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Reducing Motion Sickness by Manipulating an Autonomous Vehicle's Accelerations

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Abstract: Without intervention the widespread adoption of autonomous vehicles could be compromised by an increased incidence of motion sickness compared to conventional cars. To investigate whether passengers' motion sickness can be reduced by manipulating an autonomous vehicle's accelerations on a fixed route without altering the travel time, a human-out-of-the-loop experiment was performed in the SIMONA Research Simulator at Delft University of Technology. The experiment consisted of two different driving conditions, in which an identical 22-km road including 52 curves was travelled in 30 minutes. Condition 1 comprised larger longitudinal, but smaller lateral, acceleration values compared to Condition 2. Experimental results suggested that Condition 1 resulted in more severe motion sickness than Condition 2, with fitted learning curves providing final MIsery SCale scores of 1.19 vs. 0.80. A similar relative difference between the two conditions had been predicted by the 6-DOF Subjective Vertical Conflict model. Hence, this model has the potential to, once further developed, support the design of autonomous vehicles by reducing the need to perform costly, time-consuming experiments.

Keywords: motion sickness, autonomous vehicles, driving, mitigation, modeling

1. INTRODUCTION

At all times being able to engage in non-driving related activities will perhaps be the most prominent benefit of autonomous vehicles for their future users. Despite many other potential benefits, such as safer roads, reduced congestion and journey times, lower emission levels, and improved mobility for those unable or unwilling to drive, the widespread adoption of these vehicles might be compromised by the occurrence of motion sickness (e.g., Diels and Bos, 2016).

Whereas drivers rarely suffer from it, motion sickness is a widespread problem amongst passengers (Rolnick and Lubow, 1991). With currently only one in three car occupants being a passenger and close to six in ten of them suffering from carsickness (e.g., Schmidt et al., 2020), the percentage of car occupants experiencing motion sickness could increase from approximately 20% in conventional cars to roughly 60% in autonomous vehicles. Consequently, motion sickness mitigation measures are clearly warranted.

One opportunity for motion sickness mitigation lies in the design of the driving algorithms for these vehicles. Whereas much fundamental research has already been performed to identify the motion characteristics primarily responsible for provoking motion sickness (e.g., Cheung and Nakashima, 2006), little research thus far has focused on real-world applications, such as vehicle accelerations. Also, much of the knowledge obtained to date has come from empirical studies, having required an extensive number of experiments with human participants. Instead, performing model-based research could considerably reduce the need to perform experiments. A model quantitatively describing the development of motion sickness based on motion and visual inputs could aid in predicting motion sickness development in autonomous vehicles. A promising model for this, based on human physics, is the 6-Degree-of-Freedom (DOF) Subjective Vertical Conflict (SVC) model of Wada et al. (2020). However, this model has not yet been extensively validated.

The goal of this work is to investigate whether passengers' motion sickness can be reduced by manipulating an autonomous vehicle's accelerations on a fixed route without altering the travel time. A human-out-of-the-loop experiment was performed in which participants were subjected to two driving conditions travelling the same route in the same amount of time, but with different vehicle accelerations. The experiment results were compared to motion sickness simulations performed with the 6-DOF SVC model to investigate the model's accuracy in capturing the trend of the observed motion sickness severity.

This paper is structured as follows. The method is described in Section 2. Section 3 presents the experiment results. The paper ends with a discussion and conclusion.

2. METHOD

Rationale A human-out-of-the-loop experiment was performed to investigate whether passengers' motion sickness severity could be reduced by manipulating an autonomous vehicle's accelerations on a predefined route to be driven within

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Table 1. Acceleration profile and road layout parameter values

