Ocean Engineering 38 (2011) 22–33

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Application of the subjective vertical–horizontal-conflict physiological motion sickness model to the field trials of contemporary vessels

Hassan Khalid [a,*], Osman Turan [a], Jelte E. Bos [b], Atilla Incecik [a]

[a] Marine Design, Operation and Human Factors, Department of Naval Architecture and Marine Engineering, Universities of Glasgow and Strathclyde, 100 Montrose Street, Henry Dyer Building, Glasgow G4 0LZ, UK

[b] TNO Human Factors, P.O. Box 23, 3769 ZG Soesterberg, The Netherlands

ARTICLE INFO

Article history:
Received 17 March 2010
Accepted 6 September 2010
Editor-in-Chief: A.I. Incecik
Available online 4 December 2010

Keywords:
Motion sickness
Subjective vertical
Subjective vertical–horizontal
Field trials
Sensory conflict
Vestibular system

ABSTRACT

Subjective-vertical conflict theory (Bles et al., 1998) postulates that all motion sickness provoking situations are characterized by a condition in which the vertical (gravity) sensed by the visual, vestibular and non-vestibular proprioceptors are at variance with the subjective (expected) vertical. SV-conflict models have successfully been used by Bos and Bles (2000), Verveniotis and Turan (2002b), Bos et al. (2002a) and Dallinga et al. (2002), to predict motion sickness of passenger ferries. However, considering the prevalence of significantly high level of horizontal acceleration aboard contemporary vessels, Khalid et al. (in press) proposed a further elaboration of a physiological (subjective-vertical–horizontal, SVH-conflict) model that explicitly incorporates the effects of horizontal accelerations. They hypothesized that the explanation of motion sickness variability may improve, by considering the combined effects of subjective vertical as well as subjective horizontal conflicts (difference between the sensed and 'expected' horizontal accelerations). This paper briefly presents the SVH-conflict model and demonstrates its application to 68 field trials of 10 different vessels. Percentages of seasick passengers, observed during the field trials, are statistically compared with physiological and descriptive (O'Hanlon and McCauley, 1974; ISO 2631-1, 1997) motion sickness models. In general, SVH-conflict is statistically outperforming the descriptive models and displaying improvement over the SV-conflict model.

1. Introduction

Motion sickness or kinetosis is one of the most important design criteria for the passenger vessel (Arribas and Pineiro, 2007) and a growing concern of world's leading navies (McCauley et al., 2007). It is characterized by the feelings of dizziness, bodily warmth, sweating, drowsiness, yawning, variations in mouth dryness levels, headaches, stomach awareness, severe nausea and emesis (vomiting). The term nausea (used for seasickness) has its roots in Greek mythological word naus meaning ship, which indicates the ancient nature of motion sickness and its association with sea travel (Reason and Brand, 1975).

Sensory conflict or sensory rearrangement (Reason, 1970, 1978; Reason and Brand, 1975) is the most comprehensive theory of motion sickness, which duly accounts for the underlying physiological mechanism believed to be responsible for triggering this, otherwise a natural, response. The theory successfully provides physiologic reasoning of the sickness provoking real/virtual motions; however, its qualitative nature has limited its use in practical applications. Consequently, a significant research has focused on the development of descriptive models that could be used to predict the proportion of people likely to become sick under a known passive motion environment (O'Hanlon and McCauley, 1974; McCauley et al., 1976; Lawther and Griffin 1986, 1987, 1988; Griffin, 1990; Lobb, 2001; Turan et al., 2005).

The recent and pragmatic version of sensory conflict theory is the subjective vertical (SV) conflict theory proposed by Bles et al. (1998) and Bos and Bles (1998a, 1998b, 2002). They postulate that motion sickness can be predicted by using the conflict between the vertical (gravity) sensed by somatic, visual and vestibular systems and the expected gravity (subjective vertical) estimated by the internal observer (Central Nervous System) on the basis of previous experience. The SV-conflict model is built on the heuristic model of Oman (1982), however, simplified to limit sensory conflict to the sensed and expected gravities only.

By combining SV-conflict theory with the spatial orientation model by Merfeld and Young (1993), Verveniotis and Turan (2002a, 2002b), Turan et al. (2003, 2009) and Verveniotis (2004) developed their SV-conflict model, involving the vestibular system only. They have successfully employed this model to predict the motion sickness events, as observed through

* Corresponding author. Tel.: +44 1415484165; fax: +44 1415484784.
E-mail addresses: hassan.khalid@strath.ac.uk (H. Khalid), o.turan@na-me.ac.uk (O. Turan), jelte.bos@tno.nl (J.E. Bos).

0029-8018/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.oceaneng.2010.09.008

passenger survey aboard high speed craft (a standard catamaran, a Deep-V monohull, and a wave piercing catamaran). However, they found that these vessels displayed significantly high levels of lateral accelerations, of the order and even higher than the vertical accelerations. Furthermore, the findings of a recent EU project COMPASS (Turan, 2006), indicated greater role of horizontal accelerations for the occurrence of motion sickness aboard contemporary high speed vessels than perceived before. Similar conclusion has been drawn by Tamura and Arima (2006), while investigating the ride comfort of a high-speed passenger craft.

Stimulated by the abovementioned findings about the role of horizontal accelerations, Khalid et al. (in press) suggest an alternative statement of the SV-conflict theory as: ‘All situations producing a variance between the vertical (gravity) sensed through human’s sense modalities and the subjective vertical expected (by the nervous system) from past exposure to spatial environment causes motion sickness. In addition, the difference between horizontal accelerations (normal to gravity) sensed through the integrated sensory system and those expected from previous experience (i.e. subjective horizontal accelerations) add up to elicit motion sickness.’ They have implemented the rephrased version of the SV-conflict theory, which explicitly accounts for the horizontal accelerations. The new subjective-vertical–horizontal (SVH) conflict model, employs the sensory conflicts between (1) the sensed and expected vertical (SV-conflict) and (2) the sensed and expected horizontal accelerations (SH-conflict) to predict incidences of seasickness. Khalid et al. (in press) have also validated their model by successfully estimating statistically accurate seasickness incidences observed during the seven field trials of three passenger vessels.

This paper presents further validation of the SVH-conflict model by applying it to a total of 68 full scale trials of 10 different vessels. The paper begins with a brief description of SVH-conflict model and thereafter presents its application to the field trials of the vessels. The motion sickness incidences (MSIs) observed during the field trials are also statistically compared with the values predicted by the SVH-conflict, SV-conflict, ISO 2631-1 (1997)/BS 6841 (1987) and the Human Factors Research Incorporation (O’Hanlon and McCauley, 1974; McCauley et al., 1976) (HFRI) sickness prediction models.

2. SVH-conflict model

The schematic diagram of SVH-conflict model is shown in Fig. 1, which is an extended version of SV-conflict model (highlighted with dashed-rectangle) developed by Verveniotis and Turan (2002a, 2002b), Turan et al. (2003, 2009) and Verveniotis (2004).

The theoretical and mathematical description of the model is presented in detail by Khalid et al. (in press), therefore, the following sections of the paper provide only a brief summary.

2.1. General

The SVH-conflict model simulates vestibular system that functions as human’s inertial guidance system (Purves et al., 2004) and is one of the special somatic afferent senses. It has three bilateral and approximately orthogonal semicircular canals and the two otoliths organs. Functionally, canals detect and mechanically integrate angular acceleration of head, while otoliths sense and quantify linear accelerations (see Highstein et al. (2004), for further details on morphology, physiology and biomechanics of the vestibular system).

One way of dealing mathematically with Reason and Brand’s (1975) and Bles et al. (1998) theory of mismatch between the sensed and expected signals, is by assuming an internal model to explicitly predict the expected signals, and so far this has proven to be successful (Oman, 1982; Bos and Bles, 1998a, 1998b, 2002). Consequently, the SVH-conflict model (Fig. 1), owes its origin to optimal control theory; specifically the Luenberger observer theory (Luenberger, 1964, 1966, 1971; see Ellis, 2002). It mimics two distinctive regions; a sensor region that simulates the processing of vestibular afferents to estimate the sensed orientation/motions (gravity and horizontal acceleration). On the other hand, the internal region is laid out to simulate the processes hypothesized to take place inside the nervous system to estimate the expected gravity and horizontal accelerations.

