



Deployment of Preemption based Motion Sickness Prevention Technology on a Testbed Vehicle in Mcity

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Deployment of Preemption based Motion Sickness Prevention Technology on a Testbed Vehicle in Mcity

by

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**CENTER FOR CONNECTED
AND AUTOMATED
TRANSPORTATION**

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16. Abstract

Motion sickness when traveling in a vehicle is a common condition that afflicts one in three adults in the US. Moreover, passengers who are not driving the vehicle experience such motion sickness more acutely compared to the driver of the vehicle. This is due to the driver's ability to make anticipatory corrections when initiating a driving action that involves acceleration (e.g. speeding up, breaking, or taking turns). These anticipatory corrections by the driver (such as tightening their abdominal core muscles when braking or leaning their body/head into the direction of the turn when turning) help prepare the driver for the accelerations associated with the driving actions slightly ahead of time, whereas the passenger ends up passively reacting to these driving actions. With the impending transformation in ground transportation due to autonomous vehicles, where every occupant is a passive passenger, the deleterious effects of motion sickness on the passenger comfort and productivity during their commute is expected to be significant.

The goal of this research project was to develop an experimental vehicle testbed and passenger instrumentation for testing motion sickness mitigation solutions that employ preemptive stimuli provided to passengers in autonomous vehicles. Towards this goal, this project has led to the development of several key experimental modules and testing protocols, including a vehicle testbed comprising an active seat (with embedded haptic motors) for providing preemptive stimuli, extensive instrumentation to measure the states of the vehicle and the passenger, an Mcity drive path that is representative of city and highway driving, an automatic triggering scheme to preemptively actuate the haptic stimuli based on this drive path, and an IRB approved human subject testing protocol. The vehicle was designed to emulate an autonomous vehicle riding experience for the passenger.

This experimental setup was then used to conduct a human subject study to quantify passenger motion sickness response while performing representative task along with preemptively triggered haptic stimuli. Twenty-four healthy adults with varying levels of self-reported motion sickness susceptibility participated in the study on the Mcity test track in the above vehicle testbed. The data showed a statistically significant reduction in motion sickness as a result of preemptive haptic stimuli.

17. Key Words

Motion Sickness, Vehicle Testbed, Passenger State Measurement

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1. INTRODUCTION

Autonomous and connected vehicles promise a transportation future with several benefits including fewer road accidents and fatalities [1], reduced traffic congestion [2-3], lower energy consumption and environmental footprint [4-6], and reclaimed productivity during commutes [7-9]. But a high incidence of motion sickness among passengers remains a major impediment to widespread adoption of these promising technologies [10-13].

Motion sickness in a moving vehicle is the consequence of the inertial forces associated with frequent acceleration (e.g. speeding, braking, turning) and the resulting postural instability and sensory conflict it creates [14-16]. It is well-known that in a traditional human driven vehicle, the driver rarely gets motion sick because they anticipate the inertial consequences of their own driving actions and accordingly makes subtle preemptive corrections (e.g. adjust torso or neck, tighten core muscles) [17-20]. On the other hand, the passenger lacks the benefit of anticipation and ends up passively reacting to the inertial forces associated with driving actions. This leads to a far greater incidence of motion sickness in passengers compared the driver. In a future world of autonomous vehicles (AVs), every occupant will be a passive passenger; therefore, the deleterious effects of motion sickness are expected to be significant in AVs [18, 21–27]. In fact, attempting productive activities such as web surfing, texting, typing, or watching video in a moving car has been shown to even further increases the motion sickness [28–30].

The key idea behind this project is to anticipate impending motion events and provide preemptive inputs to the passenger (e.g. haptic stimuli) before the events actually happen. Thus, instead of a passenger reacting to an inertial event that can produce motion sickness, the passenger has awareness of the impending event and can accordingly adjust their body and/or head posture ahead of time to avert motion sickness before it even happens. The goal of this research project was to develop an experimental vehicle testbed and passenger instrumentation that can be used to demonstrate the efficacy of preemptive haptic stimuli in mitigating motion sickness under realistic driving conditions via human subject testing.