	Longitudinal acceleration			Longitudinal deceleration			Lateral acceleration		Road layout			
	$a_{\max}$	m	$\mid j_{\max} \mid$	$a_{\min}$	m	$\mid j_{\max} \mid$	$a_{\max}$	$\mid j_{\max} \mid$	d	n_{curve}	R_{curve}	curve (avg.)
	(ms^{-2})	($-$)	(ms^{-3})	(ms^{-2})	($-$)	(ms^{-3})	(ms^{-2})	(ms^{-3})	(m)	($-$)	(m)	(°)
Condition 1	4.12	0.4	7.87	-4.90	5.0	7.56	3.24	2.43	22,019	52	13	64
Condition 2	1.67	-0.15	3.94	-2.16	15.0	3.54	4.51	3.99				

a fixed amount of time. To this end, participants were passively exposed to two different vehicle motion profiles (i.e., two experiment conditions) to evaluate the difference in terms of motion sickness provocativeness. The two profiles travelled the same 22-km road including 52 curves in 30 minutes.

Independent Variables The single independent variable was the combination of longitudinal and lateral accelerations in the vehicle motion profiles. The first profile, Condition 1, had larger (longitudinal) deceleration and acceleration values before and after the curves, respectively. The second profile, Condition 2, on the other hand, contained larger lateral acceleration values in the curves.

Experiment Condition Design Both driving profiles consisted of a repetition of the following driving maneuvers on an identical road. A straight road section was driven with a constant velocity of 50 km/h. Near the end of the straight road section, before a curve, the 'vehicle' decelerated to a lower velocity with which it could safely take the turn. After having taken the turn with this lower, constant velocity, at the start of the next straight road section, the 'vehicle' accelerated again to a constant velocity of 50 km/h. The lengths of the straight sections as well as the directions of the curves and the curve degrees were varied to minimize motion anticipation, as anticipation decreases motion sickness severity (Rolnick and Lubow, 1991).

As a result of its larger longitudinal acceleration and deceleration values, Condition 1 contained a lower vehicle speed in the curves, and thus smaller lateral acceleration values, compared to Condition 2. However, within a single condition, all longitudinal acceleration profiles applied after a curve were the same, as well as all longitudinal deceleration profiles before a curve. Also, all curves were driven with the same lateral acceleration profile, except for that the duration of constant maximum lateral acceleration varied to simulate turns of different curve degrees.

The longitudinal acceleration and deceleration profiles were based on the kinematic polynomial acceleration model of Akçelik and Biggs (1987) to account for the realistic condition of zero acceleration at the start and end of the acceleration phase and smooth changes in acceleration rates. As recommended by Akçelik and Biggs, the free parameter n in the acceleration model was set equal to 1.0. The free parameter m in the model was chosen such that the maximum acceleration value was reached 1 s into the acceleration phase, and the maximum deceleration value 1.5 s before the end of the deceleration phase (Wang et al., 2004, 2005).

Finally, the longitudinal acceleration and deceleration profiles were passed through a second-order low-pass filter as given by (1) with a time constant of τ_s = 0.1 s to smooth the sharp increases at the start and end of these profiles, respectively, and thereby, reduce the excessively large jerk values. To reduce lateral jerk values, clothoids were implemented to transition between straight road sections and constant-radius-curves, meaning that the lateral acceleration profiles had a trapezoidal shape.

$$H_{acc}(s) = \frac{1}{(\tau_s s + 1)^2} \tag{1}$$

Absolute maximum acceleration values were chosen such that the longitudinal acceleration and deceleration of Condition 1 and the lateral acceleration of Condition 2 were classified as aggressive driving behaviour, whereas the lateral acceleration of Condition 1 and the longitudinal acceleration and deceleration of Condition 2 were classified as defensive behaviour (Karjanto et al., 2016). Acceleration profile and road layout parameters are listed in Table 1. The vehicle motion profiles were simulated in the horizontal plane, i.e., no vehicle suspension or road grade and/or irregularities were included, thus the designed driving profiles did not include any heave, pitch, or roll motion. Motion in these DOFs is usually modest on a smooth and level road, and would thus have a minor influence on the motion sickness.

Apparatus The experiment was performed in the SIMONA Research Simulator (SRS) at Delft University of Technology. The SRS is equipped with a 6-DOF hydraulic hexapod motion system. A static artificial horizon was projected on its 180°× 40°collimated outside visual screen, consisting of a blue upper rectangle, representing the sky, and a brown lower rectangle, representing the ground.

