Advancing ISO 2631-1 by considering pre-emesis symptoms in carsickness

Jelte E. Bos[1,2], Jan L. Souman[3], Suzanne Nooij[1], Cyriel Diels[4]

(1) TNO Human Performance, Soesterberg, the Netherlands, jelte.bos@tno.nl
(2) Vrije Universiteit, Behavioural and Movement Sciences, Amsterdam, the Netherlands
(3) TNO Integrated Vehicle Safety, Helmond, the Netherlands
(4) Royal College of Art, London, Intelligent Mobility Design Centre, United Kingdom

Abstract *– Passengers of highly automated vehicles are anticipated to experience increased levels of carsickness. In turn, this may adversely impact public acceptance and commercial success rendering mitigation methods of strategic importance. The current ISO 2631-1:1997 standard provides estimates of the likelihood of passengers reaching emesis due to motion, whilst pre-emesis symptoms are of greater interest regarding carsickness but may show a different frequency dependency. Further, it was derived for vertical motion only, whilst horizontal motion is also of greater interest to carsickness. In response, a series of motion simulator studies (n=96) were conducted exploring the impact of frequency (0.06-3.2 Hz) and motion direction (x-, y-, and z-axes) on pre-emesis symptoms assessed via the Motion Illness Symptoms Classification scale (MISC). Whilst no differences in frequency dependency were found across the three axes, the observed normalized frequency weighting function peaked at 0.23 Hz, slightly higher than the value of 0.17 Hz, and predicted more sickness than assumed by the ISO standard, in particular at higher frequencies. It is concluded that the frequency weighting for pre-emesis symptoms differs from the ISO weighting, the latter leading to a gross underestimation of the problem which calls for a revision of the current standard.*

Keywords: *ISO 2631-1:1997, motion sickness, 3D prediction, frequency weighting, pre-emesis symptoms*

Introduction

While low levels of vehicle automation are slowly penetrating the market, the acceptance of highly automated vehicles may still be jeopardized by carsickness (Bos, 2018; Bos et al., 2022a; Diels & Bos, 2016). More occupants of fully automated vehicles are expected to suffer from carsickness than those of current human-driven cars, at least if these will drive the same way human driven vehicles do (Bos et al., 2022a). Here, carsickness can be characterised by symptoms like apathy, headaches, (cold) sweating, and dizziness, possibly followed by nausea and ultimately emesis (Bos et al., 2005; Reuten et al., 2021). The mentioned threat may be prevented by reckoning the extent to which humans suffer from carsickness depending on (in particular) acceleration and frequency, and optimising vehicle ride control systems considering that sensitivity (Bos et al., 2022b). Although some efforts to quantify human sensitivity to motion sickness in response to acceleration and frequency have been made before (Donohew & Griffin, 2004; Golding & Markey, 1995; Golding et al., 1996, 1997, 2001; Griffin & Mills 2002a,b), these studies applied several different stimulus conditions and rating scales. These differences impede the development of a unified description. Moreover, in particular frequencies below 0.2 Hz were studied only sparsely, mainly due to a lack of stimulus devices having a stroke large enough to generate significant acceleration at these low frequencies (note that stroke amplitude increases with the inverse of the frequency squared for equal sinusoidal acceleration). To that end, we elaborated on the most acknowledged prediction model of motion sickness, ISO 2631-1:1997 (further simply referred to as ISO (1997)), by not only considering emesis, as ISO does, but also pre-emesis symptoms as are observed more often in cars than emesis itself (Schmidt et al., 2020).

Another shortcoming of ISO (1997) regarding (automated) land vehicles concerns the fact that it is limited (validated) for vertical motion only, as typically experienced in ships. Car motion does show considerable power in horizontal accelerations and the study by Donohew & Griffin (2004) already suggested that in the horizontal plane, the vertical frequency weighting by ISO might be different for these horizontal motions. Extending ISO to a three degrees of motion freedom (3-DoF, i.e., along the vertical (*z*-axis), longitudinal (*x*-axis) and lateral (*y*-axis)) model therefore seems essential regarding carsickness in particular.

Research question

In this paper we will particularly focus on the effect of the frequency of periodic motion along all three principal axes on pre-emesis symptoms of motion sickness. We assumed this sensitivity to show a wider range of frequencies causing pre-emesis and even more so pre-nausea symptoms than that described by ISO for emesis only, the weightings possibly being different for the three axes.

