e p g r w b o h e i
s d v u j e m u d n s l p o p s u f s k h h h m k y m i b a b b r n h t a d u n
d z b g x p c k x t l q y q m h y v t h q v h h v d t z q o m s g p u h u c f j
y t r y k v z d r v x m p g e l v i u h p j v q s e h t w t q w h c k j h z k n
x y g l i y d t s o m p j g c p r a v f b e k y t u l z v o s m u j s f t u t r
h g j y o a p u u r u f b p o o u m g s q g i q c i h d h u w v h q r v o f f j
y m z u m g a a r g w k b v p m i r a e w d r d i i z p v s i s w h z t d k s a
s x t l d n g y a d p k k k h l f v r m s s u k f r d t w e t w d t q b k t j p
d p w s s n t s x y w k d f l p o b u n k i l r d l c l j l t j w d o s f z k v
b z p d z h x n f f k j c t j p d i z e e x h n f m k k j a u o e x k n c g v x
i j k p l x k m g d d n j j l x e h o z g h q s p z y d d w b t m z x n a a r u
f o p z j v j c c a u y j e f u r y f v b z h t o f o u k x e k p o u o b v d m
d y b l h p e i v v e i r j i b s x v y a n l z i w v k p v t y o t g g s o m t
g p w i e t z p h o g a k m i w n e x m w j k l e c w x y h x t c u v q e o g z
a u l o r w s m c t g p v q i g j k z o e g j s k f o e b i c l p q j d u q i b
s u n i j m g j u u l u s h s c s z l u u y s i q y l h p d g p v t g m u w n z
o h b w v h h f l p y k c u o a q c l d o c p d a q c t j r a q v v o f c o h n
s k r p k y m h r w i f j g c p n b d y l q j b n g u u d n v t g g h c d j z d
u e o s v u l q b x n p t l y v z a v a b v z p x o s u o h d k u g n s g a g i
n z d k e s n p k k w o t n r d w f f r g x w d k y c t m c h f c y t x m p l j

Test leader's notes
Number of rows:
Number of p's:

Answer as accurately as possible! **16, 31 min**

If this was a train, how would you have classified the ride comfort?

- Very good ☐
- Good ☐
- Neither good nor bad ☐
- Bad ☐
- Very bad ☐

If you think there were any comfort disturbances, what do you think they were caused by?

- Shakings and jolts in lateral (side-ways) ☐
- Shakings and jolts in vertical ☐
- Large acceleration in side-ways ☐
- Uneven tilting motions ☐
- Something else, specify ☐

. . . . . .

How would you regard the ability to work / read on the train?

- Very good ☐
- Good ☐
- Neither good nor bad ☐
- Bad ☐
- Very bad ☐
- Do not know ☐

Comments: . . . . . .

Regarding nausea, I have just now **1, 6, 11, 16, 21, 26, 31 min**

- No symptoms ❑
- Light symptoms but no nausea ❑
- Light nausea ❑
- Moderate nausea ❑
- Strong nausea ❑

Other observations that can be of use (yawnings, tiredness, headache, pallor, cold sweating, salivation, drowsiness, dizziness, not able to read etc.): . . . . . .

How do you feel just now (physically)? **1, 6, 11, 16, 21, 26, 31 min**

- I feel fine ☐
- I do not feel quite well ☐
- I feel rather bad (miserable) ☐
- I feel bad (miserable) ☐

Test procedure

Questions about estimation of nausea and illness were given each 5 minutes from 1 min up to 41 min after test start. The p-deletion tests were undertaken each 10 minutes, from 0 to 40 min from test start plus a pre-test sample. Comfort and discomfort were judged at 16 and 31 min after test start and the ability to work/read was judged at 31 min at the end of the test ride.

