

RESEARCH ARTICLE

Development of On-Road Automated Vehicle Simulator for Motion Sickness Studies

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This paper presents the development of the Mobility Lab, an instrumented car that was developed to support research on the comfort of automated driving. The Mobility Lab was established as a platform to investigate the implications of motion sickness on human users especially when exposed to low-frequency horizontal forces while engaging in non-driving activities. First, the Mobility Lab's overview of interior setup and system architecture involving data acquisition system with its sensors is described. Then, a validation study is presented, comprising of simulations with forty-six participants by two designated drivers. The simulations were focusing on the manipulation of lateral acceleration based on defensive automated driving style settings. The consistency of the manipulations in terms of accelerations, velocities, frequencies and motion sickness dose values by both drivers was measured and compared. Subjective motion sickness assessments, as well as user rating towards the believability of the Mobility Lab platform, were also carried out. The results indicate good reliability in producing consistent simulations of automated driving experience within the desired settings. In addition, the versatility of Mobility Lab in term of flexibility on interior setup arrangement and also its measurement system makes various automated driving related experiments possible.

Keywords: Instrumented car; automated driving experience; lateral acceleration; driving style; motion sickness

Introduction

According to both taxonomies by NHTSA (National Highway Traffic Safety Administration, 2013) and BAST (Gasser & Westhoff, 2012), there are five levels of automation in which the highest level is fully automated driving. Within this level, the automated car (AC) will drive itself and perform all the driving tasks and make traffic-related decisions. Human drivers will become passive users whose journey time will be filled with non-driving activities (NDA). Currently, we are at the third automation level, but technology may arrive fast as some companies are already testing with the fourth level of the automation (Etherington, 2016). When the fully automated car is ready to be used by users, the definition of driving will change from operational directly to strategic based on the three levels of driving proposed by Michon (1985). In a fully automated mode, the human driver may just need to

enter strategic information such as the final destination or preferred arrival time. Then, the AC will take over the two lower levels of driving; tactical (such as manoeuvring and taking over) and operational (such as accelerate and braking). In terms of driving, AC is expected to operate with a defensive driving style but in highly efficient and optimized means to deliver safe and sustainable mobility. A few discussions about driving styles for the AC have been put on the table, like the implementation of assertive driving style for an automated car in order not to be bullied by the human-driven cars especially when driving in the bustling city (Gray, 2014; Jaffe, 2015). Another example is the AC that drives a bit faster than the designated speed limit, to imitate the realistic norms of human drivers' on the road (Miller, 2014). Recent studies were done by Basu, Yang, Hungerman, Singhal, and Dragan (2017) and Yusof et al. (2016) found that human drivers preferred more defensive driving styles when they were passive users subjected to several driving styles in automated driving/riding simulations.

Studies done with a semi-automated driving setup have revealed drivers' tendency to engage in NDA such as using handheld devices (Llaneras, Salinger, & Green, 2013) and watching electronics display (Carsten, Lai, Barnard, Jamson, & Merat, 2012). A survey which was completed

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by more than 3200 respondents from China, India, Japan, USA, United Kingdom and Australia found that among the top activities envisioned inside full automated cars are reading, working and watching TV or movies (Schoettle & Sivak, 2014). Indeed, the conceptual interior design and layout of future ACs unleashed by companies like Rinspeed, Johnson Controls, IDEO and Zoox support the NDA with the presence of setup and equipment that allow a productive and enjoyable journey to the destination. On the same hand, car companies like Mercedes (F125), Nissan (Nuvu), Honda (CARpet) and Volkswagen (Trimaran) have released their versions of prototypes to the public that are backing up the idea of NDA in higher- and fully-automated driving/driving. As pointed out by Diels (2014), AC's interior would be rebuilt and redesigned with the aim of enhancing entertainment, work, and social experiences.

Motion sickness (MS) is predicted to lower the physical comfort in higher and full automated experience as elaborated by the recent works (Diels, 2014; Diels & Bos, 2016; Sivak & Schoettle, 2015; Wada, 2016). They reported that this phenomenon would occur as the results of the passive roles of the drivers, the engagement in NDA and also the unconventional seating arrangements inside the future AC. In addition, the geometry of the land roads is not as straighter as the railways' track where the users would experience lower horizontal accelerations. Furthermore, with trains, slower longitudinal accelerations and decelerations can be realised because of the stretched track prior to leaving or arriving at the destination. Therefore, acceleration forces felt by the train passengers are minor, enabling them to do activities like reading a book, working on a laptop, and watching a movie/video comfortably. On the other hand, AC users, who may be doing similar tasks but are driven on the suburban roads set up, may be prone to MS. It is due to lateral forces and fore-and-aft accelerations which occur due to intersections and shorter radii corners. Lateral accelerations with low frequencies, between 0.1 to 0.5 Hz, will significantly increase the effects of MS, as has been shown in past study (Turner & Griffin, 1999). The other two equally critical contributing parameters are the duration of the exposure and the intensity of the amplitude.

Therefore, there is a need to investigate the implications of future AC users' experience when subjected to AC driving style while they are performing the NDA. To be specific, the study on the automated driving in a suburban environment where lateral forces are changing more frequently and abruptly when compared to the highway road settings. In this paper, the development of the Mobility Lab, an instrumented car for simulating the automated driving experience on real roads will be discussed. This platform was specially designed to study the effects of MS when users are engaging in the NDA. Several essential setups, such as selected driving style and modified interior cabin will be explained as well as procedures and equipment used in this study. A validation study was conducted to validate the ability of Mobility Lab in simulating consistent the AC driving simulations and therefore consistent MS dosage to all the participants.

Overview of Mobility Lab

Instrumented car

The design concept of the development of Mobility Lab is motivated by the need to simulate the AC driving/riding experience and to examine the level of MS in higher automation settings. The suitable vehicle to be used is a multi-purpose vehicle (MPV) as three rows of seats are required (see **Figure 1**).