Motion Cueing Due to the limited motion space of the SRS, the vehicle's surge, sway and yaw motion could not be fully presented. Therefore, the motion was scaled by a gain K and attenuated through a first-order high-pass filter, as given by (2). To better cue (apparent) sustained linear accelerations, a second-order low-pass filter was applied for tilt coordination, as given by (3), where the angular rate was limited to 3 °/s (Groen and Bles, 2004). Motion filtering was performed such that the motion cues experienced in the left simulator seat, where the participants sat, simulated the motion felt in the left back seat of a real vehicle, i.e., 1 m behind and 0.5 m to the left of the vehicle's center of gravity.

$$H_{\text{HP}}(s) = \frac{s}{s + \omega_{n_{\text{HP}}}} \tag{2}$$

$$H_{\text{LP}}(s) = \frac{\omega_{n_{\text{LP}}}^2}{s^2 + 2\zeta_{\text{LP}}\omega_{n_{\text{LP}}} s + \omega_{n_{\text{LP}}}^2} \tag{3}$$

In (2) and (3), $\omega_{n_{\text{HP}}}$ and $\omega_{n_{\text{LP}}}$ represent the high-pass and low-pass filter break frequencies, respectively, in rad/s, and ζ_{LP} represents the low-pass damping ratio.

For fair comparison of the two conditions, identical motion filter settings were applied for surge, sway and yaw motion with $K_{f/\omega}$ = 0.4 and $\omega_{n_{\text{HP}}}$ = 3.0 rad/s. Both pitch and roll tilt were applied with $\omega_{n_{\text{LP}}}$ = 1.5 rad/s and ζ_{LP} = 1.0.

To allow for the first-order high-pass filters, while remaining within the SRS's limited motion space, and to at the same time *virtually* enlarge the motion envelope, *off-line* prepositioning was applied below the human's perceptual threshold to avoid rendering of false motion cues. To start and end with a velocity

Table 2. Parameter values of the 6-DOF SVC model

K_a (–)	K_ω (–)	K_{ω_c} (–)	K_{v_c} (–)	K_{a_c} (–)	$K_{\omega_{vis}}$ (–)	τ_d (s)	b (ms^{-2})	τ_I (min)	P (%)
0.1	0.1	10.0	5.0	1.0	3.0	7.0	0.5	12.0	85.0

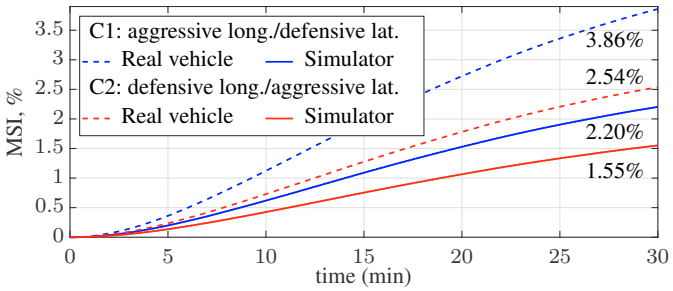


Fig. 1. MSI development according to 6-DOF SVC model.

of zero and to limit both acceleration and jerk values throughout prepositioning, the acceleration profile was designed to have a trapezoidal shape, followed by the inverted pattern to brake the second half of the distance. Prepositioning accelerations never exceeded 0.04 m/s^2 and jerk values remained below 0.1 m/s^3 (Heerspink et al., 2005; Hansson et al., 2015).

Motion Sickness Modeling To gain insight into the influence of the designed vehicle accelerations on passengers' motion sickness development, simulations were performed using the 6-DOF SVC model before the experiment. The model's output is the Motion Sickness Incidence (MSI), defined as the percentage of people who would vomit as a result of the motion which was used as input to the model.