2.2. Estimation of sensed vertical in sensor region

A consequence of Einstein’s (1907) equivalence principle is the inability of linear accelerometers (otoliths) to distinguish between gravitational (tilt) and inertial (translational) accelerations. This problems was first addressed by Mayne (1969, 1974), who suggested to low pass filter the gravitoinertial accelerations (GIA) to isolate the (constant) gravitational accelerations from GIA. The sensor region of the SVH-conflict model estimates gravity using Mayne’s principles extended to 3D motions by Mittelstaedt et al. (1989). It is important to realize that GIA sensed by the otoliths are relative to head-fixed frame of reference. Since gravity is only constant in the inertial (Earth-fixed) frame of reference, hence the low pass filtering has to take place in such as frame of reference. Consequently, the sensed GIA is first transformed to inertial frame of reference (R block), low-pass filtered (LPF_V block) to obtain

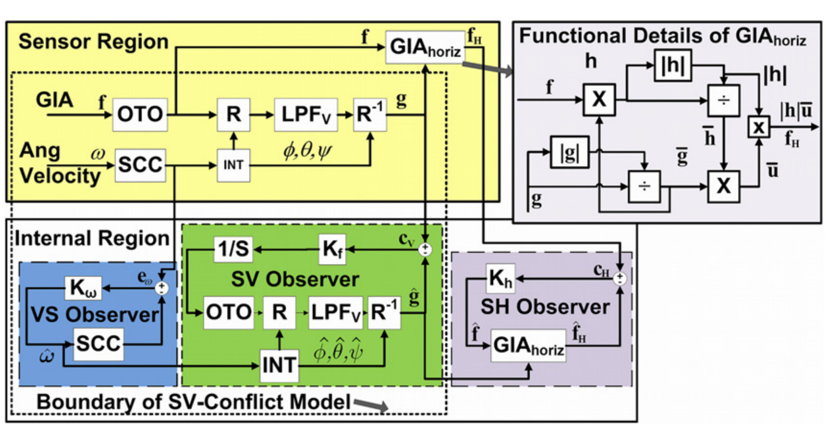

Fig. 1. Schematic diagram of ‘orientation/motion perception’ part of the subjective vertical–horizontal (SVH) conflict model of motion sickness.

gravity, and then transformed back (R^{-1} block) to describe gravity in the head-fixed frame of reference. The rotational Euler angles needed for the transformations may be obtained from the rotational velocities registered by the canals (SCC block). See Bos et al. (2001, 2002b, 2008) and Bos and Bles (2002) or recently Turan et al. (2009) for a complete mathematical description of this process.

2.3. Estimation of sensed horizontal acceleration in sensor region

The sensed horizontal accelerations are defined as the component of GIA exactly normal to sensed gravity (in the body frame of reference). It is important to note that the sensed vertical (gravity) already carries the effects of (low frequency) translational accelerations parallel to it. Therefore, this definition of sensed horizontal establishes the component of GIA not accounted by the SV-conflict. The process assumed to be used by the nervous system for estimating the sensed horizontal accelerations is fairly simple and employs a few vector manipulations (see details of GIA_{horiz} block in Fig. 1).

Firstly, a vector product of the sensed GIA ($\mathbf{f}$) [bold face letters represent vectors] with a unit vector in the direction of sensed gravity ($\bar{\mathbf{g}}$) [barred-bold letters represent unit vectors] results into a vector $\mathbf{h}$. This resultant vector has its magnitude equal to the component of GIA normal to sensed gravity but is directed out of the plane containing them i.e.

$$\mathbf{h} = \mathbf{f} \times \bar{\mathbf{g}} = \{|\mathbf{f}| \cdot |1| \cdot \sin(\gamma)\}\bar{\mathbf{n}} = |\mathbf{f}| \cdot \sin(\gamma) \cdot \bar{\mathbf{n}} \quad (1)$$

where γ is the angle between sensed GIA ($\mathbf{f}$) and gravity ($\mathbf{g}$), while $\bar{\mathbf{n}}$ is a unit vector normal to the plane containing them. Now, a cross product of the unit vectors in the direction of $\mathbf{g}$ and $\mathbf{h}$ leads to another unit vector $\bar{\mathbf{u}}$, which is normal to the sensed gravity and directed towards the GIA, while being located within the plane containing them, i.e.

$$\bar{\mathbf{u}} = \bar{\mathbf{g}} \times \bar{\mathbf{h}} \quad (2)$$

A simple multiplication of the above unit vector with $|\mathbf{h}|$ would give us the vector of our interest:

$$\mathbf{f_H} = |\mathbf{h}| \cdot \bar{\mathbf{u}} \quad (3)$$

2.4. Estimation of subjective vertical in the internal region

Internal estimates of the expected gravity (subjective vertical) are obtained with the help of two observers. The velocity storage (VS) observer keeps track of the rotational velocities sensed by the semicircular canal, which are then used by the subjective-vertical (SV) observer to estimate the required rotational transformations matrices (R and R^{-1}). The VS-observer simulates velocity storage mechanism (Raphan et al., 1977) to predict rotational velocities for the low frequency motions as semicircular canals (effectively high pass filters) do not perform very well at these frequencies. The physical laws embedded inside the SV-observer to estimate the subjective vertical $\hat{\mathbf{g}}$ (bold face hatted letters represent internal/subjective vectors), are identical to those employed by vestibular nuclei in the sensor region. Difference between the sensed and subjective verticals ($\hat{\mathbf{g}} - \mathbf{g}$) results into SV-conflict vector $\mathbf{c_V}$. This conflict is used by the compensator of the SV-observer through a proportional gain (K_f) and an integrator (s^{-1}) to steer internal estimates of gravity $\hat{\mathbf{g}}$ towards the sensed gravity $\mathbf{g}$. The frequency response of SV-observer depends on the magnitude of weighting K_f; a value of 5 (s^{-1}) causes the conflict to have its maxima around 1.0 rad/s (0.16 Hz), which is the frequency at which human beings exhibit maximum sensitivity to vertical oscillations from motion sickness view point.

2.5. Estimation of subjective horizontal accelerations in the internal regions

The expected (subjective) horizontal accelerations are estimated by the internal region using a single subjective horizontal (SH) observer. The GIA and gravity vectors' manipulation processes implemented by the SH-observer are exact copies of those (assumed to be) in the sensor region. The estimates of expected horizontal accelerations $\hat{\mathbf{f}}_\mathbf{H}$ are compared with the sensed values $\mathbf{f_H}$, resulting into the subjective horizontal (SH) conflict $\mathbf{c_H}$. This conflict is weighted (K_h) and fed back to SH-observer through a compensator, minimising the difference between sensed and subjective horizontal accelerations. The magnitude of K_h ($=1$) has been statistically estimated by fitting the SVH-conflict model to the 15 full scale trials of a high speed wave piercing catamaran vessel ($p=0.134$; $\chi^2=21.09$; dof=15).

2.6. Transformation of sensory conflicts into MSI

The SV and SH-conflicts are translated into motion sickness incidences (MSI%) using the hill function and leaky integrator proposed by Bos and Bles (1998a, 1998b). The hill functions take account of the non-linear relationship between the sensory conflicts and MSI (%). It normalizes the conflicts and small conflicts are transformed exponentially while large conflicts are translated logarithmically into MSI. Also a person does not get motion sick instantly when exposed to stimulus motions and do get relieved on its removal, likewise MSI cannot be greater than 100%. The function used to model the cumulative nature of motion sickness symptoms with passage of time is a second order low pass filter, termed as leaky integrator. The complete process of transforming the two conflicts into MSIs is depicted in Fig. 2.

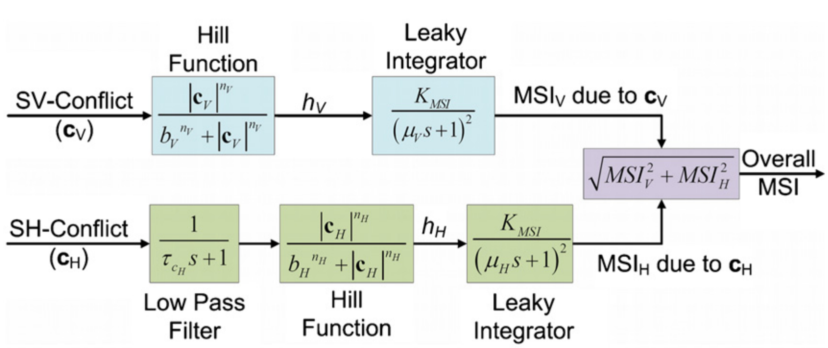

Fig. 2. Post processing of SV and SH-conflicts into overall MSI (%).

The single pole low pass filter shown in Fig. 2 is required to simulate the laboratory findings concerning elicitation of motion sickness under purely horizontal oscillations (Golding et al., 2001; Lobb, 2001; Griffin and Mills, 2002; Donohew and Griffin, 2004), which suggest a decrease in sickness sensitivity to motions with frequencies above 0.2 Hz. The parameters of the hill function and leaky integrator given in Table 1 are found to be optimum, when the model is fitted to 15 field trials of vessel G (Table 2, trial no. 7 of this vessel was discarded due to a potential experiment error; see Section 4.1).

The parameter values for the post processing of SV-conflict are exactly the same as proposed by Bos and Bles (1998a, 1998b) to replicate laboratory experiments by McCauley et al. (1976), preserving model's capability to mimic laboratory results for purely vertical oscillations. The time constant of the leaky integrator used for processing the SH-conflict is set as half of the one employed for SV-conflict. This is done to take account of lower (almost half) latency of motion sickness for purely horizontal oscillations (Golding et al., 1995).

3. Application to field trails

A total of 67 field trials were carried out aboard 3 monohull, 3 standard catamarans, 1 Deep-V monohull and 2 wave piercer catamaran passenger ships operating at diverse routes in Europe. The latter 6 vessels fall under the category of high speed craft. In addition, a single full scale trail was carried out aboard a rigid hull inflatable boat (RHIB). Due to the commercial sensitivities, the hull forms of these vessels are not reproduced here, whereas, their approximate principal characteristics are summarized in Table 2. The table is also indicating the typical journey time, area of operation and the number of field trials carried out on each vessel.