First row seats are for the driver and experimenter, while the second-row seats will be taken out to make room for the placement of a table. A partition was built between first and second-row seats to separate the experimenters and participants. A TV display, which functions are to show a movie/video or to display the windshield-view sharing what the driver sees, was mounted on the separator. The third-row seats can support up to two participants, depending on the requirement and condition of future studies. Moreover, single or split seats in the third row are preferable to allow the participants to feel at ease. A safety belt that was attached to the seat rather than the body of the car is preferred on top of adjustable seats and flexible seating layout. Renault Espace IV is one of the cars that offer this kind of seat arrangement, and because of its smart railing system, a rearward seating is also possible and safe. A device called Automatic Acceleration and Data controller (AUTOAccD) that was developed and tested (Karjanto et al., 2017) to assist the designated driver in achieving the intended AC driving styles during the experiments was also implemented inside the Mobility Lab. AUTOAccD consisted of an Arduino board that was connected to an accelerometer. The AUTOAccD display was designed to assist the designated driver in maintaining a particular driving style by showing a specific range of lateral and longitudinal forces during the AC driving simulation. In addition, a data acquisition system (DAQ) was used to synchronize and to record data from measurement sensors.

Figure 2 illustrates some of the variety of setup inside the Mobility Lab for MS studies. All the variations were possible with the existing railing system that allows the facing forward and backwards as well as a supine position. In addition, since the seat belt is attached to the seat rather than to the body of the car, safety will not be an issue. One of the seats has been modified into a table where a device such as a laptop or a tablet can be placed. Apart from showing a

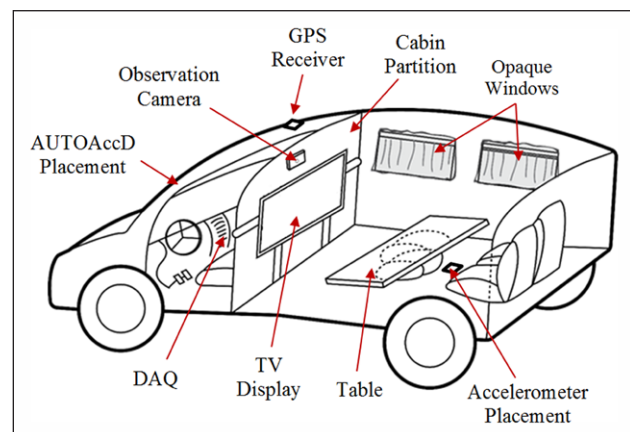


Figure 1: Mobility Lab interior layout.

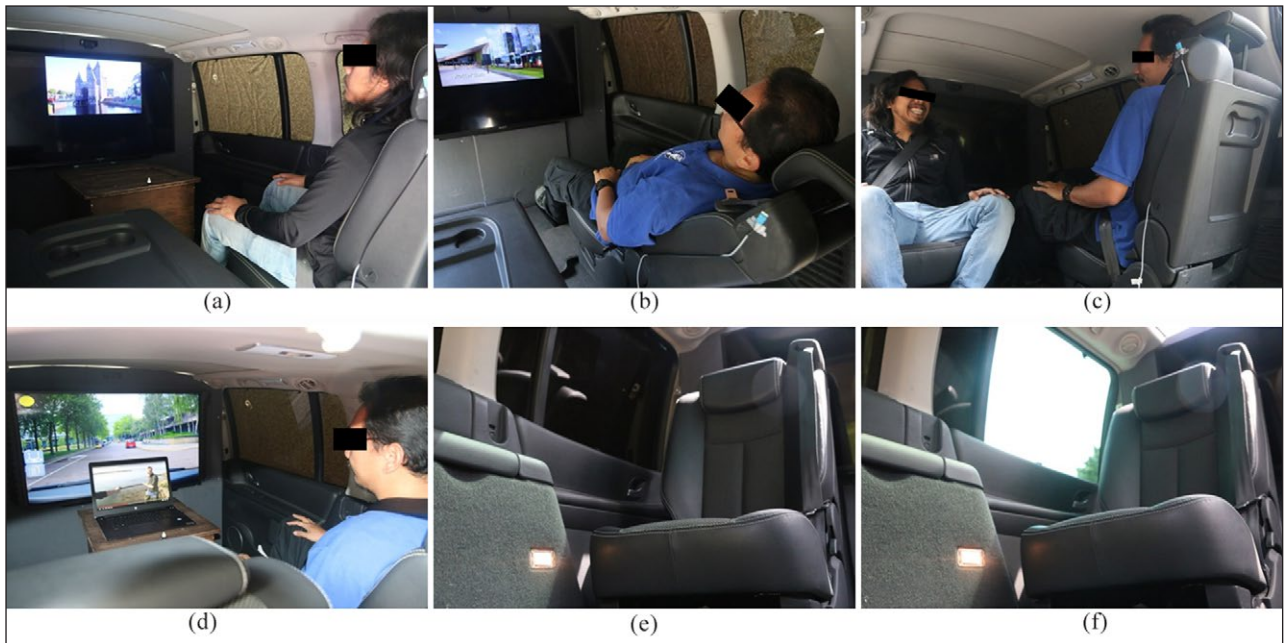


Figure 2: Several setup variations in Mobility Lab; **(a)** Upright sitting and watching a video; **(b)** Supine and watching a video; **(c)** Socializing with one passenger is facing backward, and the other is facing forward; **(d)** Watching a video on a laptop while the display acting as the front windshield (showing the incoming road); **(e)** Opaque windows (no outside view); and **(f)** Transparent window (standard view).

video like in **Figure 2(a)** and **(b)**, the display system is also connected to a live feed camera and hence has the ability to project the front windshield view of the road as shown in **Figure 2(d)**. The window on the Mobility Lab can be set as opaque or transparent as shown in **Figure 2(e)** and **Figure 2(f)**, respectively. Opaque-window setup can be employed to study the effects of modalities (e.g., light, haptic and/or audio) in mitigating MS, enhancing situation awareness (SA), or studying the development of artificial horizon inside a vehicle as suggested by previous works (Diels & Bos, 2015, 2016; Wada, 2016).

The idea of eliminating the outside view is to minimize the ceiling effect that might occur as participants might frequently switching between focusing on NDA and looking outside in order to gather information. If that was the case, therefore the real effects of independent variables are harder to be measured, and the likeliness of misinterpretation may happen. In addition, in opaque-window setup, it is assumed that when users are fully engaged in the NDA, they will become unaware of what was happening outside. Hence, with opaque-window, no distraction or cues from outside may ensure the validity of measurement in a way that reaction from participants is purely coming from the controlled variables coming from inside the ML. On the other hand, the transparent-window setup does provide a realistic setting very similar to the current and projected car’s interior based on some of the concept cars released by the automakers. Therefore, real reaction and interaction can be studied from the most realistic setup although extracting data from uncontrolled setting might be a real challenge. Some even argued about the requirement for windows on an automated vehicle because of safety concern (Wayner, 2015) and practicality point of view (Hamill, 2015).