To answer that question, this paper will present a preview concerning a subset of data acquired in a joint industry project that was supported by five car manufacturers and suppliers from 2019 to 2021. Although that project included about 200 subjects having been exposed to about 560 lab- and on-road trials in total, the subset focussed on here limits to lab data only obtained in 96 subjects and 254 trials of 20 minutes each (see further below). This preview is intended to be followed by series of full papers describing the entire set of data.

Methods

Study design

To find the frequency effect of motion sickness for the pre-emesis symptoms, we realised three separate lab experiments. All motions in these studies were single frequency sinusoidal motions characterised by peak acceleration (a_0) and frequency (f), with $a(t) = a_0\sin(2\pi ft)$. Pilot studies showed that a peak acceleration a_0 = 2 m/s^2 resulted in a fairly symmetrical distribution of sickness levels (due to inter-individual differences) within 20 minutes of exposure. This acceleration and stimulus duration was accordingly fixed for these experiments. In different trials and in chronological order we then studied the effect of frequency and motion direction along the vertical (z-) axis, longitudinal (x-) axis and lateral (y-) axis, each axis in a separate experiment.

Apparatus and frequencies

For the vertical (z-axis) motion experiment we used TNO's Desdemona facility (see Figure 1). Although this facility concerns a 6-DoF motion simulator, we only used its vertical motion, which stroke is limited to 2 m. Using a peak acceleration of 2 m/s^2 then only allowed frequencies to be studied in the range of 0.24 Hz to 3.2 Hz, the upper limit being restricted by the device's bandwidth. In this experiment we used fixed frequencies of 0.24, 0.2, 0.4, 0.8, 1.6 and 3.2 Hz as the major independent variable.

Figure 1: TNO's Desdemona facility. Although the device has six degrees of motion freedom, for the experiment described here, only the vertical degree was used

For the longitudinal and lateral experiments (x- and y-axes) the Limosine facility was used. The Limosine is a 45 m horizontal linear sled with a safe operating length of about 30 m (see Figure 2). Limited by its bandwidth and again using a peak acceleration of 2 m/s^2, the frequency range could be varied between 0.06 and 3.2 Hz. In the longitudinal experiment we used fixed frequencies of 0.06, 0.1, 0.2, 0.4, 0.8, 1.6 and 3.2 Hz as the independent variable. In the lateral experiment we limited the frequencies to 0.06, 0.1, 0.2, 0.4, and 0.8 Hz.

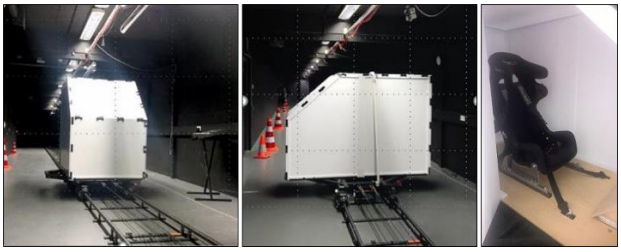

Figure 2: TNO's Limosine facility with its cabin oriented longitudinally (left), laterally (centre), and its safety / rally seat inside (right)

Dependent variable

To rate motion sickness, considering its symptoms we used the Motion Illness Symptoms Classification scale (MISC; Reuten et al., 2021), previously known as the MIsery SCale (Bos et al., 2005). This scale concerns an 11-point scale subdivided onto 5 categories (See Table 1). Each category of symptoms typically succeeds the previous during accumulation of sickness, which also holds for the levels within two of the categories. The associated numbers thus constitute a monotonous increasing series during the accumulation process of motion sickness. Because subjects were required to participate three times in our experiments, we always stopped a trial when a MISC of 7 or higher was rated to prevent subject discouragement and the household consequence of dealing with emesis.

Table 1: The Motion Illness Symptoms Classification scale (MISC)

Symptoms		*MISC*
No problems at all		0
Uneasy (no typical symptoms)		1
Dizziness, warmth, headache, stomach awareness, sweating, ..., ***but no nausea***	vague slight fairly severe	2 3 4 5
Nausea, possibly with symptoms 2-5	slight fairly severe (near) retching	6 7 8 9
Vomiting		10

Subjects and procedures

In each experiment (along the *z*-, *x*-, and *y*-axes), subjects were asked to participate three times on separate days to be exposed to different frequencies. This hence resulted in an incomplete experimental design, requiring mixed-effects models to be analysed statistically (see below). Subjects were free of self-known neuro-vestibular diseases, did not suffer from claustrophobia, did not use medication known to affect alertness or cause dizziness, and did not take alcohol 12 hours in advance of the experiment. Subjects were selected to be familiar with at least some past experienced motion sickness.