Towards this goal, we have developed several key experimental modules and testing protocols during this project. This includes a customized vehicle testbed (Dodge ProMaster Cargo Van) designed to emulate an autonomous vehicle ride experience for human test-subjects. The cargo space of this van has been retrofitted with an active seat that has embedded vibrotactile motors to provide haptic stimuli to the occupant (i.e. passenger). The testbed includes extensive instrumentation to measure the vehicle and passenger states. We have developed an Mcity drive path that is representative of naturalistic driving, and a real-time triggering software to preemptively actuate the haptic stimuli. Furthermore, we have developed a study protocol, which has been reviewed and approved by the U-M Institutional Review Board (IRB), for human subject experiments in Mcity. We have used this experimental setup and IRB protocol to conduct a Pilot Study that assesses passenger motion sickness response while they performed representative tasks, without and with preemptively triggered haptic stimuli. Healthy adults with varying levels of self-reported motion sickness susceptibility participated in the study on the Mcity test track in the above vehicle testbed. The data showed a statistically significant reduction in motion sickness due to preemptive haptic stimuli. Our team has also conducted an extensive Customer Discovery working with the University of Michigan Innovation Partnerships office. We have engaged with more than 40 industry personnel at automotive OEMs, Tier 1 suppliers, and mobility service providers about the significance of motion sickness in autonomous vehicles, current industry solutions, and bringing new solutions to industrial adoption.

2. FINDINGS

2.1 Current Motion Sickness Mitigation Solutions

While the problem of motion sickness is widely recognized and several mitigation strategies have been proposed, very few have proven to be effective. Since pharmacological solutions such as Dramamine [33–35] only target the symptoms of motion sickness (MS) and cause side effects such as drowsiness which are counter-productive, major automotive companies and research labs have explored solutions that target the source of motion sickness. These attempted solutions can be classified into three groups: (a) vehicle level, (b) cabin level, and (c) passenger level.

- a. Vehicle level mitigation solutions include active suspensions that can be controlled to limit the motion of the vehicle chassis in response to route and maneuvers of the vehicle [29,36,37], but have shown little to no improvement in motion sickness response [38]. Another approach involves path planning and limiting sharp vehicle maneuvers [39–43]. However, tamping down the accelerations, either reactively or preemptively, only partially impacts the source of motion sickness (because accelerations of a vehicle cannot be eliminated), while increasing the drive time and limiting the possible routes a vehicle can take.
- b. Cabin level mitigation solutions include passive seats [44] and active seats [45–48]. Passive seats typically use gyroscope principles to reactively isolate the person seated from the effect of inertial forces. Active seats that are actuated in various DoFs in response to sensed vehicle motion and are often triggered reactively. Passive or active seats have not shown a significant reduction in motion sickness. Other cabin level solutions include modulating temperature and scents [49]. But these options do not target the root cause of motion sickness, and instead only alleviate the symptoms (discomfort and sweating).
- c. Passenger level mitigation solutions primarily include various stimuli devices and interactive displays [12, 48, 50–54] attempt to improve the awareness of the passenger regarding vehicle motion. But the stimuli provide no reported benefits. Other more invasive solutions have attempted to disrupt neural or vestibular signals, but the underlying science and effectiveness of these invasive interventions is still unknown [55, 56].

None of these mitigation strategies have been shown to be effective so far, let alone adopted by the industry. And notably, none of them draws lessons from the one solution that is known to work – how a human driver implicitly averts motion sickness via anticipatory control of their body posture.

2.2 Industry Engagement and Feedback

Our team has had significant engagement and interaction with automotive industry partners, who have consistently highlighted motion sickness as a challenge in AVs. Many of these industry partners have served as advisors and Industry Champion on this project. In 2020, we worked with the University of Michigan’s Innovation Partnerships Office and Center for Entrepreneurship to take part in the regional Innovation Corps (I-Corps) program – Introduction to Customer Discovery. Following a systematic process, we talked to more than 40 industry stakeholders to determine significance of motion sickness as a challenge and the currently available solutions. We conducted interviews with product development, technology innovation, and commercialization leaders in the automotive industry in order to understand the market needs. The stakeholders belonged to multiple industry segments, including automotive original equipment manufacturers (OEMs), automotive suppliers, mobility service providers and tech companies. There were two key findings from this Customer Discovery exercise:

- A. It was widely recognized that improving passenger experiences and mitigating motion sickness are issues that will play a major role in the acceptance of AVs by customers. Mitigation of motion sickness

is critical for automotive manufacturers so that the public will accept potentially life-saving vehicle automation technology.