Data acquisition system and measurement sensors

One important aspect of the scope of the planned studies is to synchronize readings from all the sensors and measurement devices. All data should have a consistent time stamp with automatic data logging for analysis afterwards. National Instrument compactRIO-9030 (NI cRIO 9030) was implemented in this study because of its ability to run re-configurable field-programmable gate array (FPGA) programs on a real-time (RT) processor. In addition, NI cRIO 9030 is a rugged industrial-grade controller that can withstand up to five (5) g in vibration and therefore is suitable to be used within an instrumented car on a real road condition. The current setup of NI cRIO 9030 consists of two modules, NI 9041 and NI 9205. NI 9041 is a digital input/output module and any devices with digital output, for example, a simple clicker to indicate the awareness of presented stimuli could be implemented. NI 9205 is an analogue input module that can be connected to any analogue sensors such as accelerometer and pulse sensor.

The accelerometer used in the development of Mobility Lab is an ADXL335 which is a small, cost-efficient, and low power 3-axis accelerometer that produces analogue voltage outputs. The accelerometer was attached close to the centre of gravity of the Mobility Lab. ADXL335 can measure up to ± 3 g for both the static (e.g., gravity) and dynamic accelerations (e.g., motion) in the triaxial directions. This device has frequency responses/outputs between 0.5 to 1600 Hz in both the x and y-axis and 0.5 to 550 Hz in the z-axis (Earl, 2015). ADXL335 has been used in multiple fields of research such as sensing motion from human users (Hollocher et al., 2009) and also measuring forces from vehicles (Bergeron & Baddour, 2011; Giuliano, Marsic, & Zhu, 2012).

A GPS receiver was implemented to get an exact location when a particular measurement is taken. The model used is an Adafruit Ultimate GPS Breakout (Fried, 2016), consisting of a chipset that can provide up to 10 Hz update rate. With an active/external antenna, it has a sensitivity of -165 dBm and requires only 5 Volts input and with 20 mA current draw. Furthermore, it can give accurate time reading to provide a proper synchronization device to the whole measurement system.

Validation Study

A study with the aim to validate the capability of Mobility Lab in simulating AC driving on a consistent basis was performed by two designated drivers. Both longitudinal and vertical accelerations were controlled, but only the lateral accelerations were manipulated. Two designated drivers conducted a total of 46 simulations with the interior setup as in **Figure 2(a)**. All the simulations were done within the authors' university compound on which the speed limit is 30 km/h. The two drivers were not specially trained drivers but rather two regular drivers with more than ten years of driving experience. Within this route, there are altogether 18 turnings/corners (ten right corners and eight left corners) with a radius ranging from 6.0 to 17.6 meters (Mean = 11.1, standard deviation (SD) = 4.1). All the simulations were only done after 6 pm and onwards, and on weekends to minimize the disturbance in longitudinal directions (frequent accelerating and braking) caused by other traffic users.

Motion sickness assessment

When travelling inside a car, the human body is exposed to vibrations from longitudinal, lateral and vertical acceleration. It has been shown that there is a relationship between the magnitude, duration, frequency, and waveform of the vibration (Mansfield, 2005). For the evaluation of whole-body vibration concerning health, the vibration is measured at all frequencies within the human sensitivity range. Then, the frequency weightings are used to reflect this sensitivity, where the most sensitive range is given a more substantial weighting range than those with the less sensitive range (Basri & Griffin, 2013).

When riding in a land vehicle, the induced vibrations are in randomized forms due to many factors (driving styles, road, and such), and not in constant sinusoidal forms as in within the simulator studies. A power spectral density (PSD) can be used to illustrate these random vibrations by showing the strength of the acceleration variations as a function of frequency, giving indications of which frequencies have substantial variations (dominance) and which frequencies have weak variations (non-dominance) (Mansfield, 2005). Thus, it is important to verify at what frequency the acceleration dominated before further evaluation of motion is analyzed.

Two main standards that related to whole-body vibration are the BS 6841 (British Standards Institution, 1987) and the ISO 2631-1 (International Organization for Standardization, 1997). According to the ISO 2631-1, frequency weighting that is known as W_f is used to evaluate MS, especially any motion in a vertical direction at frequencies below 0.5 Hz. Also, the chances of human

getting MS symptoms are higher when the duration of the motion exposure is increasing. Hence, based on the ISO 2631-1, a measure of the probability of nausea called Motion Sickness Dose Value (MSDV) is implemented and calculated as:

$$MSDV_z = \sqrt{\int_0^T [a_w(t)]^2 dt}$$

where a_w is the weighted root mean square (r.m.s) of acceleration in the vertical direction with the frequency weighting W_f while T is the period of the exposure. As the frequency weighting W_f is for vertical acceleration only, Förstberg (2000) pointed out that based on other researchers, the formula can also be used for lateral acceleration. Hence, a_w is used as the weighted root mean square of acceleration in the MSDV at lateral direction when evaluating the motion.

In this study, the Motion Sickness Assessment Questionnaire (MSAQ) developed by Gianaros, Muth, Mordkoff, Levine, and Stern (2001) was used to assess MS level in multidimensional subscales, namely, gastrointestinal, central, peripheral, and sopite-related components. The total score of these subscales is the overall MS score, ranging from 11% (minimum) to 100% (maximum). Most researchers used the MSAQ only at the later stage of their studies. Since the MS level, such as drowsiness and fatigue, may be different between an individual at the beginning of the study, pre- and post-MSAQ were implemented within this study. The difference between before and after scores of MSAQ is considered the exact score of MSAQ (Brooks et al., 2010).

