Regression models for provoking motion sickness in tilting trains

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Abstract
Reduced travel times are a major issue for railway companies. Reductions can be achieved by building new lines with a high standard of track alignment or by using tilting trains on existing lines. However, for some passengers the tilt motions may provoke motion sickness and discomfort.

Modelling and prediction of motion sickness and nausea from vertical and horizontal accelerations have been investigated and developed through the combined efforts of many researchers. Vertical accelerations have been reported to have a strong influence on nausea, but less is known about the influence of roll motion. For tilting trains, where the tilt motion is used for reducing the lateral acceleration perceived by the passenger and thus improving comfort, it is likely that the primary cause of nausea is tilt motion in combination with low-frequency vertical and lateral acceleration.

In 1995, field tests were conducted with three conditions in a tilting train and in 1998 additional tests with a total of seven combinations of horizontal and roll motions were conducted in a moving base simulator at the VTI. Test subjects, mostly students, rated their illness and nausea according to a five-degree scale together with comfort, ability to work and read, etc. Evaluated variables were percentage of test subjects with motion sickness symptoms ($SMSI$) and nausea and illness ratings ($NR$ and $IR$). Additional field test were performed in Norway during November 1999.

In the train experiments, $SMSI$ was mainly correlated with the motion doses from roll accelerations. In the simulator experiments, vertical acceleration was most highly correlated with $NR$, but horizontal (lateral) acceleration together with roll acceleration were significantly better explaining variables. Net dose models with leakage of accumulated doses are a good alternative when motion environments change during the journey.

Good regression models have been found with horizontal and roll acceleration for explaining nausea ratings in the simulator. However, roll angles and horizontal accelerations are quite closely correlated in tilting trains, and roll motion doses are therefore the primary explaining variable regarding nausea in such trains. Models that take leakage into consideration are required in order to explain nausea ratings on routes with both curved and less curved sections. Optimisation of tilt motion must take into account both the risk of nausea and the risk of comfort disturbances caused by large perceived lateral accelerations, as well as the distribution of curves along the route. Also curve geometry and transition curve lengths interact significantly and must be taken into account, while preventing discomfort for passengers. Further research needs to be conducted on the basis of these aspects.

Keywords: Motion sickness, regression model, roll motion, lateral acceleration
1 Introduction

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. However, most countries have a significant amount of curved track that limits speeds and thus requires certain measures in order 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.

An alternative is to use the existing tracks and instead make it possible to tilt the car bodies of the train inwards during curving, consequently reducing the 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). However, some passengers with increased sensitivity to motion sickness may experience nausea and discomfort when riding tilting trains.

Modelling and prediction of nausea caused by vertical and horizontal accelerations have been investigated and developed over a long period of time (Golding, Finch, & Stott 1997, Golding, Müller, & Gresty 1999, Griffin 1990, Lawther & Griffin 1987, McCauley, Royal, & Wylie 1976). These models contain only translational accelerations. Combinations of roll and vertical accelerations have been reported with both minor influence (McCauley et al. 1976) and major influence (Wertheim, Bos, & Bles 1998) of roll motion on nausea.

For tilting trains, where the tilt motion is used for reducing the lateral acceleration perceived by the passengers, it is essential to develop models containing both roll, lateral and vertical accelerations. In this case, the roll motion is highly correlated to low-frequency lateral acceleration.

2 Methods and material

2.1 Train tests

In June 1995, about 70 test subjects took part in a train test carried out over a period of three days. The total trip length of 360 km from Linköping to Järna (south of Stockholm) and back had a duration of about 3 hours and was covered once a day. This route is part of the normal route for tilting trains between Stockholm, Malmö and Copenhagen (København). The test run was divided into four sections, see Figure 1.

The mean age of the subjects was 25 years and their mean self-estimated sensitivity to motion sickness\(^1\) was 2.6 for males and 3.6 for females.

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\(^1\) Subjects estimated their sensitivity on a seven grade scale from no sensitivity (1) to very high sensitivity (7).
Figure 1  Test track (bold lines) and adjoining lines in the test.

Three test conditions were used; a reference condition (A) with 70% compensation by the tilt system and two test conditions (G and F) with 55% compensation. Condition F had a limitation of maximum tilt acceleration of (4°/s²) and condition G had a limitation of tilt velocity of 2.3°/s instead of the normal 4°/s, see Table 1.

Table 1  Variation in parameters used in the tilt system during the experiment (June 1995).