These simulations were made under the assumptions that (1) the passenger would be seated in the left back seat of the vehicle, which was also the vehicle's seat the motion was cued for in the simulator, (2) the orientation of the passenger's head would follow the orientation of the vehicle, i.e., no pitch or roll movements of the head were included, and (3) no outside visuals would be available to the passenger, meaning that they would see static visuals consisting of the inside of the vehicle, and as a result, the information coming from the vestibular organs and the visual system would be conflicting. The latter assumption was made to mimic the condition that in autonomous vehicles, engagement in non-driving related tasks or a different seating orientation, for example, could preclude a view of the outside world. Table 2 lists the applied model parameter values, which were influenced by the last assumption. To simulate the static visuals, the *visually*-perceived angular velocity was set to $\boldsymbol{\omega_{vis}}$ = 0 rad/s, as static visuals were also used in the experiment.

Fig. 1 shows that the simulated MSI at the end of the 30-minute vehicle motion equaled 3.86% for Condition 1 and 2.54% for Condition 2. When the actual motion experienced in the left simulator seat – representing a vehicle's left back seat –, was used as input to the model, the simulated MSI reduced to 2.20% for Condition 1 and 1.55% for Condition 2. This reduction was the direct result of filtering the true vehicle motion to "washout" the simulator's accelerations to be able to remain within its physical motion space. However, despite motion filtering, the relative difference between the two conditions remained very similar, as it equaled 34% for the vehicle motion and 30% for the simulator motion.

Participants Seven male and six female participants (μ = 37.6 yr, σ = 9.2 yr) completed the experiment. All were staff members of TU Delft not familiar with the research. They reported a median Motion Sickness Susceptibility Questionnaire (MSSQ) score of 6 (μ = 9.9, σ = 10.4), which falls around the 30th percentile for motion sickness susceptibility (Golding, 2006). All reported to have normal or corrected-to-normal vision and no vestibular disorders. Participants were asked to refrain from consuming alcohol or other substances with similar effects at least 24 h prior to the experiment sessions. All participants provided written informed consent prior to their participation. The experiment design and protocol were approved by the Human Research Ethics Committee of TU Delft.

Experiment Procedures All participants were subjected to the two 'driving' profiles in the simulator on two separate days with an average interval of six days. The order of the two conditions was counterbalanced between participants to minimize the impact of the order effect on the dependent measures. At the start of the first session, participants were instructed on the use of the MIsery SCale (MISC) used to assess their motion sickness (Bos et al., 2005). They were also notified that the motion exposure would be aborted prematurely if they reported a MISC score of 6 twice in a row (i.e., with a 1-minute interval), or a score of 7 or higher for the first time.

During both sessions, participants were seated in the left simulator seat and instructed to maintain a relaxed posture with a straight back and look straightforward, directly at the artificial horizon projected on the SRS's outside-visuals screen. Throughout the 30-minute motion exposure as well as a 15-minute recovery period, spent seated in the non-moving simulator, participants verbally reported their MISC score as a single integer in 1-minute intervals as a response to the researcher asking 'SCORE?' over the intercom. The researcher wrote down their reply to avoid participants having to move their heads when providing their MISC scores. A depiction of the MISC was available in the simulator, on the right side of the participants' seat, and participants were allowed to actively rotate their heads to have a look at the scale at all times.

Dependent Measures The following four subjective measures were recorded for each individual:
(1) *Motion sickness susceptibility*: Participants' individual motion sickness susceptibility in comparison to the general population was determined using the short version of the MSSQ (Golding, 2006).
(2) *Motion sickness scores*: The time-course development of motion sickness was tracked on a 1-minute interval using participants' MISC scores throughout the 30-minute motion exposure and 15-minute recovery period.
(3) *Motion sickness symptoms*: Symptoms experienced during the motion exposure or recovery period were checked through the use of a dedicated motion sickness symptom checklist, including 24 commonly experienced symptoms, at the end of both experiment sessions. Symptom severity was rated on a 4-point ordinal scale.
(4) *Motion assessment*: Participants' perceived realism of the simulator motion with respect to real vehicle motion as well as the comfort of the motion were assessed using six different statements, rated on a five-point Likert scale, at the end of both experiment sessions. The questionnaire explicitly instructed to solely judge the simulator motion, i.e., not considering, amongst others, visuals and sound.