In the vertical (*z*-axis) motion experiment we included 29 subjects in 81 trials of 20 minutes each, or less in case of severe sickness. In the longitudinal (*x*-axis) motion experiment there were 45 subjects and 115 trials and in the lateral (*y*-axis) experiment 22 subjects and 55 trials. In total there were hence 96 subjects and 251 trials. 14 subjects participated in multiple experiments that were months apart. Note that in the results reported on here, i.e., only concerning the 2 m/s^2 trials, a subset of the complete set was used. Right before their first trial, the experiment was further explained, including their freedom to withdraw at any moment for any reason. Questions were answered and all subjects gave written informed consent before actual participation. The Motion Sickness Susceptibility Questionnaire (MSSQ; Golding, 2006) was administered to confirm the subjects' susceptibility to motion sickness and to control for individual differences in motion sickness susceptibility in the data analysis (see below). The subjects were then exposed to the particular motion profile and provided their MISC scores at 2-minute intervals. Following cessation of motion, subjects continued rating their MISC at 5-minute intervals until a level of 2 or less was obtained, after which they were dismissed. The latter always occurred within half an hour.

Ethical approval in agreement with the Declaration of Helsinki on ethical principles for medical research involving human subjects from the institutional review board was obtained in advance of the experiments.

Data analyses

Cumulative Link Mixed effects Models (CLMM) were used to test for significant effects of frequency and direction of motion (DoF), taking into account the incomplete experimental designs, the ordinal nature of the MISC and random effects (Christensen, 2018). These tests were performed after each experiment as well as on the pooled data to find the frequency weighting(s) when considering the total symptomatology of motion sickness. Instead of predicting the average MISC value (as in normal regression), the CLMM test predicts the proportion of observations p with a MISC score above a certain critical value c (ranging from 0 to 7), at a specific timepoint and motion (axis and frequency). A probit link function (i.e., a cumulative normal distribution) was used as the probability function in the current analyses. The basic model equation of this approach is:

$$p(\text{MISC}>c) = 1 - \Phi(\vartheta_c - \mathrm{X}^{\mathrm{T}}\boldsymbol{\beta})$$

where Φ represents the cumulative normal distribution, ϑ_c represents the threshold value between MISC value c and c+1, X the design matrix with frequency, time, DoF, MSSQ, age and gender, and $\boldsymbol{\beta}$ the vector of predictor coefficients that have to be estimated (see Christensen, 2018, for details).

After these fundamental analyses to establish any significant effects, we relied on the ISO (1997) approach of using a Butterworth filter to quantify the frequency weighting(s), which, after all, concerned our main research question.

Results

Statistical tests

Although the CLMM analyses did show some interaction between frequency and motion direction (DoF), the resulting effect size thereof was considerably smaller than the main effect found for frequency and interindividual variability.

Moreover, independent of the criterion c, this probability showed a peak at around 0.2 Hz with decreasing sickness for both lower and higher frequencies. Assuming a peak frequency value exactly equal for all criteria c and normalizing the weighting functions to $w(f) = 1$ at its peak value, all weightings were furthermore found to be about equal.

For practical reasons we therefore here tentatively conclude that for predicting motion sickness in (automated) vehicles, a single frequency weighting function suffices for all three DoFs and criteria c.

Frequency weighting

Using equation A.5 from ISO (1997) with the frequency parameters f_1 to f_6 and resonant quality factors Q_4 to Q_6 fitted to the standardized estimated regression coefficients for the different motion

frequencies from the CLMM analysis, we found the curve as shown in Figure 3. The peak of this function occurs at 0.23 Hz, slightly higher than the value of 0.17 Hz as predicted by ISO.

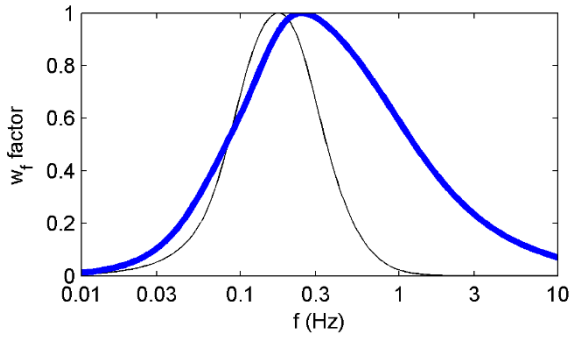

Figure 3: Normalized frequency weighting functions w_f. The thin black line gives the ISO weighting for emesis, the bold blue line a normalized fit to our 3-DoF data for the pre-emesis symptoms

