Motion Sickness Alleviation via Anticipatory Control of Active Seats in Autonomous Vehicles

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DISCLAIMER

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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.

This goal of this research project was to develop an experimental vehicle testbed and passenger instrumentation for subsequently testing motion sickness mitigation solutions that employ preemptive actuation of Active Seats 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 for preemptive intervention, extensive instrumentation to measure the states of the vehicle and the passenger, an MCity drive path that is representative of city and highway driving, a triggering scheme to preemptively actuate the Active Seat based on this drive path, and an IRB approved human subject testing protocol. The vehicle is designed to emulate an autonomous vehicle riding experience for the passenger.

Going forward, these experimental modules will be integrated into an operational technology that can be deployed in MCity and be experimentally validated in realistic driving conditions with human subjects.

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 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 care 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 make preemptive corrections via a tip/tilt Active Seat before the events actually happen. Thus, instead of a passenger reacting to an inertial event that can produce motion sickness, the seat adjusts the passenger’s posture ahead of time to avert motion sickness before it even happens. This goal of this research project was to develop an experimental vehicle testbed and passenger instrumentation for subsequently testing and evaluating this motion sickness mitigation strategy. experimentally demonstrate its efficacy 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 riding vehicle experience for human test-subjects. The cargo space of this van has been retrofitted with a tip/tilt Active Seat. The testbed includes extensive instrumentation to measure the vehicle and passenger states. We have developed an MCity drive path that is representative of naturalistic city and highway driving, and a triggering scheme to preemptively actuate the Active Seat. Furthermore, we have developed a study protocol, which has been reviewed and approved by the U-M Institutional Review Board (IRB), for future human subject experiments in MCity. Our team has also conducted a Customer Discovery working with the U-M Office of Tech Transfer. We have talked to more than 40 industry personnel at automotive OEMs, Tier 1 suppliers, and mobility service providers about the significance of motion sickness in autonomous vehicles and current industry solutions.
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 primarily 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 also reactive. Neither of these passive or active seats have shown 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, leave 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.

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 Office of Tech Transfer and took part in the regional Innovation Corps (I-Corps) program – Introduction to Customer Discovery. Following a disciplined 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 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 the efficacy of any of these strategies. The proposed motion sickness prevention strategy based on anticipatory control of Active Seats 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, which was the goal of this project.

2.3 Experimental Design and Development Strategy

The underlying idea in this project is to provide anticipatory control of an Active Seat to favorably alter the posture of a passive passenger before an inertial event has happened. Our expectation is that this will make the passenger more like the driver of a traditional vehicle in terms of motion sickness response. To be able 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 Seat

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.
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 DoFReality (Model #P3) [73b] that offers actuated pitch, roll, and yaw rotations with ±10° range in each direction has also been developed (Fig. 6) for mounting in the cargo space of the testbed vehicle. This seat is instrumented with IMUs to measure its roll, pitch, and yaw.
Fig 3. On-board Auxiliary batteries to power the Active Seat, computers, and instrumentation

Fig 4. On-board instrumentation and data acquisition

Fig 5. On-board computer

Fig 6. 3-DoF Motion Simulator Active Seat
2.5 Development of Instrumentation system to measure Vehicle and Passenger states

We have developed an extensive instrumentation to monitor the states of the vehicle, the passenger seat, 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 seat states include it yaw, pitch, and roll measured with respect to the vehicle body using IMUs as well as optical encoders integrated with the motors of the Active Seat. 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

<table>
<thead>
<tr>
<th>Location</th>
<th>Sensors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passenger</td>
<td>Head IMU – InvenSense ICM 20948 [74]</td>
</tr>
<tr>
<td></td>
<td>Torso IMU – InvenSense ICM 20948 [74]</td>
</tr>
<tr>
<td></td>
<td>Physiological Sensor – Empatica E4 Wristband [75]</td>
</tr>
<tr>
<td>Testbed</td>
<td>Depth Sensor, Microphone, RGB Camera – Azure Kinect Depth Sensor [76]</td>
</tr>
<tr>
<td>Vehicle</td>
<td>Gaze Tracker – Tobii Eye Tracker 5 [77]</td>
</tr>
<tr>
<td></td>
<td>Vehicle IMU &amp; GPS – Lord MicroStrain 3DM-GX5-45 GPS-Aided IMU [78]</td>
</tr>
<tr>
<td></td>
<td>Vehicle Cabin Humidity &amp; Temperature – HTU21D [79]</td>
</tr>
<tr>
<td>Cabin &amp; Seat</td>
<td>Seat Accelerometers – MEAS 606M1 [80]</td>
</tr>
<tr>
<td>Seat</td>
<td>Seat IMU - InvenSense ICM 20948 [74]</td>
</tr>
</tbody>
</table>

**Fig 7. Test Subject Instrumentation**

Test Subject with Wearable Instrument Packs (Head-mounted, and Chest-mounted)
2.6 Triggering scheme to preemptively actuate the Active Seat

For future experimental testing, we have developed a path in MCity to emulate naturalistic driving conditions that trained drivers will traverse with the testbed vehicle (Dodge ProMaster Van). This MCity path 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: 20 stop events, 15 left turns, and 11 right turns. The peak longitudinal acceleration magnitude is 2 m/s^2 while the peak lateral acceleration magnitude is 4 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 seat and 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.

Since this MCity driving path is pre-determined, we have developed a triggering scheme to send preemptive commands to the Active Seat before an inertial event (e.g. braking, accelerating, or turning) occurs. Fig.8 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 half 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 GSP 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 on-board Active Seat is actuated. At Time C, the vehicle has completed the turn event, and the Active Seat is reset in preparation for the next inertial event.
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.

3. Recommendations
The primary recommendation of this work is integrate the various experimental modules and testing protocol developed above and conduct experimental testing and validation of the proposed motion sickness mitigation system in MCity under realistic driving conditions with human subjects. A secondary recommendation is to improve and refine the various experimental modules and testing protocols, based on initial testing results.

As described above, we have already developed a vehicle testbed comprising an Active Seat for preemptive intervention, extensive instrumentation to measure the states of the vehicle and the passenger, an MCity drive path that is representative of city and highway driving, a triggering scheme to preemptively actuate the Active Seat based on this drive path, and an IRB approved human subject testing protocol.

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 this technology to be incorporated by automotive OEMs and Tier 1 suppliers within their ongoing AV 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 last one year. It took us longer than we expected, and cost us more than we planned, to acquire a suitable vehicle. Also, the modifications have taken much longer because the internal U-M technical team as well as external contract engineering firms have been 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 two publications (one published and one under review) 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. This project has also produced an IRB approved study that covers human subject testing in moving vehicles to evaluation motion sickness incidence and prevention. 12 graduate students (Ph.D. and Masters), 10 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/submitted the following papers, and there are three additional papers that are currently in preparation based on this work.


b. We have submitted the following patent applications:

- 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

  Title: Passenger State Modulation System For Passenger Vehicles Based On Prediction And Preemptive Control
  Inventors: Shorya Awtar, Nishant Jalgaonkar, and 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:


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: 12 graduate students (Ph.D. and Masters), 10 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:* 12 graduate students (Ph.D. and Masters), 10 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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