- B. While there are several solutions for motion sickness mitigation being tried in the industry, there are no published studies demonstrating their efficacy. The proposed motion sickness prevention strategy based on providing preemptive haptic stimuli to the passengers was positively received in all our interactions. The industry partners conveyed a strong desire to see experimental results in real-world driving conditions with human subjects.

These interactions and findings reinforced the need to develop a suitable experimental platform and testing protocols for evaluation of motion sickness and demonstrate novel methods to mitigate sickness which was the goal of this project.

2.3 Experimental Design and Development Strategy

The underlying idea of this project is to provide anticipatory awareness to the passenger so that they favorably alter their posture before an inertial event has happened. Our hypothesis was that this will make the passenger more like the driver of a traditional vehicle in terms of motion sickness response. To test this idea in a realistic setting where we can validate its motion sickness mitigation efficacy on human test-subjects, we have developed several key experimental modules and testing protocols over the course of this project, as described below.

2.4 Development of Vehicle Testbed equipped with Active Stimuli

We have developed a fully-instrumented vehicle testbed, based on a 2018 Dodge ProMaster Cargo Van (Fig.1), that is retrofitted with various passenger interfaces and is designed to emulate an autonomous vehicle riding vehicle experience for the test-subject passengers (Fig.2). The cargo space of this van has been custom upgraded to include a 120V, 3000 Watt electrical power supply to power the various actuation (Fig.3), instrumentation and data acquisition modules (Fig.4), and on-board computer (Fig.5); 35,000 BTU heating and cooling for passenger comfort; sound-deadening and internal lining for insulation and limiting road noise; floor padding for to ensure safety and comfort, and, structural mounting of seats, storage shelves, and multi-displays.



Fig 1. 2018 Ram ProMaster Cargo Van modified to conduct Motion Sickness study (Vehicle Testbed)



Fig 2. Vehicle Testbed: Cargo Space modified to include Active Seat, Display Panels, Instrumentation Shelf

The cargo space modifications include integration of an active seat (Fig.2) and associated sensing and computational hardware needed for this project (Fig.4 and Fig.5). The modified van can provide AC power to support on board computers and data acquisition systems. Certain sensors are mounted directly to the test vehicle such as a Lord MicroStrain 3DM-GX5-45 which is an integrated IMU and GPS unit, and a HTU21D humidity and temperature sensor to constantly monitor the cabin environment during the testing. This cargo van is configured to accommodate up to two test-subject passengers at a time, along with a driver and researcher in the front cabin. The driver and researcher are separated from the test-subject passengers to emulate an autonomous vehicle experience for the test-subjects. An active seat from DoF Reality (Model #P3) with a seat cushion with embedded vibrotactile motors has also been developed (Fig. 6). These haptic / vibrotactile motors are strategically placed along the seat back and cushion to provide clear information / stimuli to the passenger.



Fig 3. On-board Auxiliary batteries to power the active seat (with vibrotactile motors), computers, and instrumentation