Procedures

The simulations of AC driving were executed using the Wizard of Oz approach inspired by the works of Baltodano, Sibi, Martelaro, Gowda, and Ju (2015). The driving wizard operated the Mobility Lab simulating AC driving as if it would be produced in a real AC. Using the AUTOAccD, a specific driving style can be consistently produced and controlled as per different driving styles will provide greater dispersion in the horizontal accelerations (Griffin & Newman, 2004a). In this study, we want to compare the consistency of different drivers in simulating AC driving with the assistance of AUTOAccD. Hence two driving wizards were assigned to perform the simulations.

Regardless of the driving style a person has, one is more likely to accept the more defensive AC driving style (Basu et al., 2017; Yusof et al., 2016). For that reason, the defensive AC driving style was selected for the validation study. The defensive AC driving style settings were implemented based on Karjanto et al. (2017) on which the lateral acceleration was aimed to be at around 0.29 g or 2.84 m/s² while longitudinal acceleration was kept to a minimum. In addition, the driving wizard drove the Mobility Lab with a constant rate of acceleration and deceleration to mimic a driving style of a real AC (Baltodano et al., 2015). The temperature inside the Mobility Lab was monitored and regulated at 20°C during all simulations.

Upon the arrival of the participant, an experimenter greeted and asked the participant to read the informed consent as well as answering the pre-MSAQ. After that,

the experimenter ushered the participant to the Mobility Lab and letting her/him enter the car. The driving wizard was already inside the Mobility Lab from the very beginning. He was concealed by the dark tinted cover on the side window and stayed hidden when the experimenter escorted the participant to the car. The participant was told to wear a seatbelt all the time during the driving session and to watch a video on the TV display. An emergency button was introduced to the participant on which s/he could stop the driving session at any time if needed. After the driving session, the experimenter led the participant back to starting point, where s/he has to answer the post-MSAQ. In addition, the participant was asked to fill in the riding quality questionnaire to express their judgement of the behaviour of the AC driving style. The reasons for implementing riding quality questionnaire were twofold. First, it was to assess the realism of the simulated AC driving and second, it was to compare the consistency of the simulations performed between the two driving wizards.

Participants

The participants' susceptibility to MS was assessed by using the short version of the MS susceptibility questionnaire (MSSQ) (Golding, 1998, 2006). MSSQ evaluates the level of MS based on the occurrence of the sickness in childhood and adulthood. However, since the research focuses specifically on land transport MS, the MSSQ score used here was based only on the ground vehicle elements. Only participants who are mild (2nd and 3rd quartile) and highly susceptible (4th quartile) were selected (Mean = 73.2, SD = 23.0). Forty-six participants (27 male and 19 female) aged between 18 and 47 years old (Mean = 26.2, SD = 5.4) participated in this study. Driving wizard 1 simulated 23 simulations with 23 participants of which 12 are mildly susceptible and 11 highly susceptible (Mean = 71.6, SD = 24.3) while driving wizard 2 simulated 23 simulations with 10 mildly susceptible and 13 highly susceptible participants (Mean = 74.7, SD = 22.1).

Data analysis

The raw acceleration data signal from the ADXL335 accelerometer was first imported into National Instruments DIAdem software and converted from analogue voltage input into calibrated acceleration value. Then, the Savitsky-Golay filter with a window length of 24 and 5th polynomial order was implemented to reduce signal noise while maintaining the shape and height of waveform peaks. The de-noised acceleration data was then converted into PSD using Fast Fourier Transform (FFT) with Hanning windows function, and periodic corrections setting was used to improve the accuracy of greatest amplitude. In addition, the de-noised accelerations were also converted into frequency-weighted acceleration W_p and the final values of MSDV in triaxial directions were calculated using the same software.

The statistical analyses were done using IBM SPSS Statistics version 23. A normality test using Shapiro-Wilk method was run to determine the distribution of the sample. Based on the outcome of the test, the associated statistical analysis will be employed. For the within-groups means comparison, Wilcoxon signed rank tests (WRST)

were used, whereas, for the between-groups comparison, Mann-Whitney U tests (MWUT) were used. In order to employ MWUT, first, histogram graphs were plotted to check the distributions. If the tabulated scores had differently shaped distributions, MWUT were performed to examine the differences in distributions rather than the differences in medians between the groups. For the correlation studies, Spearman's correlations were calculated to measure the direction and power of the relationship between two ordinal variables of interest. The monotonicity of the two ordinal variables was first checked to see whether associations exist between the two variables. The significance level of p used in this study was 0.05 unless stated otherwise.

Results and Discussion

Acceleration and speed

Table 1 shows the tabulations of the mean, standard deviation (SD) and coefficient of variation (CV = SD/Mean) for r.m.s. accelerations in lateral direction and velocities produced by the driving wizards across eighteen turnings/corners.

Based on the velocity data, both driving wizards drove consistently at every corners/turnings. Both of the CVs for the produced velocity are small (between 3% and 13%), indicating that lower dispersions around the mean velocities. On the other hand, the r.m.s. accelerations produced higher distributions (between 8% and 42%) although the consistency between the two driving wizards is still similar to each other. As mentioned by Land and Lee (1994), human drivers gaze at the tangent point of the inside corner/turning one or two seconds before the bend and maintain their gaze on the bend throughout the turning/cornering. Therefore, although the velocities were well-maintained, the accelerations produced were slightly dispersed as both driving wizards might focus on different points of tangent when taking the turnings/corners and therefore resulted in various radii, which would directly affect the simulated lateral accelerations.

Power spectral density

The mean distributions of all accelerations in the triaxial directions across the frequency spectrum for the two driving wizards were tabulated as a function of PSD (see **Figure 3**). Both driving wizards produced almost identical distributions in the triaxial directions and succeeded in simulating the intended defensive AC driving style. Dominant low-frequency motions (lower than 0.50 Hz and especially around 0.25 Hz) have been shown in the past studies to be highly correlated with MS (Donohew & Griffin, 2004; Lawther & Griffin, 1987; Turner & Griffin, 1999). In this study, for the x- and y-directions, the dominant frequencies were both lower than 0.25 Hz. Furthermore, the highest peak of the acceleration in the y-axis was almost ten times larger compared to the highest peak in the x-axis. The significant differences between the x-axis and y-axis amplitudes were anticipated as this study would like to simulate a defensive AC driving style based on the previous settings (Karjanto et al., 2017; Yusof et al., 2016). Furthermore, by visually inspecting both x- and y-directions (see **Figure 3**), there are several overlapped