To quantitatively describe the differences in motion sickness development between the two 'driving' profiles, learning curves

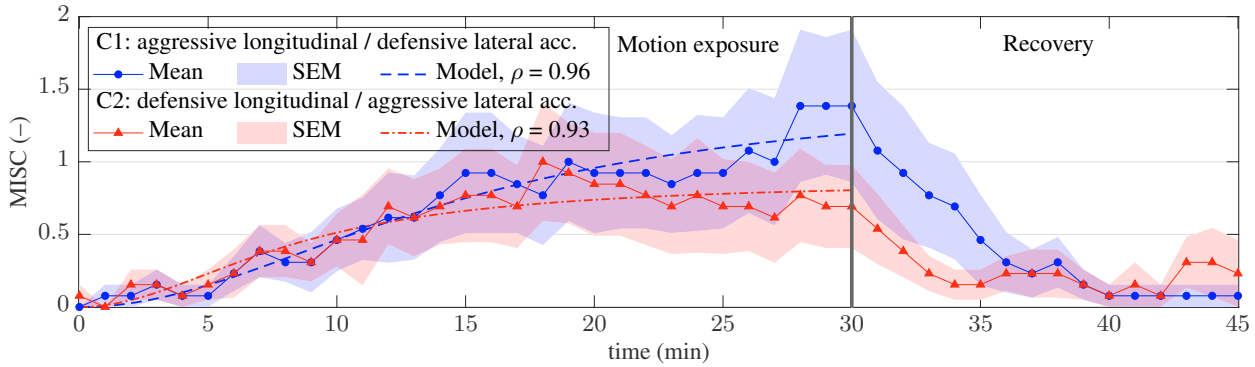


Fig. 2. Time-course development of MISC scores for both experiment conditions.

were fitted to the combined MISC scores of all 13 participants throughout the motion exposure, where the considered learning curve model is given by:

$$\text{MISC} = A/(1 + (t/B)^{-2}) \tag{4}$$

In (4), t is the time and A and B are to be determined constants. This model was chosen as people cannot be "sicker than sick", meaning that the maximum sickness value must be reached asymptotically. Fitting such a curve naturally means that the assumption is made that MISC data follow an interval scale.

Hypotheses Based on the simulations with the 6-DOF SVC model, it was hypothesized that the development of motion sickness can be impacted by driving the same route within the exact same amount of time with different vehicle accelerations. Related to this, it was expected that Condition 2 would result in less severe motion sickness compared to Condition 1.

3. RESULTS

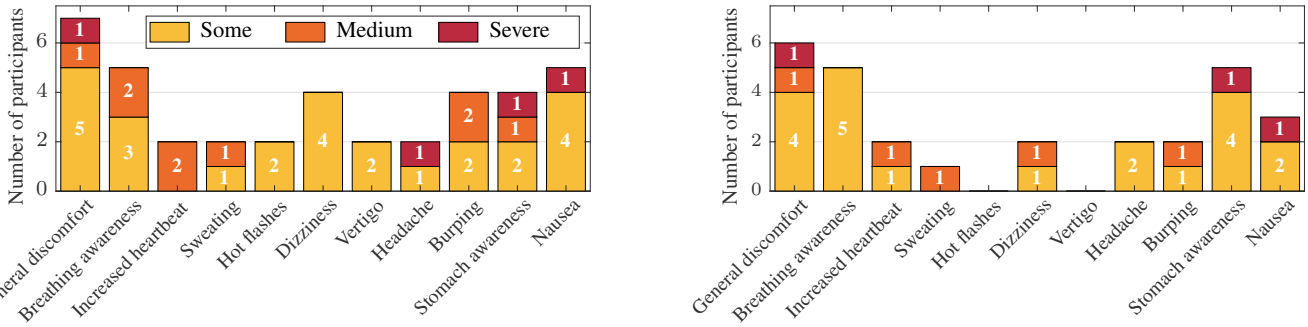
MISC Scores Fig. 2 shows the development of the mean MISC scores and the corresponding Standard Error of the Mean (SEM) throughout the motion exposure and recovery period for both experiment conditions. Throughout roughly the first 15 minutes, the MISC scores developed similarly in both conditions, after which a further increase in mean MISC score was seen for Condition 1, while the mean MISC score for Condition 2 seemed to slightly decrease again. At the end of the motion exposure, the mean MISC score for Condition 1 equaled 1.38, compared to 0.69 for Condition 2. A Wilcoxon signed-rank test confirmed, however, that there was no statistically significant difference between the MISC scores of the two conditions at the end of the motion exposure (Z = -1.594, p = 0.111). The learning curves provided MISC scores of 1.19 and 0.80 at the end of the motion exposure for Conditions 1 and 2, respectively. No participant reported a MISC score of 6 or higher, or otherwise requested to terminate the motion exposure early, in either of the two conditions. Therefore, no experiment sessions were aborted prematurely.