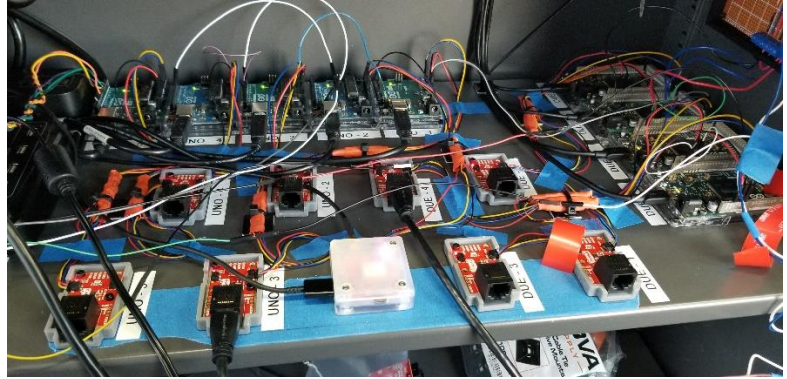


Fig 4. On-board instrumentation and data acquisition



Fig 5. On-board computer

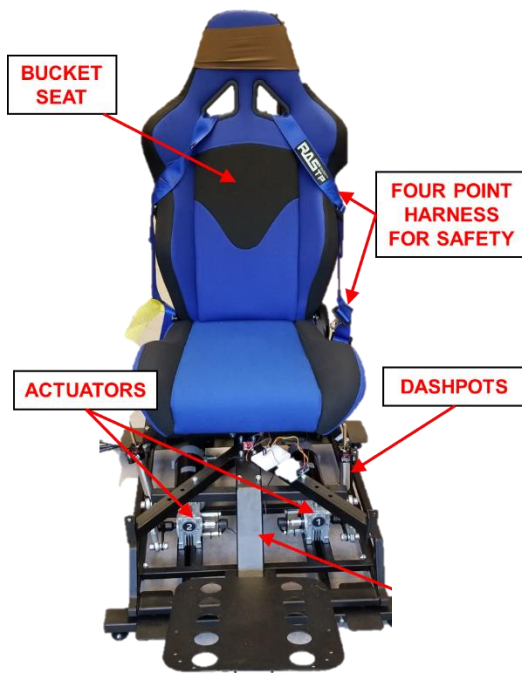


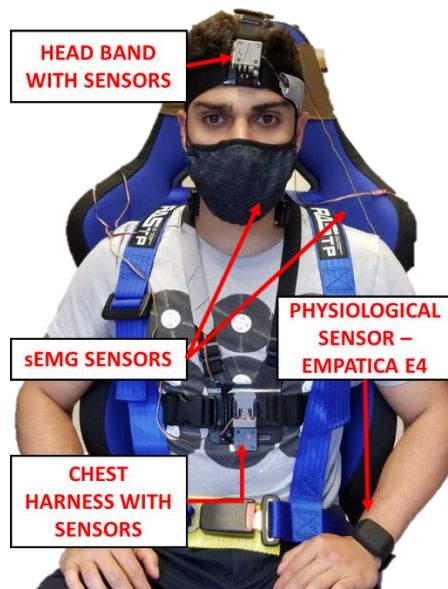
Fig 6. Active Seat with embedded Vibrotactile Motors

2.5 Development of Instrumentation system to measure Vehicle and Passenger states

We have developed extensive instrumentation to monitor the states of the vehicle and the passenger (see Table 1). Vehicle states include its position, orientation, and velocity measured using GPS, IMUs (comprising accelerometer, rate-gyros, magnetometers), and speedometer. Passenger physiological states including perspiration, temperature and heart rate are captured using an Empatica E4 wristband, which comprises a photoplethysmography sensor to measure blood volume pulse for computing heart rate, an electrodermal activity sensor to measure microscopic changes in sweat level to assess arousal of the sympathetic nervous system, an infrared thermopile to measure changes in skin temperature, and an event mark button to tag events and an internal real-time clock. Passenger kinematic states measurements include roll, pitch, and yaw of the passenger head and torso using accelerometers, rate-gyros, magnetometers, sEMG, and image tracking (e.g. ArUco marker). These wearable instrument packs are shown in Fig.7 below.

Table 1. Instrumentation

Location	Sensors
Passenger	Head IMU – InvenSense ICM 20948 [74]
	Torso IMU – InvenSense ICM 20948 [74]
	Physiological Sensor – Empatica E4 Wristband [75]
Testbed Vehicle	Depth Sensor, Microphone, RGB Camera – Azure Kinect Depth Sensor [76]
	Gaze Tracker – Tobii Eye Tracker 5 [77]
	Vehicle IMU & GPS – Lord MicroStrain 3DM-GX5-45 GPS-Aided IMU [78]
	Vehicle Cabin Humidity & Temperature – HTU21D [79]



Test Subject with Wearable Instrument Packs (Head-mounted, and Chest-mounted)



Head-mounted Wearable Instrument Pack

Fig 7. Test Subject Instrumentation

2.6 Mcity Driving Path and Preemptive Triggering of Vibrotactile Motors

For experimental testing, we developed a path in Mcity to emulate naturalistic driving conditions that trained drivers traverse with the testbed vehicle (Dodge ProMaster Van). This Mcity path (Fig.8) includes a combination of dense urban sections (with multiple stops and turns) and an open highway section (straight driving at relatively stable speeds). The total distance covered in the path is just under 2 miles, and it takes about 8 minutes to cover the entire path (avg. speed < 15mph). The driving profiles, i.e. accelerations associated with braking, right and left-turning events, have been extracted from an on-road naturalistic driving study (NDS) [81]. The inertial events included in the path are: 13 stop events, 18 left turns, and 10 right turns. The peak longitudinal acceleration magnitude is 4 m/s^2 while the peak lateral acceleration magnitude is 6 m/s^2 . The path also allows for sufficient time between inertial events (at least 5~6 seconds) such that preemptive actions of motion sickness prevention systems (i.e. active passenger stimuli) can be triggered. Lastly, the track also allows for sufficient safety stop areas in case the subject or researchers need to bring the vehicle testbed to a stop.