Table 1: Mean, standard deviation, and coefficient of variation for the two driving wizards on eighteen turnings/corners.

| Corner | Dir. | R.m.s. acceleration _y (m/s ²) | | | | | | Velocity (km/h) | | | | | |
|--------|-------|--|------|--------|------------------|------|--------|------------------|------|--------|------------------|------|--------|
| | | Driving wizard 1 | | | Driving wizard 2 | | | Driving wizard 1 | | | Driving wizard 2 | | |
| | | Mean | SD | CV (%) | Mean | SD | CV (%) | Mean | SD | CV (%) | Mean | SD | CV (%) |
| 1 | Left | 0.95 | 0.36 | 37.72 | 1.04 | 0.44 | 42.12 | 17.54 | 1.40 | 7.99 | 18.40 | 1.79 | 9.73 |
| 2 | Right | 1.33 | 0.20 | 15.04 | 1.39 | 0.22 | 15.83 | 20.52 | 0.91 | 4.43 | 20.49 | 1.53 | 7.47 |
| 3 | Right | 1.25 | 0.21 | 16.80 | 1.42 | 0.17 | 11.97 | 21.53 | 1.23 | 5.71 | 22.44 | 1.13 | 5.04 |
| 4 | Right | 1.09 | 0.15 | 13.76 | 1.15 | 0.19 | 16.52 | 23.75 | 0.94 | 3.96 | 23.35 | 1.15 | 4.93 |
| 5 | Right | 1.06 | 0.34 | 32.08 | 1.26 | 0.29 | 23.02 | 15.50 | 1.67 | 10.77 | 15.06 | 1.74 | 11.55 |
| 6 | Right | 1.45 | 0.31 | 21.38 | 1.57 | 0.25 | 15.92 | 17.18 | 2.35 | 13.68 | 17.77 | 1.43 | 8.05 |
| 7 | Left | 1.44 | 0.16 | 11.11 | 1.57 | 0.27 | 17.20 | 22.00 | 1.72 | 7.82 | 22.58 | 1.39 | 6.16 |
| 8 | Left | 1.48 | 0.37 | 25.00 | 1.51 | 0.41 | 27.15 | 23.57 | 2.84 | 12.05 | 23.49 | 1.68 | 7.15 |
| 9 | Left | 1.35 | 0.20 | 14.81 | 1.47 | 0.29 | 19.73 | 23.57 | 1.98 | 8.40 | 23.84 | 1.67 | 7.01 |
| 10 | Left | 1.50 | 0.26 | 17.33 | 1.67 | 0.25 | 14.97 | 19.24 | 2.33 | 12.11 | 19.75 | 2.05 | 10.38 |
| 11 | Right | 1.34 | 0.21 | 15.67 | 1.47 | 0.13 | 8.84 | 20.77 | 1.22 | 5.87 | 22.23 | 1.30 | 5.85 |
| 12 | Right | 1.06 | 0.14 | 13.21 | 1.10 | 0.14 | 12.73 | 23.56 | 1.15 | 4.88 | 23.48 | 1.04 | 4.43 |
| 13 | Right | 1.01 | 0.34 | 33.66 | 1.33 | 0.20 | 15.04 | 15.62 | 1.60 | 10.24 | 14.97 | 1.52 | 10.15 |
| 14 | Right | 1.54 | 0.19 | 12.34 | 1.60 | 0.21 | 13.13 | 17.96 | 1.92 | 10.69 | 17.92 | 1.13 | 6.31 |
| 15 | Left | 1.47 | 0.17 | 11.56 | 1.60 | 0.32 | 20.00 | 22.54 | 0.91 | 4.04 | 22.61 | 1.34 | 5.93 |
| 16 | Left | 1.64 | 0.17 | 10.37 | 1.62 | 0.35 | 21.60 | 24.78 | 1.33 | 5.37 | 23.81 | 1.62 | 6.80 |
| 17 | Left | 1.36 | 0.31 | 22.79 | 1.49 | 0.44 | 29.53 | 23.79 | 2.05 | 8.62 | 23.56 | 1.32 | 5.60 |
| 18 | Right | 0.84 | 0.20 | 23.81 | 1.03 | 0.11 | 10.68 | 21.83 | 1.78 | 8.15 | 22.99 | 0.89 | 3.87 |