The variation in MISC scores among participants was considerable for both conditions, from around 10 minutes into the motion exposure, until about 5 minutes into the recovery period. Immediately after the motion had stopped, MISC scores decreased almost exponentially for both conditions. However, for Condition 2, the MISC scores started to fluctuate again after its initial decrease. While many participants experienced a consistent decrease in MISC scores after the motion had stopped, one participant reported fluctuating MISC scores throughout the recovery period for both conditions and two participants reported those for Condition 2 only, of which one explicitly stated that throughout the recovery period of Condition 2 at times they felt as if they were being driven through a curve again. Overall, the fluctuating scores throughout the recovery period of Condition 2 can thus be attributed to a few participants, and cannot be considered a general trend.

When comparing the results of the two experiment groups with opposite order of conditions, a small order effect was observed. In the group that first performed Condition 1, followed by Condition 2 (C1-C2), the MISC scores were consistently higher for Condition 1 compared to Condition 2. In the other group, having performed Condition 2 first, followed by Condition 1 (C2-C1), the MISC scores were actually lower for Condition 1 than for Condition 2 throughout approximately the first 18 minutes. However, after 30 minutes of motion, also for this group the MISC scores were higher for Condition 1 compared to Condition 2. When comparing the MISC scores at the end of the motion exposure, as provided by the individual groups' learning curves, the relative difference in MISC scores between the two conditions was around 30% (1.71 vs. 1.25) for Group C1-C2, and over 40% (0.60 vs. 0.34) for Group C2-C1, with Condition 1 resulting in the higher score. It must be noted that Group C2-C1 thus reported much lower overall MISC scores than Group C1-C2, despite having similar distributions in participants' MSSQ scores. Expressing the differences in MISC scores between the two conditions using means and percentages again assumes the data to follow an interval scale.

Overall, the MISC scores indicate that Condition 2 led to somewhat less severe motion sickness compared to Condition 1. This is in line with the pre-experimental simulations with the 6-DOF SVC model, that provided a higher MSI for Condition 1 compared to Condition 2.