The passenger areas on board these vessels were divided into various zones to account for the lever-arm effects of the vessels' rotational motions. The significant wave heights as well as root mean square surge, sway, heave, roll, pitch and yaw accelerations (averaged over the passenger zones) are summarized in Table A.1 of Appendix A, for all trials of the ten vessels. The exact loading conditions and routes are not given in this paper due to the confidentiality issues. It is important to highlight that these field trials were either undertaken by the partners of COMPASS project consortium (Turan, 2006) or by the department of Naval Architecture and Marine Engineering (NAME) of the University of Strathclyde on its own.

Table 1
Hill function and leaking integrator parameters.

Parameter	SV-conflict	SH-conflict
b	0.7	2.5
n	2	1.0
K_{MSI} (%)	85	85
μ (min)	12	6

3.1. Motion measurements

In all field trials, motion reference units (MRUs) were employed to log the six degrees of freedom motion histories of the vessels. MRU has three linear accelerometers and three angular rate Coriolis gyroscopes, arranged orthogonally. The system is designed as 'strap down' inertial navigation system with no gimbals or turn-able mechanical platform. A software interface (RS232 compatible) digitally eliminates the parasitic gravitational accelerations (resulting from rotational motions) from the linear motion signals before logging them. The linear and rotational motions recorded by MRU may be used to calculate linear inertial accelerations at other onboard positions of interest (passenger zones) using (Huston and Liu, 2001):

$$\vec{a}_P = \vec{a}_{mru} + \vec{\alpha}_{mru} \times \vec{r}_{mru\to P} + \vec{\omega}_{mru} \times (\vec{\omega}_{mru} \times \vec{r}_{mru\to P}) \tag{4}$$

where, 'a' is the linear acceleration vector, 'α' is the angular acceleration vector, 'r' is the position vector directed from MRU to the location of interest and 'ω' is the rotational velocity vector. Considering Eq. (4), and the input requirement of SVH model (Fig. 1), the motion records included the three translational and rotational accelerations and the three rotational velocities at the MRU installation position, logged at a sampling rate of 10 Hz.

3.2. Sickness measurement

The number of passengers experiencing emesis during the field trials was established by distributing and collecting the comfort survey questionnaire developed in the COMPASS project (Turan, 2006). The questionnaire, shown in Fig. B1 of Appendix B, is similar to the ones used in past field studies concerning motion sickness (Lawther and Griffin, 1988; Turner and Griffin, 1999; Haward et al., 2000; Turner et al., 2000; Dobie et al., 2001; Verveniotis and Turan, 2002b). It has several check-box type questions, seeking to gather information on demographics (age, gender, past motion sickness history, use of anti-sickness medicines, etc.), motion sickness characteristics of the journey, sitting comfort, motion induced interruptions, commuter's expectations, satisfaction, fatigue and the enjoyment features for the voyage. This paper makes use of the question pertaining to

Table 2
Approximate principal characteristics of the vessels.

Characteristics	Vessels									
	A	B	C	D	E	F	G	H	I	J
Hull form[a]	Cat	DV	MH	MH	Cat	Cat	WP	WP	MH	RHIB
L_{BP} (m)	120	130	160	163	33	37	90	90	91	10
Beam (m)	40	20	29	27	10	10	25	25	16	2.8
Draught (m)	4.5	3.5	7.0	6.5	2.0	2.0	3.5	3.5	3.0	Variable
Speed (knots)	40	40	20	22	35	38	40	40	16	52
Passengers	800	1700	2500	2000	270	380	850	850	600	10
Cars	200	400	400	3600	Nil	Nil	200	200	100	Nil
Journey time (h)	1.5–2.0	2.0–3.0	10.0–16.0	14.75–15	0.75–3.50	1.5–1.75	2.75–3.75	3.0–3.8	2.0–3.0	1.75
Operating around[b]	UK	GR	FI	IT	NO	GR	UK	UK	UK	UK
Total trips	2	4	3	6	24	4	16	4	4	1

[a] MH: Monohull, Cat: Standard Catamaran, DV: Deep-V, WP: Wave Piercer Catamaran.
[b] FI: Finland, GR: Greece, IT: Italy, NO: Norway, UK: United Kingdom.

the occurrence of emesis and statistical evaluation of other comfort features shall be covered elsewhere.

Prior to the distribution of questionnaires, the public address (PA) systems of the vessels were used to briefly inform the passenger about the purpose and scope of the study. They were told that the participation is on voluntary basis. The questionnaires were handed out to the passengers by the members of research teams well after the ship was under way, so that the subjects start experiencing some level of discomfort, if any. Collection of the questionnaires was carried out on completion of each voyage, before the ship's berthing. All questionnaires, with conflicting or missing information about the motion sickness and comfort feelings were discarded. In addition, visual surveillances were maintained by the research teams providing subjective assessment of the onboard comfort situations. However, unlike past studies (e.g. Lawther and Griffin, 1986), no exclusions were made on the basis of age (e.g. children) and other predisposing factors (e.g. use of alcohol or anti-sickness medication). This was done to ensure an accurate representation of general passenger population as well as to avoid any biasness of the sample data. The questionnaire return rate varied from as low as 20% to as high as 70%.

One point that needs to be highlighted here pertains to the adaptation or habituation (Crossland, 1998). The majority of people ($\approx$95%) are known to acquire the so-called 'sea legs', whereby they become partly/fully immune to the prevailing motion environment. Unless there are large variations in the subsequent vessel motions, these 'habituated' people do not suffer from seasickness. As such, the SVH-conflict model does not incorporate any (conflict driven) function changing the settings of the internal model so as to minimize the conflict, and thus account for habituation. Nevertheless, unlike the descriptive (HFRI and ISO/BS) models, SVH model is capable of simulating variations in sensory conflict, thereby seasickness, with the changes in sea severity. Therefore, it is expected that the SVH (also the SV) model would outperform the descriptive (HFRI and ISO/BS) models for the prolonged journeys in moderate sea condition. However, a large set of long journeys' database would be needed to validate this assumption. Here, we are presenting only nine long journey sea trials of two vessels (see Table 2).

3.3. Statistical evaluation procedure

In addition to vessel motions, the personalized factors tabulated in Table 3, are kown to influence the inclination (susceptibility) of an individual to become seasick (Lawther and Griffin, 1986; Griffin, 1990; Guedry, 1991; Benson, 1999; Stevens and Parsons, 2002; Bos et al., 2007). A glance on the factors enlisted in the table reveals that the real passengers' population aboard any ship would exhibit significant variations in their susceptibility to become seasick. Thus, the motion sickness response of a real ship's passengers may be treated as a random variable. It is important to appreciate that part of the variability attributable to aforesaid factors might be accounted for by considering a susceptibility function, such as the one proposed by Bos et al. (2007). However, the primary scope of this research is to develop a model that could predict motion sickness for general passenger population during the design stages. Therefore, use of the susceptibility function is deliberately avoided.

Table 3
Factors influencing susceptibility.

Features	Role
Gender	Females are more inclined to become motion sick
Age	There is peak around 11 years in females and 21 years in males with a decline in sickness susceptibility on either side
Past history	People with past experience of motion sickness on other modes of transportation have higher inclination to become seasick aboard ships
Sleep deprivation	Lack of sleep exacerbates susceptibility
Psychological features	Introverts tend to exhibit greater motion sickness
Activity	Tasks requiring mental concentration reduce susceptibility
Temporal aspects	Consumption of alcohol, inflammation of inner ear, headaches and gastrointestinal disorder renders are person more susceptible

The variable of our interest i.e. MSI, has a dichotomous nature on an individual level (emesis/no emesis). Hence, with the assumption of independence (of the individual emesis event), we may employ discrete binomial distribution for its representation. Also, under moderate motion conditions, a small percentage of people would be expected to reach the vomiting stage. In such a case, if the hypothetical (model) estimate of seasick passenger proportion is p_{VI}, then the likelihood (*P-value*) of observing n vomiting incidences during the field trial of a vessel with N passengers returning questionnaires shall be given by (McDonald, 2008):

$$p=\sum_{k=0}^{N} B(k,N,p_{VI})\ \ \forall B(k,N,p_{VI}) \le B(n,N,p_{VI})$$

$$\text{Where, } B(k,N,p_{VI})=\frac{p_{VI}^{k}(1-p_{VI})^{(N-k)}N!}{k!(N-k)!} \tag{5}$$

It should be noted that above equation represents exact binomial test for small hypothetical proportion (null hypothesis H_0=observed MSI is not different from hypothetical i.e. model estimates). At 5% significance level, *P-values* larger than 0.05 would imply that model estimates for the given trial are not different from the observed values. It is, however, not enough to verify the validity of a model for the individual field trials and a statistical test should be carried out to confirm its suitability for the multiple trials of all vessels. This could be achieved by employing the χ^2 goodness-of-fitness test, where the test statistics may be calculated using (McKenzie, 2008):

$$\chi^2=\sum_{i=1}^{N_{trials}} -2\ln(p_i) \tag{6}$$

where, p is the *α-error* of each field trial calculated using Eq. (5), and N_{trials} is the total number of trials of all vessels. The test statistics given by Eq. (6) may be used to calculate the one-tailed probability of the χ^2 distribution with N_{trials} degrees of freedom. This probability represents the overall *P-value* of all trials and vessels (for the model under consideration).