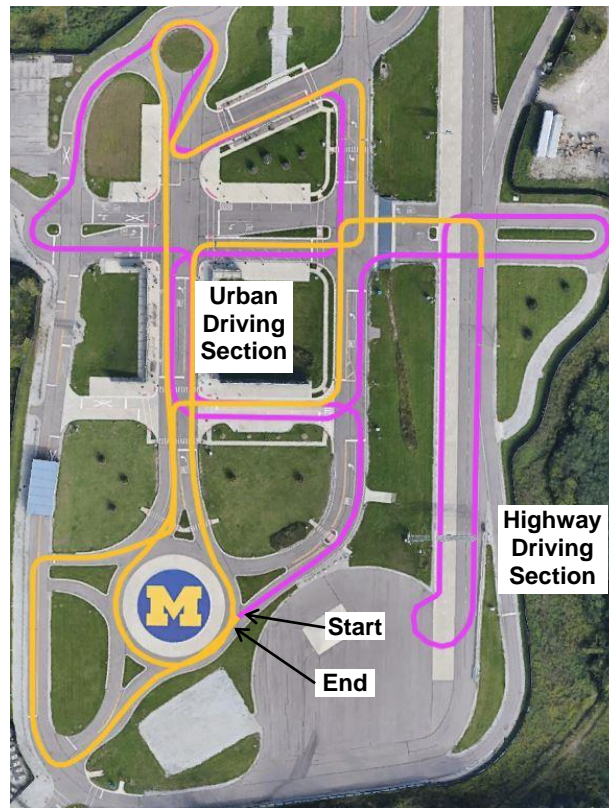


Fig 8. Mcity Driving Path designed for testing Motion Sickness occurrence and mitigation

Since this Mcity driving path is pre-determined, we have developed a triggering scheme to send preemptive commands to the vibrotactile motors before an inertial event (e.g. braking, accelerating, or turning) occurs. Fig.9 shows how this is implemented. The vehicle schematically shown in this figure is our test vehicle, and has a real time GPS sensor on-board that provides real time location and speed with minimal delay (less than a few milliseconds) and high accuracy (better than a meter). At Time A, the vehicle approaches an inertial event (right turn) but has not yet entered the geo-fence defined by the red dashed line close to the start of the turn. Outside the geo-fence, the vehicle is too far to take any preemptive action for preventing motion sickness. At Time B, the vehicle enters the geo-fence and its instantaneous position and speed (measured by the GPS sensor) are used to determine how far the vehicle is from the start of the turn

event. Also, prior driving data from the driver is used to determine how the motion of the vehicle will change as the vehicle approaches the turn. When the time of vehicle to reach the turn event is less than or equal to the required time to preemption, the vibrotactile motors in the active seat are actuated. At Time C, the vehicle has completed the turn event, and the vibrotactile motors are off.