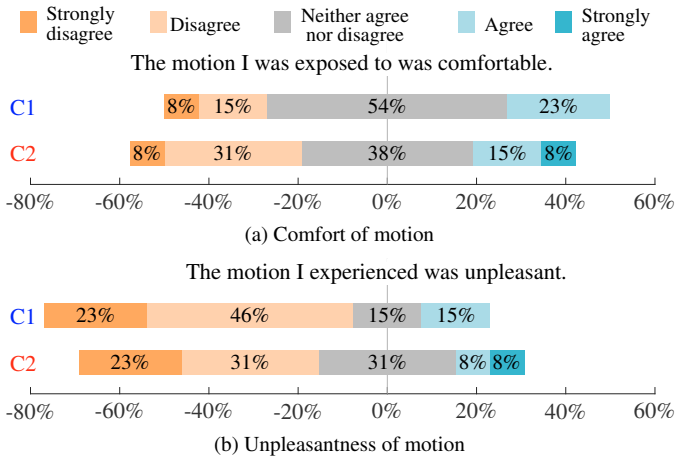
Motion Sickness Symptoms Figs. 3(a) and 3(b) show the occurrence of common motion sickness symptoms for Conditions 1 and 2, respectively. Only the participants that experienced a particular symptom to at least some extent are included. Most symptoms have either been reported by more or by the same number of participants, but then with a higher severity, for Condition 1 compared to Condition 2, including general discomfort, awareness of breathing, and nausea. The exception to this is that in Condition 1, four participants reported some dizziness, and even though in Condition 2, only two participants reported dizziness, one of them experienced it to a medium extent. Also, in Condition 1, four participants had suffered from stomach awareness, of which one on a medium level, and another one to a severe extent, while in Condition 2, five participants mentioned stomach awareness. However, only one



(a) Condition 1: aggressive longitudinal / defensive lateral accelerations

(b) Condition 2: defensive longitudinal / aggressive lateral accelerations

Fig. 3. Occurrence of common motion sickness symptoms throughout or right after the motion exposure.



(a) Comfort of motion

(b) Unpleasantness of motion

Fig. 4. Subjective motion comfort responses.

participant reported to have felt severe stomach awareness, the other four had suffered from it to some extent.

Subjective Motion Comfort Fig. 4 shows the responses to two comfort statements of the motion assessment questionnaire. Surprisingly, more participants disagreed with the statement that the motion they were exposed to was comfortable for Condition 2, compared to Condition 1 (see Fig. 4(a)). However, one participant strongly agreed with the statement for Condition 2, compared to no participants for Condition 1. Equivalently, more participants disagreed with the statement that the motion of Condition 1 was unpleasant, compared to Condition 2 (see Fig. 4(b)). Both statements therefore indicate that participants seemed to subjectively favor Condition 1 over Condition 2, which contradicts the MISC scores and motion sickness symptoms in Figs. 2 and 3, respectively. Wilcoxon signed-rank tests confirmed, however, that there were no significant differences between the two conditions in terms of subjective comfort (Z = -0.447, p = 0.655) or unpleasantness (Z = -1.134, p = 0.257).

When examining individual responses, seven out of 13 participants provided the same responses for Conditions 1 and 2, four somewhat more positive responses for Condition 1 compared to Condition 2, while two seemed to prefer Condition 2 over Condition 1. However, only for two out of the four participants who seemed to subjectively favor Condition 1 over Condition 2, their MISC scores supported that statement. For the other two, their average MISC scores were actually lower for Condition 2 compared to Condition 1. On the other hand, for the two participants that seemed to prefer Condition 2 over Condition 1, the MISC scores underwrote that statement for only one of them, whereas the other reported MISC scores of 0 throughout the entire motion exposure and recovery period of both conditions and explicitly mentioned after the second session that they "felt that there was not much difference between the two sessions in terms of the motion". Surprisingly, five out of the six participants who provided different responses for the two conditions, were more positive about the condition they had experienced in the first session (4×C1, 1×C2) than the one of the second session, where the participant favoring C2 was the person with only MISC scores of 0.

4. DISCUSSION

Even though no statistically significant difference could be found between the MISC scores at the end of the 30-minute motion exposure of the two experiment conditions, both the MISC scores and the reported motion sickness symptoms suggested that Condition 2 led to less severe motion sickness compared to Condition 1, as was also predicted by the pre-experimental simulations with the 6-DOF SVC model, despite a small order effect being present in the MISC scores. These results are in line with the hypothesis that the development of motion sickness can be impacted by driving the same route within the exact same amount of time, but with different vehicle accelerations.