3.4. MSI prediction

In this study, the physiologic (SVH and SV-conflict) models were implemented in SIMULINK®. We assumed the passengers to be seated and passively moving with ship without executing any volitional head movements. Resultantly, we treat the linear accelerations and rotational velocities recorded by MRU and recalculated for the specific locations as a direct input to the labyrinthine apparatus. The three linear accelerations calculated for each passenger zone [using Eq. (4)] and angular velocities measured by MRU were fed as input to these models. In return, the models estimated the proportions of people likely to vomit in each zone.

Since, the distribution of passengers in various zones is sporadic (very few people stick to one place) and we do not have information on their exact dispersal throughout the journeys, we assume them to be equally distributed in all zones. Thus, the MSIs averaged over the considered passenger zones represent the overall MSI for a particular trip of a given ship.

The descriptive motion sickness models used in our study are those by the Human Factors Research Incorporation (O'Hanlon and McCauley, 1974; McCauley et al., 1976) (HFRI) and ISO 2631-1 (1997)/BS 6841 1987. The details of these models are not reproduced here as these are very well covered in literature (e.g. see Benson, 2002; Turan et al., 2009).

4. Results and discussion

4.1. Individual trial results

The observed and predicted MSIs for the individual field trials of all (10) vessels are given in Tables C.1–C.10 of Appendix C. These tables also contain the exact binomial test *P-values*, representing the prediction accuracy of each model (HFRI, ISO/BS, SV and SVH) to a given field trial of a specific vessel. Statistically speaking, *P-value* is just an indicator of the significance of an outcome. However, in our discussions we use it to gauge the relative fitness of the models. Thus, a larger *P-value* indicates a greater probability of observing the recorded MSI (%) during a field trial, given the values estimated by the relevant model are statistically accurate i.e. a better fitting of the model.

By assuming $p<0.05$ to be significant, $p>0.5$ as highly insignificant, and in between values to be insignificant, we may collate the relative statistical accuracy of each model. These significance categories are, respectively, considered to represent the no-fit (NF), good-fit (GF) and very-good-fit (VGF) of the models. The numbers of full scale trials falling under each of these significance/fitting categories for the given vessel and MSI model are summarized in Table 4. The following may easily be observed from this table and those in Appendix C.

HFRI model

- This model is unable to accurately predict the MSIs for 22 (32.4%) field trials.
- It predicts the smallest sickness and most successfully fits the sea trials with small or no vomiting incidences.
- With the exception of Trip no. 7 of vessel G, this model is predicting MSIs less than the observed values in all trips to which it is failing to fit.
- The model's inability to fit the long duration field trials of vessel C may be attributed to habituation. However, it is surprising to see its accuracy for all the long journeys of vessel D (which makes sense: an underestimation over all may give a correct prediction some time during habituation).

ISO/BS model

- This descriptive model is inaccurate for 9 (13.2%) trials, rendering it better than HFRI model.
- Considering the trials to which the model is unable to fit, it can be seen that it is predicting lower sickness events for the three field trials of high speed vessels (A and B) and over estimating in rest of the cases (vessels B, C, D and G).
- Significantly higher MSIs are predicted by the model for the long duration field trials of vessel C and D, which again, may be due to habituation effects.

SV-conflict model

- The SV-conflict model is predicting statistically inaccurate MSI for only 4 (5.9%) field trials. It is displaying a better fit to the observed data than the HFRI and ISO/BS models.
- Within the 'non-fitted' 4 trials, this model has predicted lower MSIs for the two field trials of high speed vessels B and E.
- The higher predicted MSI for the long duration field trial (no. 5) of vessel D may be attributed to 'habituation' effects. Whereas, the higher estimates of MSI for the full scale trial (no. 7) of vessel G is in line with all other models.

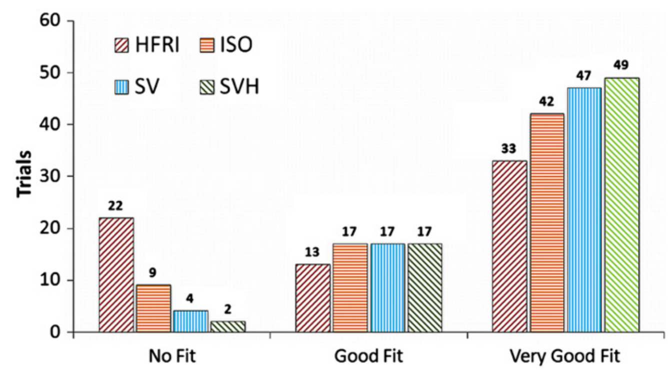

Fig. 3. Summary of kinetosis models' fitting.

Table 5
Overall fitness of the motion sickness models to the 67 trials of 10 ships.

Model	dof	χ^2	Overall *P*-value
HFRI	67	517.627	7.96E−71
ISO/BS	67	161.281	9.59E−10
SV	67	81.513	0.1094
SVH	67	77.761	0.1734

Table 4
Summary of the field trials falling under a particular fitness/significance category for the given vessel and model.

Vessel	Statistical fitting/significance level												
	Trips	HFRI model			ISO/BS model			SV-conflict model			SVH-conflict model		
	Fitting[a] *P*-value	NF <0.05	GF 0.05–0.5	VGF >0.5	NF <0.05	GF 0.05–0.5	VGF >0.5	NF <0.05	GF 0.05–0.5	VGF >0.5	NF <0.05	GF 0.05–0.5	VGF >0.5
A	2	2	–	–	1	–	–	–	–	2	–	–	2
B	4	4	–	–	2	–	2	1	–	3	–	2	2
C	3	3	–	–	3	–	–	–	1	2	–	2	1
D	6	–	5	1	2	4	–	1	2	3	1	2	3
E	24	1	–	23	–	2	22	1	–	23	–	2	22
F	4	3	–	1	–	1	3	–	2	2	–	2	2
G	16	6	7	3	1	7	8	1	8	7	1	5	10
H	4	2	1	1	–	1	3	–	3	1	–	1	3
I	4	1	–	3	–	1	3	–	1	3	–	1	3
J	1	–	–	1	–	–	1	–	–	1	–	–	1
Total	**68**	**22**	**13**	**33**	**9**	**17**	**42**	**4**	**17**	**47**	**2**	**17**	**49**
Percent (%)	**100.0**	**32.4**	**19.1**	**48.5**	**13.2**	**25.0**	**61.8**	**5.9**	**25.0**	**69.1**	**2.9**	**25.0**	**72.1**

[a] NF: no-fit; GF: good-fit; VGF: very-good-fit.

SVH-conflict model

- This physiological model is estimating statistically accurate MSI for all but 2(2.9%) field trials. Thus, SVH-conflict is displaying better performance than the SV-conflict, ISO/BS and HFRI models.
- As with the SV-conflict model, a higher estimate of MSI for the long journey (no. 5) of vessel D may be due to the habituation.
- However, as far as trial no. 7 of vessel G is concerned, it is evident that observed MSI of this trial is significantly different ($p \ll 0.05$) from the high values predicted by all four models (HFRI, ISO/BS, SV and SVH). Interestingly, in this specific trial 24 people (21%) reported severe nausea but none mentioned emesis, or at least not reported to have vomited. It appears that the survey questionnaires were distributed and collected before the motion sickness experienced by the passengers could reach the stage of emesis. In addition, as part of the visual surveillance, the researchers conducting this trial observed signs of vomiting in toilets. Therefore, results of this specific trial have been discarded and also not used for the calibration of SVH-conflict model.

The modelwise summary of results for all vessels and trials are plotted in Fig. 3. It can easily be observed from this figure that the two physiologic models (SVH and SV) are statistically more accurate than the descriptive models (HFRI and ISO/BS). Also, by having the least of no-fit as well as the most of very-good-fit results, SVH-conflict is appearing to be better than the other three models. However, we need to verify this observation by an overarching statistical test for all field trials, irrespective of the vessel type, as presented in the next section.

4.2. Overall statistical fitness

The χ^2 statistics for the four MSI prediction models (HFRI, ISO/BS, SV and SVH) have been calculated using Eq. (6). These statistics, pertaining to the 67 field trials of the 10 ships (trial no. 7 of vessel G has been discarded, see Section 4.1), are summarized in Table 5. The table is also giving the overall *P-values* (supporting the null hypothesis). It can be observed that the SVH model with smallest χ^2-statistics is showing, respectively, 5%, 107% and 565% statistical improvement (calculated using the ratios of χ^2 statistics) over SV, ISO/BS and HFRI models. Furthermore, the overall *P-values* concerning HFRI and the ISO/BS models are highly significant, indicating a lack of statistical fit.

As such SVH model is displaying marginal improvement over SV model (5%). However, this may be attributable to the facts that more than 60% (42) field trials were either carried out aboard monohull vessels (14 trials, 20%) or the weather conditions were so calm that no emesis event took place aboard HSC (28 trials, 40%). In the former case the SVH model is expected to display characteristics identical to SV model as the predominant motions of the classical monohull vessels are in the vertical directions. On the other hand, little difference is likely to prevail between the two types of physiologic models for small motions of HSC.

4.3. Model limitation

There are several factors that are likely to influence MSI that are not explicitly accounted for by the physiologic (SVH and SV) motion sickness models presented in this paper. These include (1) the susceptibility of passengers, (2) their level of habituation to prevailing vessel motions, (3) effects of their volitional head/body movements, (4) visibility of horizon (through windows), (5) predisposing factors like use of alcohol, anti-sickness medications, etc. Nevertheless, the statistical inferential techniques used in this work to compare the model predictions with the observed proportion of emesis events, do indirectly account for the variability displayed by the general passenger population in the aforementioned factors. Thus, within the limitations of such statistical methods (e.g. assuming emesis to be dichotomous and independent event), it is evident from Table 5 that the physiologic models in general, and SVH in particular, are displaying performance superior to the descriptive models.