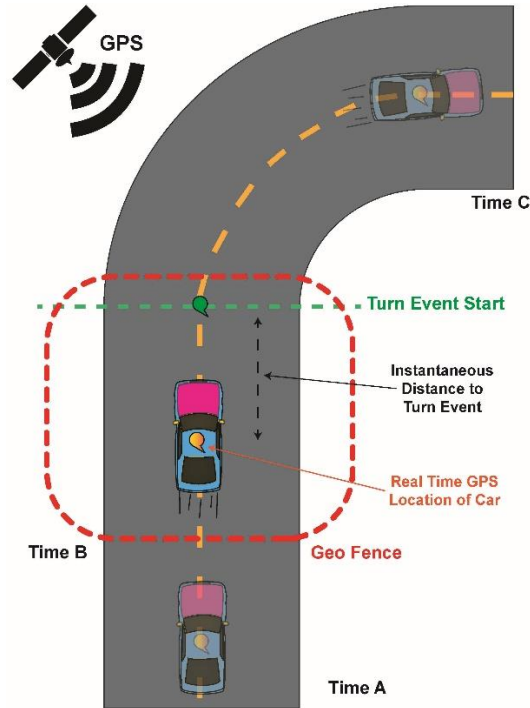


Fig 9. Preemptive Triggering of the Vibrotactile Motors

2.7 Development of Human Subject Testing Protocol

To enable future deployment and experimental validation of the proposed motion sickness mitigation systems, we have prepared and submitted a human-subject study and testing protocol to the U-M Institutional Review Board (IRB) and have received an approval (HUM00199425: Motion Sickness Response in vehicles when using Preemptive Interventions via Active Systems). This IRB approved study will be used in the proposed research tasks to ensure the safety and well-being of human subjects, researchers, and any pedestrians. It includes various protocols that must be followed to protect the rights of the subjects participating in the study, and ensure their person and data are kept safe throughout the study.

2.8 Human Subject Participants in Pilot Study

Six participants were recruited for this Pilot Study. Of the six participants, three were female, and three were male. Participants had self-reported their motion sickness susceptibility and motion sickness frequency. Based on their susceptibility and frequency, participants were grouped into three categories of motion sickness response: low, moderate, and high motion sickness susceptibility. The six participants were evenly distributed across the three categories of motion sickness response. The average age of female participants was 24 years, and average age of male participants was 26 years.

2.9 Experimental Results

Participants were driven in the above-described vehicle testbed along the above-described Mcity drive path,

with and without the preemptive haptic stimuli, while performing various productive tasks on a tablet. During these trips, they were asked to self-report their motion sickness scores using a heuristic motion sickness scale that was adapted from prior work [32]. The numeric scale goes from 0 to 10, with 0 being no motion sickness and 10 being severe motion sickness and the research van is brought to a stop immediately. The researcher onboard the research vehicle would prompt the participant to report their motion sickness score every 90 seconds.

In Fig 10, the mean motion sickness scores for six participants across all three test conditions are plotted as a function of time (over 23 min). Initially (for the first 5 min), the motion sickness response was found to be similar across all three test conditions (TC). The difference in rate of accumulation of motion sickness is most apparent between 5mins and 15mins. The rate of motion sickness accumulation is highest for TC 2 (i.e., haptic stimuli OFF, passenger productive tasks ON), and lowest for TC 1 (i.e., haptic stimuli ON, passenger productive tasks OFF). The rate of motion sickness accumulation for TC 3 (i.e., haptic stimuli ON, passenger productive tasks ON) was found to be similar to TC 1, with only a small spike towards the end. Therefore, the pilot data supported the hypothesis that even when the participant was performing a task, the preemptively triggered haptic stimuli system helped reduce their motion sickness accumulation (compare TC3 with respect to TC2). However, additional data from a larger sample of participants is required for meaningful statistical analysis.

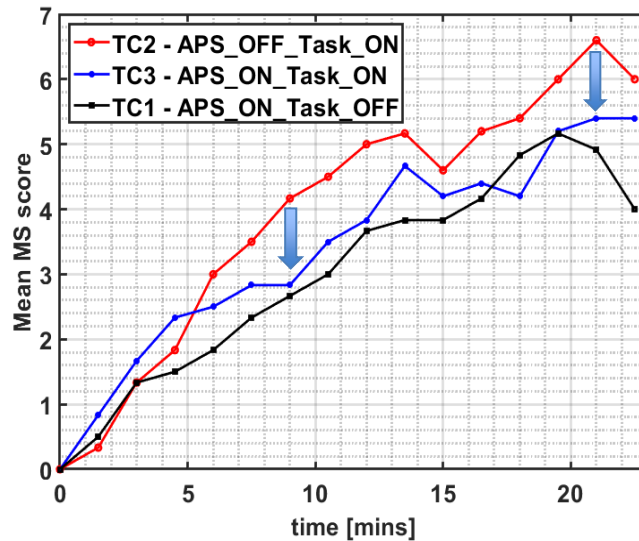


Fig 10. Motion Sickness accumulation under various Test Conditions

Every participant was interviewed after their participation in every test condition and asked to describe their experience qualitatively. When asked about their experience performing productive tasks during the study, five out of the six participants indicated that it was harder to perform the tasks in a moving car as compared to the baseline tasks performed in a room. When asked about their experience with the haptic stimuli during the study, all six participants indicated that the haptic stimuli system was comfortable and did not cause any annoyance or discomfort. When asked if they found the haptic stimuli to be informative (i.e., decipher the motion events from stimuli), all six participants indicated that the stimuli were informative across both TC 1 and TC 3.