Appendix G Seat layout of test train

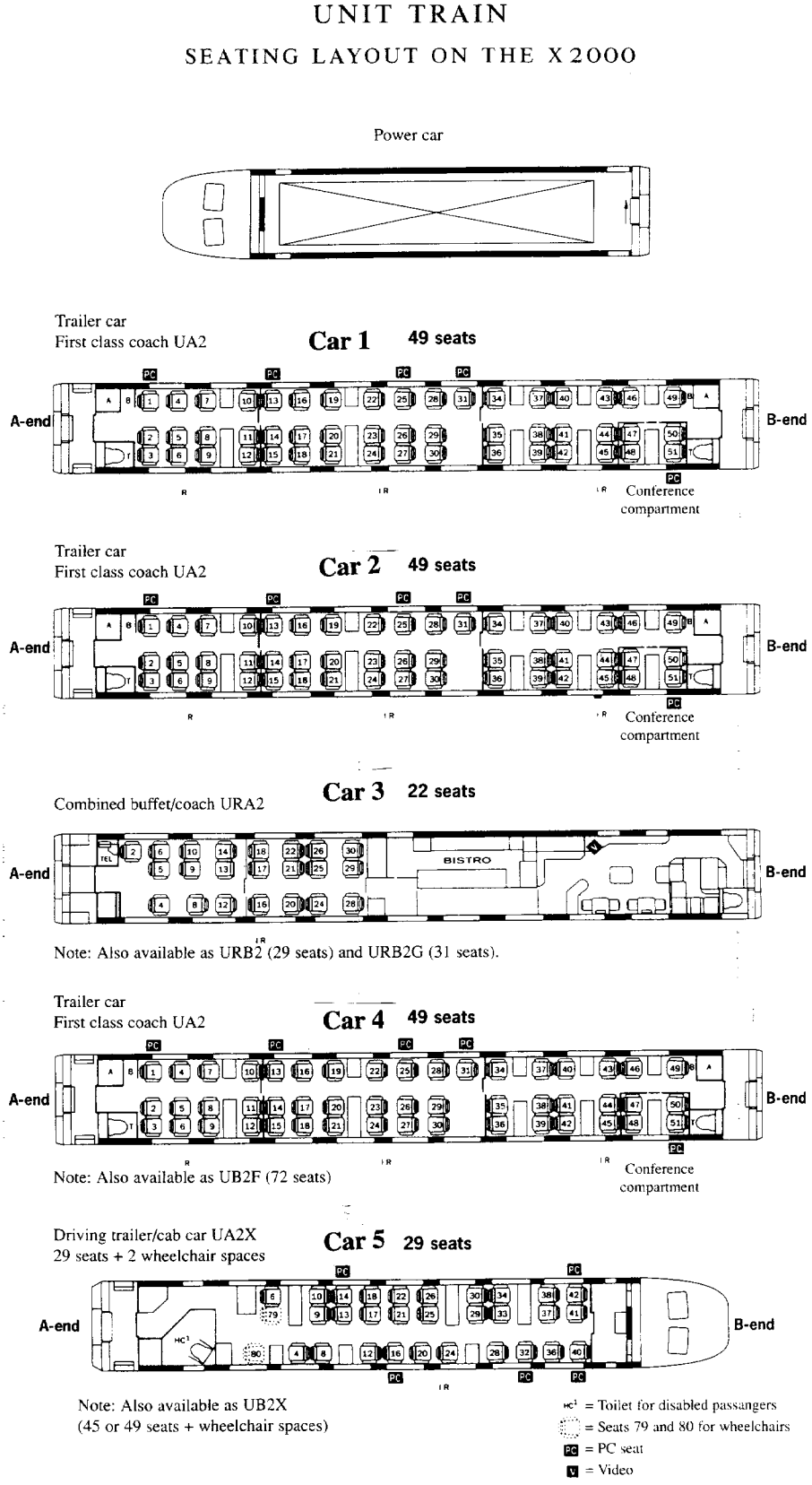

Figure G-1 Layout of test train in experiment 3. Source: SJ (1995).