On the other hand, the responses to the motion assessment questionnaire seemed to suggest otherwise. Participants provided more positive responses concerning Condition 1 than Condition 2. However, as for some participants their MISC scores contradicted their questionnaire responses, it might be that these responses were less reliable. Whereas MISC scores are based on the typical progression of motion sickness symptoms and the motion sickness symptom checklist is directly based on the symptoms a participant experienced in the past hour, the motion assessment questionnaire has a more subjective nature. Participants' responses to the two conditions can only be compared to one another indirectly, and with an average interval of six days between the conditions, it could be that participants judged the Likert scale differently during the two sessions.

Still, when comparing the MISC scores and the reported motion sickness symptoms, some discrepancies were found. In the motion sickness symptom checklist, several participants indicated to have experienced some or even severe nausea during one or both of the sessions (see Fig. 3). According to the MISC, however, some nausea corresponds to a score of 6, while severe nausea corresponds to a score of 8. The fact that no participant has ever reported a score higher than 5 at any time during the experiment indicates a discrepancy between the reporting of MISC scores and motion sickness symptoms by participants.

This discrepancy between MISC scores and symptoms might have been related to participants being hesitant to report a score of 6 or higher, as they were aware that it would lead to the premature abortion of the session, while, in their judgement, they still felt well enough to continue. Therefore, it could be considered to, in future experiments, only explain how to use the MISC, but not inform participants in advance of at what score the session will be aborted, in an attempt to minimize discrepancies between reported MISC scores and symptoms.

To gain insight into the accuracy of the 6-DOF SVC model, one would preferably quantitatively compare the model's predicted MSI with the observed MISC scores. However, unfortunately, this is problematic to do, as the MSI is considered ratio data, whereas, in reality, the MISC scores are ordinal data, and not interval data. Therefore, comparisons between the MSI and the MISC scores should always be made with caution. Still, some parallels and distinctions between the two are drawn for this experiment, as real-world observations such as MISC scores are crucial to be able to improve the applicability and accuracy of the 6-DOF SVC model.

The predicted MSI and the observed MISC score developments did not follow the same trend (see Figs. 1 and 2), with the latter increasing faster than the simulated MSI. Apart from being different data types, this can be considered a direct result of the definitions of these measures. Whereas the MISC concerns a scale focusing on the progression of motion sickness symptoms, the MSI is a measure of the occurrence of vomiting, the symptom that on the MISC is rated as a 10, the highest score possible. Since vomiting is almost always preceded by other motion sickness symptoms lower on the MISC, such as dizziness, stomach awareness or nausea (Bos et al., 2005), it is to be expected that the MSI "lags behind" the MISC score development.

Both the predicted MSI and the observed MISC scores indicated that Condition 1 resulted in more severe motion sickness compared to Condition 2. Whereas the MSI showed a relative difference between the two conditions of 30%, the MISC learning curves indicated a relative difference of 33%. Even though these values can of course not be compared one-to-one, due to the different definitions or natures of these measures and the fact that the MISC is actually an ordinal scale, and not an interval scale, it does suggest that the difference between the two experiment conditions predicted by the 6-DOF SVC model, is in the right order of magnitude and hence, the 6-DOF SVC model is a promising tool to, once further developed – especially when given some additional attention to its output measure –, support the design of autonomous vehicles by reducing the need to perform costly, time-consuming experiments.

5. CONCLUSION

This paper investigated whether an autonomous vehicle's accelerations can be manipulated to reduce passengers' motion sickness on a fixed route without altering the travel time. A human-out-of-the-loop experiment was performed in which participants were subjected to two different driving profiles, covering the same route within the same amount of time, but with different vehicle accelerations. Even though no significant differences were found in motion sickness between the two conditions, results suggested that Condition 1, with larger longitudinal, but smaller lateral, acceleration values, resulted in more severe motion sickness than Condition 2. The 6-DOF SVC model had predicted a similar relative difference in motion sickness between the two conditions, and can thus be considered a promising motion sickness prediction model to be further developed, to ultimately aid in reducing the need for costly, time-consuming experiments in autonomous vehicle design.

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