3. RECOMMENDATIONS

This Pilot Study has demonstrated the efficacy of a preemptively triggered haptic stimuli in mitigating

motion sickness in a small number (6) of participants. The evidence from this Pilot Study motivates the need for a larger human subject study to investigate the efficacy of preemptively triggered haptic stimuli using the proposed research methodology and protocols.

The Pilot Study was conducted in realistic driving conditions, using a research vehicle and a closed test track to emulate real world motion of a vehicle. The results from the study demonstrate that a haptic stimuli system triggered preemptively can help reduce motion sickness, even when the participant is performing a representative task. Even with the currently limited data, a potential recommendation of this project is for the automotive industry to consider the integration of preemptive haptic stimuli (a low low-cost and low-complexity technology) within their vehicles to help avoid or reduce the occurrence of motion sickness for passengers.

Another recommendation of this work is that a thoroughly designed experimental setup (including the various modules described above) and testing protocols are critical for evaluating motion sickness occurrence and mitigation solutions in a systematic and scientific manner. Based on all the industry feedback we have received, such experimental validation and deployment in Mcity under realistic driving conditions is a critical step towards translating this technology from R&D towards industrial adoption. Such a Proof-of-Concept demonstration will pave the path for such technologies to be incorporated by automotive OEMs and Tier 1 suppliers within their ongoing AV product platforms and timeline.

A key challenge faced during this project was in acquiring a vehicle to develop the experimental vehicle testbed. There have been significant shortages in the supply of cargo vans (along with any new or used vehicle) in the 2021-2022 timeframe. It took us longer than we expected and cost us more than we planned to acquire a suitable vehicle. Also, the modifications took much longer because the internal U-M technical team as well as external contract engineering firms were back-logged. Overall, this impacted the project timeline, schedule, and scope.

4. OUTPUTS, OUTCOMES, AND IMPACTS

4.1 Synopsis of Performance Indicators

This project has contributed to the body of knowledge via three publications and an additional three manuscripts that are currently in preparation. This work has also led to new intellectual property (inventions) in the form of a US and an international patent application, and an additional invention disclosure. This project has also produced an IRB approved study that covers human subject testing in moving vehicles to evaluate motion sickness incidence and prevention. 30 graduate students (Ph.D. and Masters), 16 undergraduate students, and 1 research engineer participated in this project in various R&D roles and received mentorship and training in transportation topics including human factors in transportation; mechatronic design, fabrication, and testing; instrumentation and data acquisition; vehicle testbed development; human subject testing protocols; and computer programming and simulation.

4.2 Outputs

- a. We have published the following papers, and there are three additional papers that are currently in preparation based on this work.
 - Nishant Jalgaonkar, Daniel Sousa Schulman, Sneha Ojha, Shorya Awtar, “A Visual-Vestibular Model to Predict Motion Sickness Response in Passengers of Autonomous Vehicles,” *SAE International Journal of Advances and Current Practices in Mobility*, 3(5):2421-2432, <https://doi.org/10.4271/2021-01-0104>, 2021
 - Daniel Schulman, Nishant Jalgaonkar, Sneha Ojha, Ana Rivero Valles, Monica Jones, Shorya