<table>
<thead>
<tr>
<th>Tilt condition</th>
<th>Cant def. [mm]</th>
<th>Tilt comp. [%]</th>
<th>Max. tilt velocity [°/s]</th>
<th>Max. tilt acceleration [°/s²]</th>
<th>Typical max. lateral acceleration in car body [m/s²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>245</td>
<td>70</td>
<td>4</td>
<td>no limit¹</td>
<td>0.6</td>
</tr>
<tr>
<td>F</td>
<td>245</td>
<td>55</td>
<td>4</td>
<td>4</td>
<td>0.8</td>
</tr>
<tr>
<td>G</td>
<td>245</td>
<td>55</td>
<td>2.3</td>
<td>no limit</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Remarks:  
¹ Tilt conditions A-D were tested in earlier experiments.  
² 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 °/s².

Measured motion quantities were lateral and vertical accelerations on the floor of the car body together with roll accelerations. Subjects answered questionnaires on comfort and nausea after each test section.

2.2 Simulator tests

The simulator tests took place during 1998, with 42 test subjects making a total of 205 test runs. Seven test conditions were used, with three levels of horizontal (lateral) acceleration at 0, 0.825 and 1.1 m/s² and three levels of corresponding roll motion giving compensation levels of 0, 56, 75 and 100%, see Figure 2. The principal shape of the motion sequence of the horizontal (lateral) acceleration is shown in Figure 3. A number of these motion sequences

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2 70% tilt compensation means that tilting the car body compensates for 70% of the lateral acceleration in the track plane and thus the passengers perceive only the remaining 30%.

3 ° indicates degree.
and similar motions were added together to give a total test sequence lasting 60 sec. The total test sequence was repeated 31 times, giving a total time of 31 min for the test run. Typical horizontal and vertical train vibrations in the range of 1 – 15 Hz were added to the total motion environment (Figure 4). Acoustic noise recorded inside trains was played through loudspeakers inside the cabin. The following motion quantities were recorded: vertical and lateral acceleration and roll velocity inside the cabin. By using time differentiation, lateral jerk and roll acceleration were generated. Motion quantities were filtered with the motion sickness filter \( w_f \) and then r.m.s. values were calculated over the 60 sec motion sequences for all test conditions.

![Coding of test conditions](image)

**Figure 2** Test design of simulator experiment. The different test conditions are numbered 1 – 7.

Most of the subjects were employed repeatedly in the tests, taking part from two to seven times. Mean age was about 25 years for both genders, with a total range of 17 – 48. The mean self-estimated sensitivity to motion sickness\(^4\) was 2.7 for males and 3.3 for females.

![Principal motion sequence](image)

**Figure 3** Principal motion sequence. Layout for 100% horizontal acceleration and 100% roll motion.

\(^4\) On a seven-grade scale from 1 = no sensitivity to 7 = very high sensitivity.
2.3 Evaluation variables
Both the train and the simulator tests used a *Nausea Rating*\(^5\) scale \((NR)\) and *Illness Rating*\(^6\) scale \((IR)\) as well as a score of typical motion sickness symptoms. Evaluation variable for the train test was *Symptom of Motion Sickness Incidence* \((SMSI)\), which corresponds to the percentage of a test group having *nausea* or *dizziness* or *not feeling well*. In the simulator test, the \(NR\) scale was the first choice for evaluation.

3 Regression models

3.1 Models
A possible regression model may contain the following motion quantities:

\[ NR = f(a_z, a_y, a_r, t) \]

where \(f\) is function, \(NR\) is nausea rating, \(a_z\), \(a_y\) and \(a_r\) are vertical, lateral and roll acceleration, and \(t\) time

A model might also contain variables such as self-estimated sensitivity, whether the subject is rested/not rested and other human factor related quantities that may influence the resulting nausea. A possible model might be:

\[ NR = f(\text{motion variables, sensitivity, human factors, } t) \]

3.2 Model developed from train tests
Regression analysis showed that the incidence of symptoms of motion sickness \((SMSI)\) could best be explained by the *motion dose*\(^7\) of roll acceleration \((a_r)\) evaluated for each test section, see Figure 5. Evaluation per test section assumes that the accumulated motion dose from previous test sections has leaked away. Motion doses from perceived lateral acceleration \((a_{yc})\)

\(^5\) \(NR = 0\) No symptoms up to \(NR = 3\) Moderate nausea and \(NR = 4\) Strong nausea.

\(^6\) \(IR = 0\) I feel all right up to \(IR = 3\) I feel bad (miserable) and \(IR = 4\) I feel very bad (miserable).

\(^7\) Motion dose = \( \int (a_{yc})^2 \, dt \)^{0.5} [ms\(^{-1.5}\)], where \(a_{yc}\) is acceleration \(a\) filtered by \(w_f\) – motion sickness filter. *Motion dose* is equivalent \(MSDV\) (Motion Sickness Dose Value) as defined in ISO 2631-1.
inside the car body as well as vertical acceleration ($a_{zc}$) showed much lower correlation with SMSI. The coefficient of determination ($r^2$) is relatively good (0.44), showing that 44% of the variation in SMSI is explained by the motion dose of roll acceleration.