5. Conclusion

This paper presents a new physiologic kinetosis model (SVH-conflict), developed using an alternate statement of the SV-conflict theory. The model explicitly takes account of the horizontal motions by implementing an alternative component in the SV model. The paper also demonstrates application of the SVH, SV, ISO/BS and HFRI models to predict MSI observed during the 68 field trials of 10 different vessels operating in different areas of Europe.

In terms of individual sea trials, the HFRI model failed to fit almost 1/3 of the full scale trials. The SV-conflict model has displayed better statistical performance than the ISO/BS, which in turn is much superior to HFRI model. The SVH-conflict model is exhibiting ‘very-good ($p > 0.5$)’ statistical fitting to almost 3/4 field trials and has only two ‘non-fitting’ MSI estimations, which might be attributable to ‘habituation’ and ‘experiment error’.

The overarching statistical goodness-of-fit test applied to the 67 field trials of all 10 ships indicates that SVH-conflict model is statistically, albeit marginally, more accurate than the existing SV-conflict model. These two physiological models are, in turn, much superior to the descriptive motion sickness estimation models (HFRI and ISO/BS).

Appendix A. Trial conditions and vessel motions

Significant wave heights and resulting motions of the vessels are shown in Table A1.

Table A.1
Significant wave heights and resulting motions of the vessels.

Vessel	Trip	Hs (m)	RMS accelerations (averaged over passenger zones)					
			Surge (m/s^2)	Sway (m/s^2)	Heave (m/s^2)	Roll (°/s^2)	Pitch (°/s^2)	Yaw (°/s^2)
A	1	2.8–3.0	0.0462	0.2214	0.1775	0.0114	0.0021	0.0032
	2	3.2–3.5	0.0522	0.2137	0.2107	0.0101	0.0031	0.0031
B	1	0.7–1.5	0.0377	0.1150	0.1794	0.0060	0.0031	0.0020
	2	1.8–2.6	0.1031	0.2603	0.3327	0.0120	0.0074	0.0025
	3	1.4–2.0	0.0318	0.1395	0.1662	0.0059	0.0026	0.0018
	4	1.5–2.1	0.0499	0.1242	0.2035	0.0068	0.0038	0.0021

Table A.1 (*continued*)

Vessel	Trip	Hs (m)	RMS accelerations (averaged over passenger zones)					
			Surge (m/s^2)	Sway (m/s^2)	Heave (m/s^2)	Roll ($^\circ/s^2$)	Pitch ($^\circ/s^2$)	Yaw ($^\circ/s^2$)
C	1	1.0–2.0	0.0182	0.0637	0.1008	0.0010	0.0013	0.0007
	2	2.0–3.0	0.0173	0.0741	0.0830	0.0014	0.0014	0.0013
	3	2.0–3.0	0.0154	0.0588	0.0792	0.0012	0.0011	0.0006
D	1	0.9–1.1	0.0594	0.2536	0.2471	0.0044	0.0041	0.0044
	2	1.4–2.5	0.0613	0.2586	0.2624	0.0045	0.0041	0.0044
	3	1.9–3.7	0.0726	0.2580	0.3013	0.0044	0.0042	0.0042
	4	1.1–2.5	0.0693	0.2457	0.2760	0.0045	0.0042	0.0042
	5	3.2–7.5	0.0913	0.2901	0.3836	0.0046	0.0050	0.0044
	6	1.0–1.3	0.0604	0.2403	0.2428	0.0041	0.0039	0.0041
E	1	0.5–0.8	0.0439	0.0926	0.1408	0.0087	0.0082	0.0038
	2	< 0.5	0.0159	0.0532	0.0271	0.0042	0.0022	0.0025
	3	0.7–1.2	0.0574	0.0757	0.2217	0.0072	0.0120	0.0039
	4	0.5–0.7	0.0422	0.0962	0.1358	0.0093	0.0077	0.0040
	5	< 0.5	0.0185	0.0899	0.0518	0.0114	0.0037	0.0032
	6	< 0.5	0.0184	0.0844	0.0477	0.0098	0.0035	0.0032
	7	0.8–1.2	0.0678	0.1181	0.2597	0.0125	0.0140	0.0044
	8	< 0.6	0.0302	0.0927	0.0792	0.0070	0.0045	0.0034
	9	< 0.5	0.0283	0.0883	0.0698	0.0078	0.0040	0.0034
	10	< 0.5	0.0259	0.0824	0.0653	0.0073	0.0040	0.0033
	11	< 0.25	0.0125	0.0545	0.0240	0.0053	0.0018	0.0026
	12	< 0.5	0.0216	0.0659	0.0385	0.0059	0.0028	0.0035
	13	0.5–0.7	0.0404	0.0703	0.1362	0.0056	0.0073	0.0035
	14	0.5–0.6	0.0359	0.0841	0.1148	0.0055	0.0064	0.0031
	15	< 0.6	0.0306	0.0829	0.0955	0.0082	0.0056	0.0035
	16	< 0.5	0.0229	0.0581	0.0544	0.0040	0.0035	0.0027
	17	< 0.5	0.0227	0.0702	0.0446	0.0050	0.0029	0.0029
	18	0.6–1.0	0.0494	0.0769	0.1781	0.0056	0.0099	0.0037
	19	< 0.5	0.0297	0.0636	0.0812	0.0042	0.0048	0.0026
	20	0.6–1.0	0.0449	0.0683	0.1680	0.0057	0.0089	0.0027
	21	< 0.5	0.0278	0.0854	0.0656	0.0066	0.0044	0.0030
	22	< 0.6	0.0290	0.0874	0.0906	0.0091	0.0051	0.0033
	23	< 0.5	0.0249	0.0655	0.0485	0.0037	0.0031	0.0023
	24	< 0.5	0.0254	0.0787	0.0515	0.0071	0.0032	0.0032
F	1	1.0–1.3	0.1182	0.3633	0.3841	0.0208	0.0220	0.0223
	2	1.5–1.7	0.0648	0.2996	0.3972	0.0232	0.0150	0.0148
	3	0.8–1.2	0.0597	0.2129	0.3047	0.0150	0.0142	0.0102
	4	1.0–1.2	0.1089	0.2197	0.4445	0.0193	0.0182	0.0142
G	1	1.7–1.8	0.0879	0.2126	0.3055	0.0144	0.0087	0.0033
	2	1.6–1.7	0.0568	0.2208	0.2253	0.0130	0.0063	0.0032
	3	1.6–1.7	0.1043	0.2478	0.3507	0.0166	0.0103	0.0035
	4	1.5–1.6	0.0403	0.1622	0.1564	0.0095	0.0044	0.0024
	5	1.5	0.0811	0.2116	0.2801	0.0133	0.0082	0.0034
	6	1.6–1.7	0.0595	0.2246	0.2104	0.0128	0.0063	0.0032
	7	2.3–2.6	0.1440	0.3079	0.4356	0.0201	0.0145	0.0051
	8	2.0–2.1	0.0696	0.2865	0.2500	0.0167	0.0064	0.0044
	9	2.1–2.2	0.1138	0.2472	0.3575	0.0162	0.0112	0.0041
	10	2.2	0.0655	0.2823	0.2371	0.0160	0.0069	0.0044
	11	2.2–2.4	0.1697	0.3671	0.5175	0.0264	0.0173	0.0055
	12	2.4	0.0751	0.3346	0.2678	0.0179	0.0070	0.0053
	13	2.6–2.9	0.2159	0.4037	0.7122	0.0325	0.0215	0.0058
	14	2.6–2.7	0.0774	0.3525	0.2932	0.0182	0.0075	0.0046
	15	0.6–0.7	0.0421	0.0933	0.1575	0.0053	0.0051	0.0019
	16	0.6–0.7	0.0286	0.0766	0.1194	0.0038	0.0043	0.0016
H	1	0.8–0.9	0.0340	0.1507	0.1263	0.0097	0.0031	0.0018
	2	0.9	0.0464	0.1521	0.1550	0.0109	0.0045	0.0022
	3	0.5–0.7	0.0289	0.1284	0.1021	0.0087	0.0027	0.0015
	4	0.8–1.0	0.0569	0.1732	0.1866	0.0116	0.0053	0.0028
I	1	2.5	0.0924	0.1501	0.2955	0.0026	0.0065	0.0026
	2	2.1	0.0450	0.1288	0.1918	0.0026	0.0035	0.0024
	3	1.8	0.0213	0.0659	0.0648	0.0015	0.0015	0.0015
	4	1.9	0.0398	0.0720	0.1056	0.0021	0.0027	0.0016
J	1	0.5	0.1823	0.2093	0.7685	0.1178	0.1488	0.0601

Appendix B. Survey questionnaire

The questionnaire is shown in Fig. B1.

Passenger Survey (Student Research Project) [Please fill in towards the end of your journey]

This survey is part of a PhD research project investigating the effects of ship motion on passenger comfort. We would be grateful if you could spare the time to fill in the following questionnaire, which will be collected from you. Please answer the following questions about your own impressions of your journey by ticking the relevant boxes (e.g. √ or X) or entering the requested information in the spaces provided. It would further improve our analysis if you could fill one questionnaire each for the accompanied children, if any.