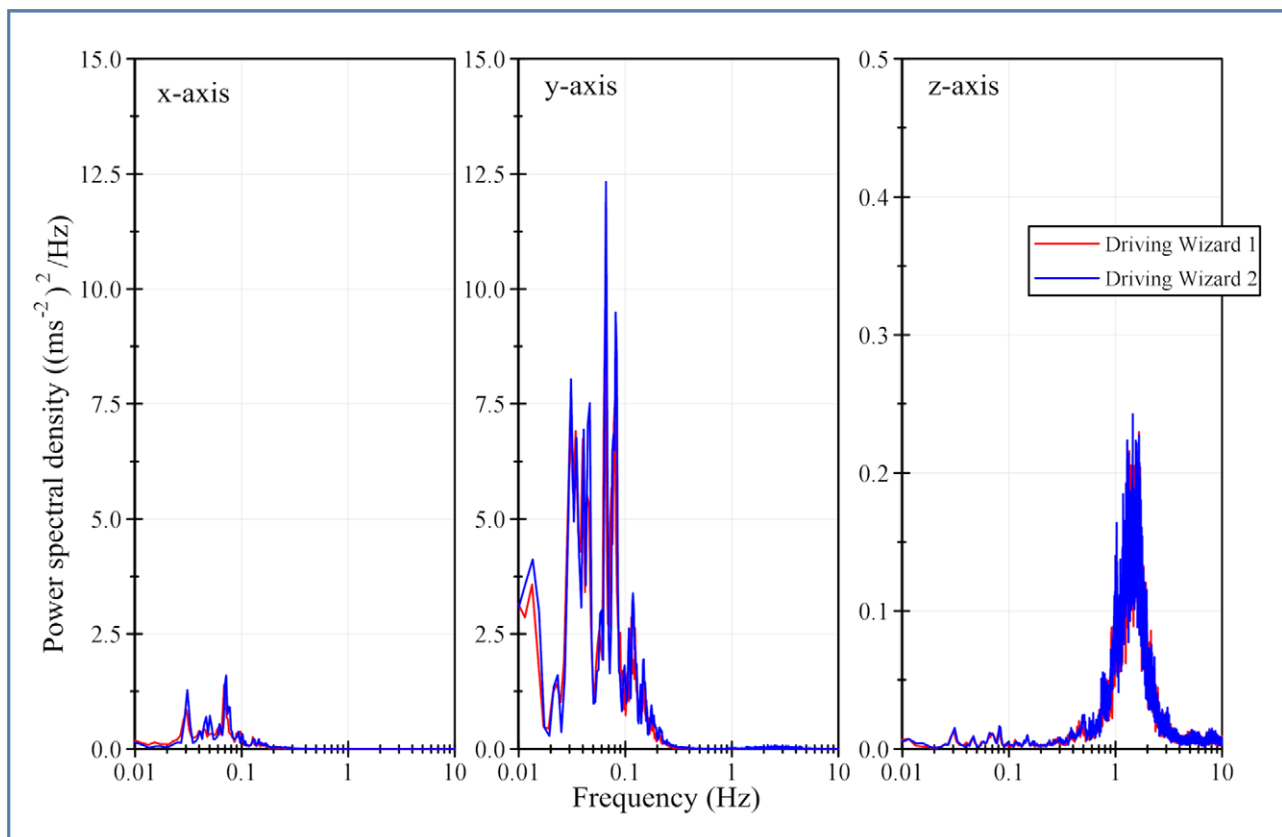


Figure 3: Mean acceleration PSDs in triaxial directions for the two driving wizards.

peaks of acceleration at different frequencies from the two driving wizards indicating that both drivers produced almost identical accelerations at the same frequencies. Therefore, both driving wizards managed to drive at about similar pace, entering a corner at almost the same time and exerting almost the same lateral acceleration at every corner.

For the vertical (z-axis) acceleration, high-frequency ranges of motions (peak at around 1 to 2 Hz) were produced but only with small amplitudes. The reason was that the routes were made out of cobblestone and therefore both driving wizards yielded high-frequency spectrums of motions. High-frequency motions in the z-axis are associated with discomfort as they would disturb human postures but are not a factor contributing to motion sickness development (Griffin & Newman, 2004a). Vertical-direction comfort assessment is usually treated using vibration dose value (VDV) in which the fourth power analysis was used instead of second power as is used in MSDV (International Organization for Standardization, 1997). In

a study by Mark, Turner, and Griffin (1999), motions produced by five different buses on the road (ranging from the highway to cross-country road) were measured, and the recorded amplitude was between 0.1 and 0.4 while in this study the recorded values were only up to 0.25. Therefore, in terms of comfort within the z-axis, this study yielded a comparable vibration as was found in the previous on-road study.

Motion sickness dose value (MSDV)

Based on PSD results, only x- and y-axis accelerations were further analyzed using MSDV technique (see **Table 2**) due to the fact that MS only occurs at low-frequency horizontal oscillations (International Organization for Standardization, 1997; Turner & Griffin, 1999). Each of the driving wizards performed 23 simulations and was averaged into a single projection in each axis (see **Figure 4**). Both driving wizards completed the journeys at almost the same duration with each CVs at around 2%. The CVs for lateral MSDV_y for both driving wizards were at around 15%

Table 2: Mean, standard deviation and coefficient of variation for exposure time, MSDV in both x-and y-direction for the two driving wizards.

| Driving wizard | Exposure time (s) | | | MSDV _x (m/s ^{1.5}) | | | MSDV _y (m/s ^{1.5}) | | |
|----------------|-------------------|-------|--------|---|------|--------|---|------|--------|
| | Mean | SD | CV (%) | Mean | SD | CV (%) | Mean | SD | CV (%) |
| 1 | 544.09 | 11.48 | 2.11 | 2.27 | 0.35 | 15.48 | 6.68 | 0.99 | 14.82 |
| 2 | 534.04 | 11.72 | 2.19 | 2.47 | 0.23 | 9.34 | 7.29 | 1.16 | 15.89 |