3.3 Models developed from simulator tests
Regression analysis shows that for one variable the vertical acceleration is most suitable for explaining the nausea ($NR$) provoked by the experiment, followed by horizontal lateral acceleration and roll acceleration. However, horizontal and roll acceleration together is a better predictor of nausea in the simulator test than vertical acceleration alone. Quadratic relations between nausea ratings and horizontal or roll acceleration are possible, but are difficult to determine because of few levels of input variation and a large spread of responses. This model, which combines horizontal acceleration with roll acceleration, has $r^2 = 0.85$ and highly significant explanation variables, see Figure 6. This figure shows a comparison between measured nausea ratings at time 26 min ($NR_{26}$) and predicted $NR_{26}$. The motion quantities are filtered with the ISO 2631-1 $W_f$ filter. The quadratic relation shows the highest degree of determination, although both models show good predictions.

Possible regression models, under the conditions of constant motion environment (constant and continuous motions) for roll and lateral acceleration in the horizontal plane (as in the simulator experiment):

**Model A:**
\[ NR = -0.30 + (0.060 \cdot a_{yH,rms,uf} + 0.40 \cdot a_{r,rms,uf} \cdot \sqrt{t}) \quad [m/s^{1.5}] \quad r^2 = 0.79 \]

**Model B:**
\[ NR = -0.15 + (0.058 \cdot a_{yH,rms,uf} + 7.44 \cdot a_{r,rms,uf}^2 \cdot \sqrt{t}) \quad [m/s^{1.5}] \quad r^2 = 0.85 \]

Remarks: $a$ is acceleration [m/s$^2$, rad/s$^2$] and $t$ time [s]. Indices used relate to acceleration: $yH$ horizontal (lateral), $r$ roll and $w_f$ ISO 2631-1 filter for motion sickness.
Comparison between different regression models
Simulator test, Nausea ratings at 26 min (NR26). Motion quantities are w/ filtered

Figure 6  Comparison between different regression models using horizontal (lateral) acceleration and roll acceleration. Nausea ratings (NR26) are measured on the abscissa and the predicted NR26 according to model on the ordinate.

3.4 Proposed motion dose model
The accepted model for predicting motion sickness is the motion dose model (MSDV) using vertical accelerations. The model is defined in ISO 2631-1. (ISO 1997). However, vertical acceleration by itself cannot explain the high level of nausea in the experiment. Therefore, the influences from lateral acceleration and roll velocity/roll acceleration are essential in the test environments used (Förstberg 2000). The motion dose method can be extended to other translations or to angular accelerations (Turner & Griffin 1999). However, when considering the provoking of nausea on actual journeys with tilting trains, leakage of nausea has to be taken into consideration. Such a model has been proposed as the net dose model (Kufver & Förstberg 1999). This model can be rewritten with lateral (horizontal) and roll acceleration as input acceleration and with the same dimension as in the motion dose evaluation.

\[
\begin{align*}
ND(t) &= \left[ \int_0^t (c_y \cdot a_{yH,wf}^2(\tau) + c_{rx} \cdot a_{wH,wf}^2(\tau)) \cdot e^{c_z(t-\tau)}d\tau \right] [m/s^{1.5}] \\
NR &= c_{NR} \cdot ND \\
\end{align*}
\]

Remarks: \( a \) is acceleration (lateral [m/s^2] or roll [rad/s^2]), and \( t \) time [s]. Indices used relate to acceleration: \( yH \) horizontal (lateral), \( rx \) roll and \( wf \) ISO 2631-1 filter for motion sickness. \( c \) are constants where \( c_y [-] \), \( c_{rx} [m^2/\text{rad}^2] \), \( c_{NR} [s^{1.5}/\text{m}] \) and \( c_z \) is a time constant for leakage [1/s].

Future research with tilting trains and subjects must be carried out in order to determine the different coefficients.
4 Discussion and conclusions

Roll motion, as evaluated, as motion dose from roll accelerations or roll velocity seems to have a significant influence on motion sickness in tilting trains. The simulator study shows that a combination of horizontal acceleration and roll acceleration motion doses is a highly significant explanation variable. Vertical acceleration generated in the simulator test is generally of an insufficient magnitude to provoke nausea. Horizontal acceleration alone seems to be an important explanation variable.

Roll and horizontal acceleration motion doses are highly correlated in tilting trains, which implies that a regression model can only utilise one of the variables.

The proposed models for the simulator tests with the explanation variables, motion doses of horizontal acceleration and roll acceleration show good agreement with NR26. The coefficient of determination ($r^2$) is high; at least 0.80 for the proposed models. Additionally, the self-estimated sensitivity is shown as a significant explanation variable.

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6 References


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