1. Your age and gender
Male Female
Gender: (please tick one box)
Enter your age in years:

2. At which port did you board this ship?

3. Where in the ship have you spent most time?
Please enter a zone according to the plan on the back of this sheet

4. Did you do any of the following activities on this voyage? (please tick all appropriate boxes)
Reading
Operating computer or game
Listening to music etc.
Talking
No particular activity
Resting or sleeping
In restaurant, bar or shop
Looking outside vessel
Other (specify):

5. Have you had more than two alcoholic drinks?
No Yes
During the voyage
Up to 12h before the voyage

6. Have you felt any of the following on this voyage? (please tick all the appropriate boxes)
Feeling hot or sweating
Headache
Change in skin colour
Mouth watering
Cold sweating
Drowsiness
Dizziness
Stomach awareness
Nausea (feeling sick)
Vomiting

7. Which of the following corresponds most closely with the worst you felt on this voyage? (please tick one box only)
I felt all right
I felt slightly unwell
I felt quite ill
I felt absolutely dreadful

8. If you did feel unwell or vomited, how long after the start of the voyage did each occur?
Hours:Minutes
Felt unwell :
Vomited :

9. Have you taken any anti-seasickness tablets?
No Yes
Please tick one box

10. Do you travel regularly by sea? (please tick one box in each column)
All vessels This type of vessel
Rarely or never before
Twice a year or less
Up to 6 times a year
More than 6 times a year

11. Have you ever suffered from sickness in the following? (please tick all appropriate boxes)
Ships or boats
Coaches or buses
Cars
Aircraft
Trains

12. Please indicate how uncomfortable the vessel motions on this voyage made you feel while sitting (other than through seasickness)? (tick one box)
Extremely uncomfortable
Very uncomfortable
Uncomfortable
Fairly uncomfortable
A little uncomfortable
Not uncomfortable

13. Please indicate how much the vessel motions made you unsteady or caused loss-of-balance while standing or walking? (please tick one box)
Extremely unsteady
Very unsteady
Unsteady
Fairly unsteady
A little unsteady
Not unsteady

14. Please indicate how difficult the vessel motions made any of the following tasks or activities, other than through sea sickness? (please tick one box in each column)
Eating & drinking Reading Writing Other (specify)
I did not do this
Extremely difficult
Very difficult
Difficult
Fairly difficult
A little difficult
Not difficult

15. Which of the following have caused you the most discomfort during this voyage? (please tick one box in each column)
Most discomfort 2nd most discomfort
Sea Sickness
Discomfort while sitting
Unsteadiness/loss-of-balance while standing
Difficulties with tasks or activities
Noise
Vibration
Air quality
Other (specify):
No discomfort experienced

16. How did the comfort of the voyage compare with your expectations?
Less comfortable than expected
Same as expected
More comfortable than expected

17. Please indicate your satisfaction with the comfort of this voyage (please tick one box)
Extremely satisfied
Very satisfied
Satisfied
Fairly satisfied
A little satisfied
Not satisfied, may return
Not satisfied, will not return

18. Please indicate how fatiguing (tiring) you have found this voyage (please tick one box)
Extremely tiring
Very tiring
Fairly tiring
Tiring
A little tiring
Not tiring

19. Please indicate your enjoyment of this voyage (please tick one box)
Extremely enjoyable
Very enjoyable
Enjoyable
Fairly enjoyable
A little enjoyable
Not enjoyable

20. If there is any other information you would like to add, please use the space provided on the back of this sheet.

Fig. B.1. Passenger comfort survey questionnaire.

Appendix C. Full scale trial results

The observed and predicted MSIs for the individual field trials of all (10) vessels are given in Tables C1–C10.

Table C.1
Observed and predicted MSIs along with models' fitness statistics—vessel A.

Trip	Observed			HFRI		ISO/BS		SV		SVH	
	N[a]	VI[b]	MSI (%)	MSI (%)	P	MSI (%)	P	MSI (%)	P	MSI (%)	P
1	248	14	**5.65**	**0.54**	0.000	**3.75**	0.128	**5.51**	0.889	**6.11**	0.894
2	229	18	**7.86**	**1.12**	0.000	**4.67**	0.028	**7.50**	0.802	**8.00**	1.000

[a] N: total replies.
[b] VI: people reported to have vomited.

Table C.2
Observed and predicted MSIs along with models' fitness statistics—vessel B.

Trip	Observed			HFRI		ISO/BS		SV		SVH	
	N[a]	VI[b]	MSI (%)	MSI (%)	P	MSI (%)	P	MSI (%)	P	MSI (%)	P
1	340	7	**2.06**	**0.75**	0.015	**4.92**	0.011	**2.69**	0.614	**3.13**	0.347
2	335	53	**15.82**	**5.44**	0.000	**11.35**	0.012	**15.63**	0.940	**16.24**	0.882
3	187	12	**6.42**	**0.70**	0.000	**5.52**	0.523	**5.62**	0.632	**6.18**	0.879
4	475	29	**6.11**	**1.07**	0.000	**5.59**	0.617	**3.95**	0.024	**4.53**	0.098

[a] N: total replies.
[b] VI: people reported to have vomited.

Table C.3
Observed and predicted MSIs along with models' fitness statistics—vessel C.

Trip	Observed			HFRI		ISO/BS		SV		SVH	
	N[a]	VI[b]	MSI (%)	MSI (%)	*P*	MSI (%)	*P*	MSI (%)	*P*	MSI (%)	*P*
1	262	4	**1.53**	**0.15**	0.001	**4.80**	0.009	**1.05**	0.359	**1.59**	1.000
2	388	8	**2.06**	**0.38**	0.000	**5.44**	0.002	**2.66**	0.634	**2.95**	0.368
3	221	4	**1.81**	**0.28**	0.004	**5.69**	0.008	**2.74**	0.536	**3.01**	0.427

[a] N: total replies.
[b] VI: people reported to have vomited.

Table C.4
Observed and predicted MSIs along with models' fitness statistics—vessel D.

Trip	Observed			HFRI		ISO/BS		SV		SVH	
	N[a]	VI[b]	MSI (%)	MSI (%)	*P*	MSI (%)	*P*	MSI (%)	*P*	MSI (%)	*P*
1	22	0	**0.00**	**6.21**	0.397	**9.18**	0.258	**3.82**	1.000	**4.15**	1.000
2	43	1	**2.33**	**6.71**	0.366	**10.86**	0.083	**10.16**	0.124	**10.39**	0.126
3	24	1	**4.17**	**8.34**	0.717	**16.24**	0.162	**9.80**	0.726	**10.02**	0.507
4	50	1	**2.00**	**7.23**	0.265	**13.89**	0.012	**9.22**	0.086	**9.43**	0.086
5	27	0	**0.00**	**11.94**	0.068	**22.12**	0.002	**13.90**	0.026	**14.36**	0.026
6	51	1	**1.96**	**6.08**	0.372	**10.22**	0.060	**4.81**	0.519	**5.03**	0.520

[a] N: total replies.
[b] VI: people reported to have vomited.

Table C.5
Observed and predicted MSIs along with models' fitness statistics—vessel E.

Trip	Observed			HFRI		ISO/BS		SV		SVH	
	N[a]	VI[b]	MSI (%)	MSI (%)	*P*	MSI (%)	*P*	MSI (%)	*P*	MSI (%)	*P*
1	54	0	**0.00**	**0.03**	1.000	**2.38**	0.641	**1.27**	1.000	**2.29**	0.638
2	38	0	**0.00**	**0.00**	1.000	**0.22**	1.000	**0.30**	1.000	**0.68**	1.000
3	28	0	**0.00**	**0.04**	1.000	**3.66**	0.626	**1.32**	1.000	**2.18**	1.000
4	52	0	**0.00**	**0.03**	1.000	**2.42**	0.639	**1.27**	1.000	**2.29**	0.635
5	43	0	**0.00**	**0.00**	1.000	**0.41**	1.000	**0.30**	1.000	**1.13**	1.000
6	24	0	**0.00**	**0.00**	1.000	**0.49**	1.000	**0.30**	1.000	**1.13**	1.000
7	19	0	**0.00**	**0.18**	1.000	**4.29**	1.000	**2.34**	1.000	**3.45**	1.000
8	5	0	**0.00**	**0.00**	1.000	**1.04**	1.000	**0.53**	1.000	**1.25**	1.000
9	7	0	**0.00**	**0.00**	1.000	**1.08**	1.000	**0.53**	1.000	**1.25**	1.000
10	63	0	**0.00**	**0.00**	1.000	**1.09**	1.000	**0.53**	1.000	**1.25**	1.000
11	15	0	**0.00**	**0.00**	1.000	**0.17**	1.000	**0.30**	1.000	**0.67**	1.000
12	8	0	**0.00**	**0.00**	1.000	**0.49**	1.000	**0.30**	1.000	**0.84**	1.000
13	26	0	**0.00**	**0.01**	1.000	**2.27**	1.000	**0.36**	1.000	**1.14**	1.000
14	4	1	**25.00**	**0.00**	0.000	**1.54**	0.060	**0.63**	0.025	**1.67**	0.065
15	52	0	**0.00**	**0.00**	1.000	**1.64**	1.000	**0.61**	1.000	**1.67**	1.000
16	15	0	**0.00**	**0.00**	1.000	**0.36**	1.000	**0.31**	1.000	**0.74**	1.000
17	14	0	**0.00**	**0.00**	1.000	**0.54**	1.000	**0.31**	1.000	**0.94**	1.000
18	20	0	**0.00**	**0.02**	1.000	**2.79**	1.000	**0.79**	1.000	**1.66**	1.000
19	137	0	**0.00**	**0.00**	1.000	**1.83**	0.188	**0.61**	1.000	**1.46**	0.275
20	38	0	**0.00**	**0.06**	1.000	**3.18**	0.635	**0.73**	1.000	**1.52**	1.000
21	30	0	**0.00**	**0.00**	1.000	**1.21**	1.000	**0.47**	1.000	**1.42**	1.000
22	55	0	**0.00**	**0.01**	1.000	**1.88**	0.629	**0.33**	1.000	**1.49**	1.000
23	37	0	**0.00**	**0.00**	1.000	**0.82**	1.000	**0.30**	1.000	**0.86**	1.000
24	114	0	**0.00**	**0.00**	1.000	**1.02**	0.635	**0.30**	1.000	**1.05**	0.637

[a] N: total replies.
[b] VI: people reported to have vomited.