- Awtar, “A Visual-Vestibular Model to Predict Motion Sickness for Linear and Angular Motion”, Human Factors, DOI: [10.1177/00187208231200721](https://doi.org/10.1177/00187208231200721), 2023
- Nishant Jalgaonkar, Daniel Schulman, Adam Kim, Jiayi Chen, Shorya Awtar, “Preemptive haptic stimuli to mitigate car sickness and its influence on task performance: a pilot study”, 2023 IEEE 26th Intelligent Transportation Systems Conference (ITSC23), Bilbao, Spain, pp. 5014-5019, DOI: [10.1109/ITSC57777.2023.10422144](https://doi.org/10.1109/ITSC57777.2023.10422144)
- b. We have submitted the following patent applications and invention disclosure:
- U.S. Patent Application No. 17/072,802, Filed: October 2020
Title: Passenger State Modulation System For Passenger Vehicles Based On Prediction And Preemptive Control
Inventors: Shorya Awtar, Nishant Jalgaonkar, and Daniel Schulman
 - International Patent Application: PCT/US2020/056198, Filed: October 2020
Title: Passenger State Modulation System For Passenger Vehicles Based On Prediction And Preemptive Control
Inventors: Shorya Awtar, Nishant Jalgaonkar, and Daniel Schulman
 - UM Invention Disclosure (UM File #2024-026). “Preemptive stimuli to occupants of a Moving Vehicle”, Jul 2023. Inventors - Shorya Awtar, Nishant Jalgaonkar, Daniel Schulman
- c. We have published this work and associated publications on the following websites:
- <https://psdl.engin.umich.edu/preact.php>
 - <https://psdl.engin.umich.edu/publications.php>
- d. The U-M Institutional Review Board (IRB) has reviewed and approved the following study:
- HUM00199425: Motion Sickness Response in vehicles when using Preemptive Interventions via Active Systems, PIs: Nishant Jalgaonkar, Shorya Awtar
- e. We have made the following presentations based on this project:
- “PREACT: Motion Sickness Mitigation in AVs”, Presenter: Shorya Awtar, 2022 CCAT Global Symposium on Connected and Automated Vehicles and Infrastructure, URL: <https://www.youtube.com/watch?v=8YagIsVsvDk>
 - “PREACT: Motion Sickness Alleviation in Autonomous Vehicles via Preemptive Interventions”, Presenter: Shorya Awtar, Center for Connected and Automated Transportation (CCAT) Research Review, May 2023, URL: <https://www.youtube.com/watch?v=fqcpDsM9zF0>
 - “Preemptive haptic stimuli to mitigate car sickness and its influence on task performance: a pilot study”, Presenter: Daniel Schulman, 2023 IEEE 26th Intelligent Transportation Systems Conference (ITSC23), Bilbao, Spain, Paper #446

4.3 Outcomes

- a. *Increased understanding and awareness of transportation issues:* This report and above listed publications help increase understanding and awareness of human factors (specifically, motion sickness) in transportation.
- b. *Increases in body of knowledge:* See the list of publications above
- c. *Improved processes, technologies, techniques and skills in addressing transportation issues:* See list of patent applications above

- d. *Enlargement of the pool of trained transportation professionals:* 30 graduate students (Ph.D. and Masters), 16 undergraduate students, and 1 research engineer participated in this project in various R&D roles and received mentorship and training in transportation topics including human factors in transportation (including motion sickness); mechatronic design, fabrication, and testing; instrumentation and data acquisition; vehicle testbed development; human subject testing protocols; and, computer programming and simulation. Enabled by the research, engineering and professional experience gained on this project, these trained professionals have gone on to successfully pursue internships, co-ops, full time jobs, and graduate school in transportation, automotive, semiconductor manufacturing, and robotics fields.

4.4 Impacts

- a. *Increases the body of knowledge and technologies:* See list of publications and patent applications above.
- b. *Enlarges the pool of people trained to develop knowledge and utilize new technologies and put them to use:* 30 graduate students (Ph.D. and Masters), 16 undergraduate students, and 1 research engineer participated in this project in various R&D roles and received mentorship and training in transportation topics including human factors in transportation (including motion sickness); mechatronic design, fabrication, and testing; instrumentation and data acquisition; vehicle testbed development; human subject testing protocols; and, computer programming and simulation. Additionally, the PI directly leveraged the research outcomes of this project to develop a new instructional lab module on kinematic state measurements using encoders, inertial sensors (accelerometers and rate-gyro), computer vision (using ArUco Marker and camera), and sensor fusion (for state estimation) in a newly introduced undergraduate course (ME499: Applied Mechatronics and Robotics).
- c. *Improves the physical, institutional, and information resources that enable people to have access to training and new technologies:* This project has led to the development of a custom-designed, one of its kind, experimental vehicle testbed equipped with an active seat, various displays and user interfaces, and extensive instrumentation for state measurement. This vehicle testbed serves as a physical and institutional resource that will serve human factors research in transportation for many years in several subsequent projects.

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