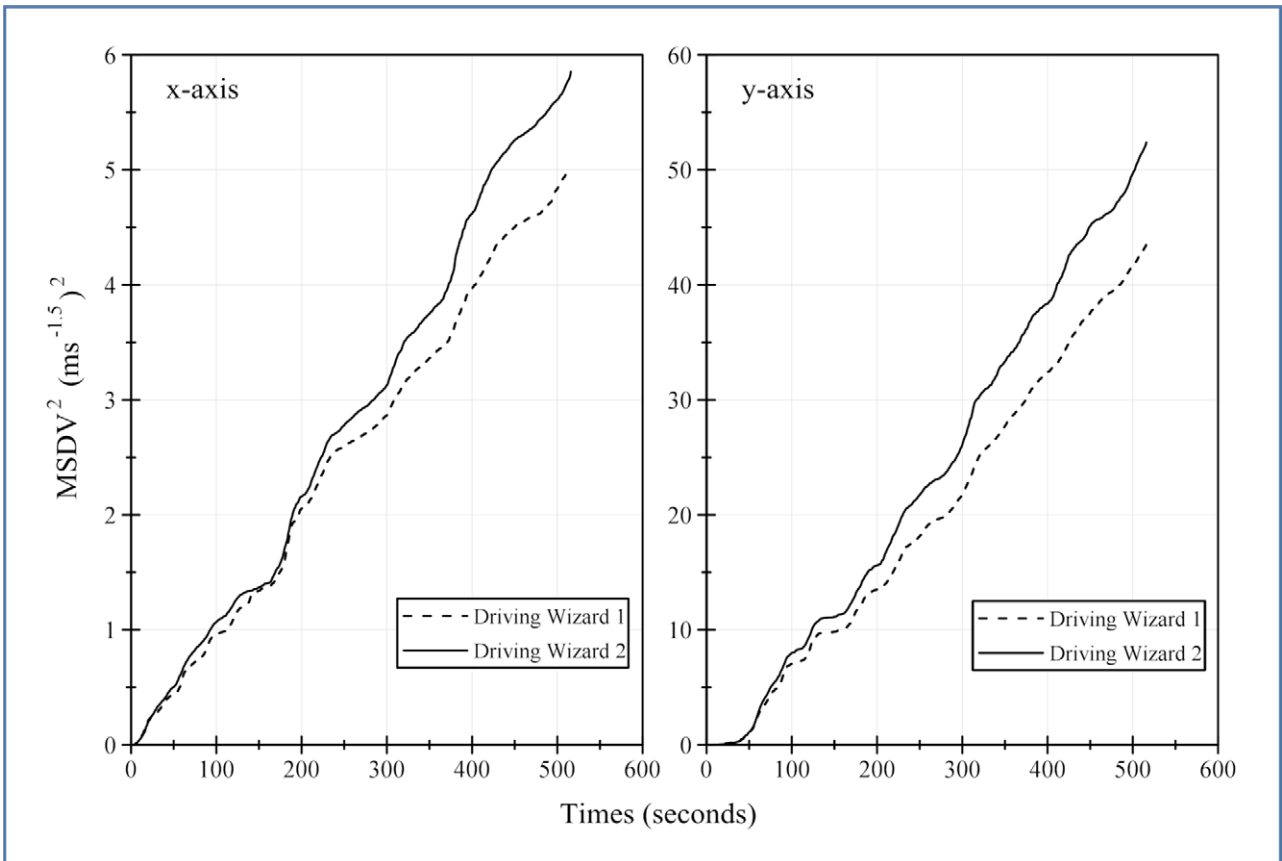


Figure 4: Averaged MSDV with frequency-weighted acceleration in the longitudinal (x-axis) and lateral (y-axis) direction for the two driving wizards.

and are three times higher compared to the study of one driver who drove a car for 40 times by Griffin and Newman (2004a). It should be noted here that compare to their result, this study only lasted for about 9 to 10 minutes (which indicates smaller mean value) for each simulation rather than 30 minutes simulation in their study.

On the other hand, CV was greater for driving wizard 2 compared to driving wizard 1 in MSDV_x. Griffin and Newman (2004a) also found that variations between different drivers were high and could produce a range of various motions. Although both driving wizards simulated the intended automated defensive driving style, the mean MSDV_x² and MSDV_y² for driving wizard 2 were higher than driving wizard 1 (see **Figure 4**). It can be explained by referring back to Table 1 that in general driving wizard 2 drove the car, on average, at slightly higher velocity and acceleration when compared to driving wizard 1. In addition, the MSDV_y² result indicates a linear relationship with respect to time and slightly higher when compared to a similar study from Griffin and Newman (2004a). Both the current and Griffin and Newman (2004a) studies had a similar condition in which drivers drove a suburban-type of the route with corners and junctions. However, in this particular study, the focus of the setup was limited and specified to defensive AC driving style with finite settings as defined by Karjanto et al. (2017), while in their study they only defined it as “normal manner” driving style. Since the development of Mobility Lab is focusing on the user experience in the AC, the mean value of the MSDV_y at both 6.68 and 7.29 ms^{-1.5} indicates sufficient motion to get people to experience MS. The MSDV_y generated in this study was similar to the ones from Griffin and Newman (2004b) with obstructed outside view for study setting. For the 30 minutes duration, they recorded value of MSDV_y of 16.0 ms^{-1.5}. In the current study with 9-minute duration, the generated MSDV_y was already at 6.68 to 7.29 ms^{-1.5} (categorized as mild MS). It could be simply increased, if required, by elongating the exposure time.

Motion sickness assessment questionnaire

WSRT were performed to determine whether there are significant differences between the MSAQ scores before and after the participants were exposed to the motions inside the Mobility Lab. Along with the total score, the compo-

nents of MSAQ were analyzed individually as different activation by the different participants is likely to occur (Gianaros et al., 2001). Gastrointestinal and central elements indicate statistical significance between the mean scores for pre-and post-MSAQ (see **Table 3**). Meanwhile, for the peripheral and sopite components, the results were mixed depending on the susceptibility and who drove the Mobility Lab. For the total MSAQ score, except the mildly susceptible participant for driving wizard 1, all the other participants indicated a statistically significant increase in the MSAQ scores. Therefore, the simulations performed by both drivers managed to get the participants to experience MS. However, the highly susceptible participants showed greater significance generally when being compared to the mildly susceptible participants, regardless either driving wizard 1 or 2 who was driving the Mobility Lab.

In this study, the differences between pre- and post-MSAQ were taken as the final MSAQ scores as these scores reflect better interpretations of the experienced MS over a certain time period (Brooks et al., 2010). An MWUT was performed to see if there are differences in MSAQ components and total scores between the mildly and highly susceptible participants from the simulations from the two driving wizards. Histogram graphs were plotted beforehand, and it was found that the distributions of the MSAQ total scores were not similar. The MWUT confirmed that there were no statistically significant differences in total MSAQ score for mildly ($U = 35.50, z = -1.621, p = 0.107$) and highly ($U = 61.50, z = -0.580, p = 0.569$) susceptible participants for the simulations conducted by the two drivers, using an exact sampling distribution for U (Dinneen & Blakesley, 1973). The same findings were obtained when further analyses were performed on the four components of the MSAQ scores. Therefore, a consensus can be drawn that both types of the participants experienced similar MS level regardless whether driving wizard 1 or 2 who was simulating the fully-automated driving experience using the Mobility Lab.

Scatter-plot graphs were plotted beforehand to find the correlation between MSSQ and MSAQ scores, and visual inspections indicated that there were monotonic relationships between them. Therefore, Spearman correlation was performed to access the connection between the scores

Table 3: WSRT scores for pre- and post-MSAQ total score and its components for mildly and highly susceptible participants.