Table C.6
Observed and predicted MSIs along with models' fitness statistics—vessel F.

Trip	Observed			HFRI		ISO/BS		SV		SVH	
	N[a]	VI[b]	MSI (%)	MSI (%)	*P*	MSI (%)	*P*	MSI (%)	*P*	MSI (%)	*P*
1	93	6	**6.45**	**1.63**	0.004	**5.31**	0.639	**7.08**	1.000	**7.79**	0.846
2	50	4	**8.00**	**1.71**	0.011	**6.01**	0.543	**6.96**	0.777	**7.90**	1.000
3	66	0	**0.00**	**0.35**	1.000	**3.36**	0.176	**2.92**	0.269	**3.90**	0.187
4	172	7	**4.07**	**1.31**	0.008	**5.33**	0.609	**6.26**	0.273	**7.18**	0.138

[a] N: total replies.
[b] VI: people reported to have vomited.

Table C.7
Observed and predicted MSIs along with models' fitness statistics—vessel G.

Trip	Observed			HFRI		ISO/BS		SV		SVH	
	N[a]	VI[b]	MSI (%)	MSI (%)	*P*	MSI (%)	*P*	MSI (%)	*P*	MSI (%)	*P*
1	58	1	**1.72**	**2.01**	1.000	**8.24**	0.089	**5.29**	0.373	**5.98**	0.263
2	140	5	**3.57**	**0.31**	0.000	**5.13**	0.563	**3.45**	0.817	**4.43**	0.836
3	48	3	**6.25**	**2.84**	0.155	**8.62**	0.797	**5.80**	0.757	**6.60**	1.000
4	137	5	**3.65**	**0.13**	0.000	**3.84**	1.000	**2.46**	0.396	**3.37**	0.810
5	38	2	**5.26**	**1.37**	0.096	**7.18**	1.000	**4.32**	0.679	**5.21**	1.000
6	68	0	**0.00**	**0.58**	1.000	**4.59**	0.077	**3.39**	0.177	**4.46**	0.077
7	114	0	**0.00**	**5.36**	0.003	**11.35**	0.000	**9.47**	0.000	**10.38**	0.000
8	109	3	**2.75**	**1.24**	0.154	**6.35**	0.165	**5.41**	0.290	**6.53**	0.122
9	38	2	**5.26**	**2.84**	0.294	**9.93**	0.583	**7.30**	1.000	**8.21**	0.767
10	64	6	**9.38**	**0.49**	0.000	**5.39**	0.159	**5.05**	0.140	**6.19**	0.291
11	64	7	**10.94**	**7.46**	0.334	**12.85**	0.851	**10.52**	0.839	**11.48**	1.000
12	64	2	**3.13**	**1.88**	0.340	**6.85**	0.324	**7.42**	0.238	**8.51**	0.174
13	37	9	**24.32**	**18.26**	0.392	**22.09**	0.695	**20.11**	0.538	**21.00**	0.686
14	45	5	**11.11**	**1.20**	0.000	**5.93**	0.190	**7.44**	0.384	**8.76**	0.593
15	51	0	**0.00**	**0.06**	1.000	**3.43**	0.423	**1.44**	1.000	**1.92**	1.000
16	100	1	**1.00**	**0.00**	0.001	**1.74**	1.000	**0.30**	0.260	**1.04**	1.000

[a] N: total replies.
[b] VI: people reported to have vomited.

Table C.8
Observed and predicted MSIs along with models' fitness statistics—vessel H.

Trip	Observed			HFRI		ISO/BS		SV		SVH	
	N[a]	VI[b]	MSI (%)	MSI (%)	*P*	MSI (%)	*P*	MSI (%)	*P*	MSI (%)	*P*
1	67	0	**0.00**	**0.09**	1.000	**3.54**	0.178	**1.37**	1.000	**2.38**	0.413
2	76	2	**2.63**	**0.17**	0.007	**4.27**	0.774	**1.20**	0.231	**2.11**	0.676
3	37	1	**2.70**	**0.05**	0.017	**2.98**	1.000	**1.12**	0.340	**2.09**	0.542
4	45	1	**2.22**	**0.41**	0.171	**4.84**	0.725	**1.18**	0.414	**2.39**	1.000

[a] N: total replies.
[b] VI: people reported to have vomited.

Table C.9
Observed and predicted MSIs along with models' fitness statistics—vessel I.

Trip	Observed			HFRI		ISO/BS		SV		SVH	
	N[a]	VI[b]	MSI (%)	MSI (%)	*P*	MSI (%)	*P*	MSI (%)	*P*	MSI (%)	*P*
1	46	0	**0.00**	**1.51**	1.000	**6.01**	0.114	**5.96**	0.114	**6.31**	0.118
2	81	4	**4.94**	**0.51**	0.001	**4.30**	0.780	**5.18**	1.000	**5.52**	1.000
3	78	0	**0.00**	**0.01**	1.000	**1.47**	0.633	**0.59**	1.000	**1.09**	1.000
4	36	0	**0.00**	**0.07**	1.000	**2.30**	1.000	**0.83**	1.000	**1.18**	1.000

[a] N: total replies.
[b] VI: people reported to have vomited.

Table C.10
Observed and predicted MSIs along with models' fitness statistics—vessel J.

Trip	Observed			HFRI		ISO/BS		SV		SVH	
	N[a]	VI[b]	MSI (%)	MSI (%)	*P*	MSI (%)	*P*	MSI (%)	*P*	MSI (%)	*P*
1	10	0	**0.00**	**0.00**	1.000	**1.30**	1.000	**0.92**	1.000	**1.76**	1.000

[a] N: total replies.
[b] VI: people reported to have vomited.

References

Arribas, F.L.P., Pineiro, A.L., 2007. Seasickness prediction in passenger ships at the design stage. Ocean Engineering 34 (14–15), 2086–2092.

Benson, A.J., 1999. Motion sickness. In: Ernsting, J., Nicholson, A., Rainford, D. (Eds.), Aviation Medicine. Butterworth & Heinmann, Oxford.

Benson, A.J., 2002. Motion sickness. In: Pandolf, K., Burr, R. (Eds.), Medical Aspects of Harsh Environments, vol. 2. Walter Reed Army Medical Center, Washington, DC, USA.

Bles, W., Bos, J.E., de Graaf, B., Groen, E., Wertheim, A.H., 1998. Motion sickness: only one provocative conflict? Brain Research Bulletin 47 (5) 481–487.