Discussion and conclusions

The frequency weighting function for pre-emesis symptoms as shown in Figure 3 clearly extends to higher frequencies, than given by ISO (1997). As we assumed, this suggests that motion sickness can be an issue even before emesis occurs as considered by ISO, Stated differently, ISO underestimates the problem of motion sickness in, e.g., cars. It could though be surprising that frequencies below the peak frequency are not that different as compared to ISO. Still, that similarity may be (partly) explained by the fact that until now hardly any data was available on motion sickness depending on frequencies below 0.2 Hz. One exception concerns the data on horizontal accelerations by Donohew & Griffin (2004) for frequencies between 0.0315 and 0.2 Hz. Based on a similar approach as used in our study they concluded on a frequency weighting function suggesting much more sickness at frequencies below 0.2 Hz than predicted by ISO and even more so than our observations and resulting weighing function. The difference may yet be understood by the fact that Donohew and Griffin used oscillations with a constant peak velocity of 1 m/s. As a consequence, peak acceleration in their experiment varied from 0.2 m/s^2 at 0.0315 Hz to 1.3 m/s^2 at 0.2 Hz (note that peak accelerations for sinusoidal motion differ by a factor of $\sqrt{2}$ from RMS values as reported by Donohew & Griffin). Because we kept peak acceleration constant at 2 m/s^2 for all frequencies reported on here, and did find significantly more sickness as compared to the data of Donohew & Griffin, we assume our data to provide a more valid weighting function, especially regarding accelerations typical of car driving. This does, however, not imply that a function different from the ISO approach or when including more data could still result in an adapted, optimised estimation.

Once the frequency weighting is known for all three axes, the next step as already applied for comfort and heath by ISO 2631-1 (1997), could be to define the 3-DoF Motion Sickness Dose Value ($MSDV_{3D}$)

$$MSDV_{3D} = [c_x MSDV_x^2 + c_y MSDV_y^2 + MSDV_z^2]^{0.5}$$

with

$$MSDV_i = [\int a_{wi}(t)^2 dt]^{0.5}$$

and c_x and c_y coefficients giving the average ratio between sickness along the *x*- and *y*-axis relative to the vertical *z*-axis. We are currently elaborating on separate publications not only giving estimates for these coefficients, but also a statistical model predicting the proportion $p(MISC>c)$ taking into account a subject's individual susceptibility, and the effect of out the window viewing.

Actual application of the knowledge described here, most importantly concerns vehicle control of accelerating, braking, lane changes, cornering, taking speed-bumps and going up- and downhill. When realised by an algorithm in automated driving, filters can be designed considering the human sensitivity to motion as shown in Figure 3, attenuating the accelerations that are most provocative regarding carsickness. Of course, safety issues do hold (in particular regarding braking), which should be considered. Note that in two-wheel steering cars any cornering always comes with a centripetal acceleration. Until proven otherwise, we assume that the frequency weighting function described above also applies to these linear accelerations in cornering.

Another application concerns the optimisation of navigation trajectories to minimise sickness, possibly offering passengers the option for choosing a longer trajectory at the benefit of causing less sickness.

A third application may be the optimisation of suspension, active suspension in particular. This pertains not only to the reduction of vertical vibration, but also the degree of vehicle tilt into the corner to minimise lateral accelerations. With respect to the latter, however, it should be noted that a similar application in tilting trains proved to be far from trivial (Persson, 2008).

Notwithstanding current progress, several outstanding questions remain. In a second joint industry project, for example, we are already elaborating on the temporal characteristics of motion sickness: accumulation, habituation, recovery and (de)sensitisation. Besides physically induced motion sickness, such as carsickness, models as elaborated on here could or should consider specific visual factors, then also explaining visually induced motion sickness. The latter could even call for a new motion sickness standard across motion environments, as we suggested in Bos et al. (2022b). With respect to carsickness, visual factors not only concern differences between peripheral and central view, for example, but also effects of infotainment by means of (large) displays. If a display would show image motion as seen from a first person's perspective not

matching the motion of the real vehicle, that will likely aggravate sickness. In particular visual cues @@@.

And finally, not only motion sickness, but managing comfort in general is an even greater challenge (see also Kemeny, 2023). A challenge that calls for a multidisciplinary approach, perhaps based on a network in which different research institutes, universities and industries work together to create and realize research agendas with a scope beyond the typical research project duration of up to four years. That network should not only concern the automotive domain, but the aviation, maritime, VR and even health domains as well, civil and defence, commercial and governmental. We are currently exploring these directions and are open to discussion.

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