| Driver | Participant | Gastrointestinal | Central | Peripheral | Sopite | MSAQ Total |
|------------------|--------------------|----------------------------------|----------------------------------|-----------------------------|-------------------------------|----------------------------------|
| Driving wizard 1 | Mildly susceptible | $z = -2.023$ $p = 0.043^*$ | $z = -2.524$ $p = 0.012^*$ | $z = -1.261$ $p = 0.207$ | $z = -1.550$ $p = 0.121$ | $z = -1.887$ $p = 0.059$ |
| | Highly susceptible | $z = -2.552$ $p = 0.011^*$ | $z = -2.803$ $p = 0.005^{**}$ | $z = -1.483$ $p = 0.138$ | $z = -2.490$ $p = 0.013^*$ | $z = -2.845$ $p = 0.004^{**}$ |
| Driving wizard 2 | Mildly susceptible | $z = -1.997$ $p = 0.046^*$ | $z = -2.240$ $p = 0.025^*$ | $z = -0.316$ $p = 0.752$ | $z = -2.502$ $p = 0.012^*$ | $z = -2.807$ $p = 0.005^{**}$ |
| | Highly susceptible | $z = -2.805$ $p = 0.005^{**}$ | $z = -3.066$ $p = 0.002^{**}$ | $z = -1.472$ $p = 0.141$ | $z = -2.380$ $p = 0.017^*$ | $z = -3.181$ $p = 0.001^{**}$ |

* $p < 0.05$, ** $p < 0.01$.

of MSSQ and MSAQ. Spearman correlation analysis indicated that there was a positive and moderate correlation between MSSQ and total score for MSAQ, $r_s(44) = 0.407$, $p < 0.01$. The same analysis also indicated positive and moderate correlations between MSSQ and MSAQ components namely gastrointestinal ($r_s(44) = 0.376$, $p < 0.05$), central ($r_s(44) = 0.407$, $p < 0.01$), and peripheral ($r_s(44) = 0.305$, $p < 0.05$). Hence, in general, participants with a higher score (more susceptible) in MSSQ would score higher in MSAQ (experiencing greater sickness). This result was expected, as participants with higher susceptibility would experience higher MS as compared to the less susceptible participants when exposed to the same dose of MS.

Automated driving experience quality

An MWUT was performed to determine if there were differences in the simulated automated driving quality produced by driving wizard 1 and driving wizard 2. Based on the population histogram chart which was plotted beforehand, the shape of the distribution of the scores for both driving wizards was not similar, as assessed by visual inspection. The score for driving wizard 1 (mean rank = 25.35) and driving wizard 2 (mean rank = 21.65) were not statistically significantly different, $U = 222$, $z = -0.953$, $p = 0.341$. A similar test was also conducted between mildly- and highly-susceptible participants. Again, the distribution of the scores for both types of participants was not similar. The score for mildly susceptible participants (mean rank = 21.74) and highly susceptible participant (mean rank = 25.26) were not significantly different, $U = 224$, $z = -0.908$, $p = 0.364$.

In general, both results showed that the simulated AC driving style was consistent since there were no statistical differences, regardless of the driving wizard or susceptibility to MS. Furthermore, all participants rated quite high in the quality score with an average of 6.7 out of 10. The perception of how realistic the simulated AC driving style has indicated that the Mobility Lab represented an actual highly AC driving style. In addition, there were no monotonic relationships between highly AC driving quality and the MSAQ scores. Hence, the Mantel-Haenszel test of trend was conducted to determine whether there is a linear association between both scores that can be represented in a contingency table. Indeed, the test of trend showed no statistically significant linear association between both scores. Hence, it can be concluded that the simulated automated driving quality's score was not influenced by the MS that was experienced by the participants during the experiment.

Conclusion

In this study, an on-road AC simulator known as Mobility Lab was developed with the purpose to investigate the effects of MS on the future AC users. Mobility Lab has the ability to be used to test a variety of setups in which the passenger can have the unconventional seating arrangements as well as engaging in various NDA. This variety of setups can be done without compromising the safety of the users and at the same time can be done in the real road environment. The ability of DAQ that was coupled to

analogue and digital modules will allow for connections with different sensors such as an accelerometer, GPS, and pulse sensors among others. In addition, DAQ has the ability to synchronize all the collected measurements so that reaction to stimuli and given forces can be accurately analyzed.

Mobility Lab has taken a behaviour-like approach in which the driving style of the car is controlled and made consistent in order to make the participant believe that it is indeed a fully AC. Apart from presenting the behaviour-like experience, the appearance of the instrumented car should be upgraded like the implementation of a fake LIDAR and sensors-lookalike around the car. These physical add-ons can improve the believability of the Mobility Lab to be used as a platform for AC driving experiments. Hence, participants will behave more naturally when they believe they are riding in an AC, rather than just asking them to imagine themselves riding an AC whereas they are actually riding a typical car.

A validation study indicated that the consistency of the designated driving wizards could be controlled in order to perform repeatable simulations on the real road. In simulating the horizontal acceleration mainly in the lateral direction, particular attention needs to be paid to the variation of the turning and cornering method. Although both velocity and time can be controlled, within lateral acceleration, a different focus on the tangent line will create different turning/cornering radii and therefore different lateral acceleration magnitudes. Unique markers on the road and specialized training are a few suggestions in order to improve the consistency of the produced accelerations.

It was shown with the current setup and route that the participants experienced mild MS. Mild MS is an appropriate dosage to be implemented in an experiment involving human users especially if the design of the study included within-subject design. Indeed, as susceptibility to MS is different among individuals, a within-subject design is deemed desirable when designing MS-related experiments (Isu, Hasegawa, Takeuchi, & Morimoto, 2014). In addition, in this study, it was shown that, when the AC was driven in the urban area with a lot of corners and junctions, a natural setting in European cities where the speed limits are either 30 km/h or 50 km/h, it only took about nine minutes to get the participants to experience MS. The effects of MS have been shown in past study (Colwell, 2000) that it would affect the performance of the operators. In the context of AC driving/riding, studies have to be done to predict the effects and consequences mainly on the users' experience.

Last but not least, future studies that can be performed using Mobility Lab are studies that focus on designing user interactions and experiences. For instances, the effects of interaction between passengers when socializing or interaction with new interfaces in the interior of the AC. In addition, the effects of engaging in the NDA (e.g., reading, watching videos, sleeping, and working) while being exposed to acceleration forces induced by the AC could be conducted to assess the user experiences especially on comfort in general, and specifically on MS studies.

Ethics and Consent

Written consent was acquired from each participant prior to the experimental sessions. This was a non-clinical study, and any harming effect was clearly explained before attaining the written consent. Therefore, according to the Netherlands Code of Conduct for Scientific Practice (principle 1.2 on page 5) (Association of Universities in the Netherlands (VSNU), 2014), ethical approval was not sought for execution of this study.

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Competing Interests

The authors have no competing interests to declare.

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