Bos, J.E., Bles, W., 1998a. Modelling motion sicknes. Models for Aircrew Safety Assessment: Uses, Limitations and Requirements, 26–28 October 1998, Ohio, USA, RTO MP-20.
Bos, J.E., Bles, W., 1998b. Modelling motion sickness and subjective vertical mismatch detailed for vertical motions. Brain Research Bulletin 47 (5), 537–542.
Bos, J.E., Bles, W., 2000. Performance and sickness at sea. In: Proceedings of the Human Factors in Ship Design and Operation Conference, September 2000, RINA, London, UK.
Bos, J.E., Bles, W., 2002. Theoretical considerations on canal–otolith interaction and an observer model. Biological Cybernetics 86 (3), 191–207.
Bos, J.E., Bles, W., Dallinga, R., 2002a. Prediction of seasickness with more than one degree of freedom. In: Proceedings of the Human Factors in Ship Design and Operation Conference, October 2002, RINA, London, UK.
Bos, J.E., Bles, W., Groen, E.L., 2008. A theory on visually induced motion sickness. Displays 29 (2), 47–57.
Bos, J.E., Bles, W., Hosman, R.J.A.W., 2001. Modelling human spatial orientation and motion perception. In: Proceedings of AIAA Modelling and Simulation Technologies Conference, August 2001, AIAA.
Bos, J.E., Damala, D., Lewis, C., Ganguly, A., Turan, O., 2007. Susceptibility to seasickness. Ergonomics 50 (6), 890–901.
Bos, J.E., Hosman, R.J., Bles, W., 2002b. Visual–vestibular interactions and spatial (dis)orientation in flight and flight simulation. TNO Report TM-02-C009, TNO Human Factors, Soesterberg, The Netherlands.
Crossland, P., 1998. A rational approach to specifying seakeeping performance in the ship design process. In: Paper presented at RINA International Symposium, Warship '98.
Dallinga, R., Pinkster, D., Bos, J., 2002. Human factors in the operational performance of ferries. In: Proceedings of the Human Factors in Ship Design and Operation Conference, October 2002, RINA, London, UK.
Dobie, T., McBride, D., May, J., 2001. The effects of age and sex on susceptibility to motion sickness. Aviation Space and Environmental Medicine 72 (1), 13–20.
Donohew, B.E., Griffin, M.J., 2004. Motion sickness: effect of the frequency of lateral oscillation. Aviation, Space, and Environmental Medicine 75 (8), 649–656.
Einstein, A., 1907. On the relativity principle and the conclusions drawn from it. Jahrbuch der Radioaktivitat und Elektronik 4, 411–462.
Ellis, G., 2002. Observers in Control Systems—A Practical Guide.. Elsevier Science, London, United Kingdom.
Golding, J.F., Markey, H.M., Stott, J.R.R., 1995. The effects of motion direction, body axis, and posture on motion sickness induced by low-frequency linear oscillation. Aviation Space and Environmental Medicine 66 (11), 1046–1051.
Golding, J.F., Mueller, A.G., Gresty, M.A., 2001. A motion sickness maximum around the 0.2 Hz frequency range of horizontal translational oscillation. Aviation Space and Environmental Medicine 72 (3), 188–192.
Griffin, M.J., 1990. Handbook of Human Vibration. Academic Press, London, United Kingdom.
Griffin, M.J., Mills, K.L., 2002. Effect of frequency and direction of horizontal oscillation on motion sickness. Aviation Space and Environmental Medicine 73 (6), 537–543.
Guedry, F.E., 1991. Factors influencing susceptibility. Individual Differences and Human Factors 1991, 18.
Haward, B., Lewis, C., Griffin, M., 2000. Crew Response to Motions of an Offshore Oil Production and Storage Vessel. In: Proceedings of the Human Factors in Ship Design and Operation Conference, September 2000, RINA, London, UK.
Highstein, M.S., Fay, R.R., Popper, N.A., 2004. Springer Handbook of Auditory Research: The Vestibular System. Springer, New York, USA.
Huston, R.L., Liu, C.Q., 2001. Formulas for Dynamic Analysis. Marcel Dekker Incorporation, New York, USA.
International Organisation for Standardization, 1997. Mechanical vibration and shock: evaluation of human exposure to whole-body vibration. Part 1: general requirements. ISO 2631-1, International Organisation for Standardization, Geneva, Switzerland.
Khalid, H., Turan, O., Bos, J.E., in press. Theory of subjective vertical–horizontal-conflict physiological motion sickness model for contemporary ships. Journal of Marine Science and Technology. doi:10.1007/s00773-010-0113-y.
Lawther, A., Griffin, M.J., 1986. The motion of a ship at sea and the consequent motion sickness amongst passengers. Ergonomics 29 (4), 535–552.
Lawther, A., Griffin, M.J., 1987. Prediction of the incidence of motion sickness from the magnitude, frequency, and duration of vertical oscillation. Journal of Acoustical Society of America 82 (3), 957–966.
Lawther, A., Griffin, M.J., 1988. A survey of the occurrence of motion sickness amongst passengers at sea. Aviation Space and Environmental Medicine 59 (5), 399–406.
Lobb, B., 2001. A frequency weighting for motion sickness susceptibility in the lateral axis. In: Proceedings of the 36th UK Group Conference on Human Response to Vibration, 12–14 September 2001, Farnborough, UK, pp. 386–398.
Luenberger, D., 1966. Observers for multivariable systems. IEEE Transactions on Automatic Control 11 (2), 190–197.
Luenberger, D., 1971. An introduction to observers. IEEE Transactions on Automatic Control 16 (6), 596–602.
Luenberger, D.G., 1964. Observing the state of a linear system. IEEE Transactions on Military Electronics 8 (2), 74–80.
Mayne, R., 1969. The analogy of the vestibular organs to an inertial guidance system. In: Proceedings of the Ninth International Conference on Oto-Rhino-Laryngology, Mexico City, Amsterdam, Excerpta Medica.
Mayne, R. (Ed.), 1974. Handbook of Sensory Physiology.. Springer, Berlin, Heidelberg, New York.
McCauley, M., Royal, J., Wylie, C., O'Hanlon, J., Mackie, R., 1976. Motion sickness incidence: exploratory studies of habituation, pitch and roll, and the refinement of a mathematical model. Technical Report No. 1733-2, Office of Naval Research (Human Factors Research).
McCauley, M.E., Pierce, E.C., Matsagas, P., 2007. The high-speed navy: vessel motion influences on human performance. Naval Engineers Journal 119 (1), 35–44.
McDonald, J., 2008. Handbook of Biological Statistics. University of Delaware Available from: 〈http://udel.edu/∼mcdonald/statexactbin.html〉.
McKenzie, E., 2008. Personal Discussion Regarding Goodness-of-fit Test for Field Trials on Motion Sickness. Department of Statistics and Modelling Science University of Strathclyde, Glasgow, UK.
Merfeld, D., Young, L., 1993. Spatial orientation in the squirrel monkey: an experimental and theoretical investigation. Annals of Biomedical Engineering 21 (2) 186–186.
Mittelstaedt, H., Glasauer, S., Gralla, G., Mittelstaedt, M.L., 1989. How to explain a constant subjective vertical at constant high speed rotation about an earth-horizontal axis. Acta Oto-Laryngologica Supplementum 468, 295–299.
O'Hanlon, J.F., McCauley, M.E., 1974. Motion sickness incidence as a function of the frequency and acceleration of vertical sinusoidal motion. Aerospace Medicine 45, 366–369.
Oman, C.M., 1982. A heuristic mathematical model for the dynamics of sensory conflict and motion sickness. Acta Otolaryngology Supplementum 392, 1–44.
Purves, D., Augustine, G.J., Fitzpatrick, D., Hall, W.C., Lamantia, A.-S., Mcnamara, J.O., Williams, S.M., 2004. Neuroscience third ed. Sinauer Associates, Inc., Sunderland, Massachusetts, USA.
Raphan, T., Cohen, B., Matsuo, V., 1977. A velocity storage mechanism responsible for optokinetic nystagmus (Okn), Optokinetic after-Nystagmus (Okan) and Vestibular Nystagmus. Control of Gaze by Brain Stem Neurons 1, 37–47.
Reason, J., 1978. Motion sickness: some theoretical and practical considerations. Applied Ergonomics 9 (3), 163–167.
Reason, J.T., 1970. Motion sickness: a special case of sensory rearrangement. Advancement of Science 26 (130), 386–393.
Reason, J.T., Brand, J.J., 1975. Motion Sickness. Academic Press Inc..
Stevens, S.C., Parsons, M.G., 2002. Effects of motion at sea on crew performance: a survey. Marine Technology 39 (1), 29–47.
Tamura, Y., Arima, M. (2006). Measurement and analysis of ship motion of a high-speed passenger craft. In: Proceedings of the Sixteenth International Offshore and Polar Engineering Conference, May-June 2006, San Francisco, California, USA. International Society of Offshore and Polar Engineers (ISOPE) 4, 514–519.
The British Standards Institution, 1987. Guide to Measurement and Evaluation of Human Exposure to Whole-body Mechanical Vibration and Repeated Shock. BS 6841:1987, The British Standards Institution, London, United Kingdom.
Turan, O., 2006. A rational approach for reduction of motion sickness and improvement of passenger comfort and safety in sea transportation (COMPASS). COMPASS Project Technical Report, Universities of Glasgow and Strathclyde, Glasgow.
Turan, O., Ganguly, A., Aksu, S., Verveniotis, C., 2003. Human comfort and motion sickness onboard high speed craft. FAST. Ischia, Italy. Comitato Organizzatore FAST.
Turan, O., Sebastiani, L., Ganguly, A., Bos, J., Lewis, C.H., 2005. COMPASS project: new findings regarding effects of ship motions on human comfort and the way forward. Human Factors Impact on Ship Design International Workshop, Genova, Italy.
Turan, O., Verveniotis, C., Khalid, H., 2009. Motion sickness onboard ships-subjective vertical theory and its application to full scale trials. Journal of Marine Science and Technology 14 (4), 1–8.
Turner, M., Griffin, M.J., 1999. Motion sickness in public road transport: passenger behaviour and susceptibility. Ergonomics 42 (3), 444–461.
Turner, M., Griffin, M.J., Holland, I., 2000. Airsickness and aircraft motion during short-haul flights. Aviation Space and Environmental Medicine 71 (12), 1181–1189.
Verveniotis, C.S., 2004. Prediction of motion sickness on high-speed passenger vessels: a human-oriented approach. Ph.D. thesis, Naval Architecture and Marine Engineering, Glasgow, United Kingdom, University of Strathclyde.
Verveniotis, S.C., Turan, O., 2002a. Motion sickness Prediction Model: A Human Oriented Approach. I.M.A.M. Crete, Hellas.
Verveniotis, S.C., Turan, O., 2002b. Prediction of motion sickness in high speed craft. In: RINA High Speed Craft Conference, London, UK.