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Experimental Investigation of the Efficacy of Preemptive Tilting Seats in mitigating Carsickness☆

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ABSTRACT

Carsickness (CS) experienced by vehicle passengers is a critical unsolved challenge that impacts existing human-driven vehicles and may limit the adoption of future autonomous vehicles. If CS is reduced, then passengers can perform productive tasks during their commutes. Prior research has demonstrated that a preemptively triggered tilting seat system (TSS), i.e., a seat that tilts the passenger in the direction of the vehicle's turn, can reduce CS response. However, no previous investigations have studied the impact of TSS on passengers performing representative productive tasks when riding a real vehicle under realistic driving conditions. This paper addresses this gap by presenting a human subject study to quantify passenger CS response and assess their task performance in the presence of a preemptively triggered TSS. Twenty-nine healthy adults with varying levels of self-reported motion sickness susceptibility participated in the study across two test conditions. This is the first in-vehicle study that assessed both CS response and passenger task performance for a diverse sample of passengers under realistic driving conditions emulated on a closed test track. The results from this study demonstrated that a preemptively triggered TSS reduces CS scores for male passengers and has no negative influence on their productive task performance. The results also demonstrated that a preemptively triggered TSS did not have an effect on CS scores for female passengers but had a small positive influence on their productive task performance. In addition, the majority of the study participants (~70%) indicated via a qualitative questionnaire that they would want a preemptively triggered TSS in their car.

1. Introduction

ENGAGING in work or entertainment tasks in a moving vehicle significantly exacerbates carsickness (CS), or motion sickness of vehicle passengers, and leads to increased discomfort (Sivak and Schoettle, 2016; Pawlak et al., 2017; Sivak et al., 2015; Singleton, 2019; Isu et al., 2014; Jones et al., 2019). CS in moving vehicles also significantly impacts the passengers' motor and arithmetic skills, which can interfere with their task performance (Smyth et al., 2019; Dahlman et al., 2012; Dahlman et al., 2006; Duncan et al., 2018; Matsangas et al., 2014). This is an unaddressed problem in existing human-driven vehicles. Furthermore, with the advent of autonomous vehicles, it is expected that passengers will use their commutes productively for work and/or entertainment (Sivak and Schoettle, 2016). Therefore, preserving task performance while mitigating CS is also key to the future adoption of autonomous vehicles.

Currently, CS is most commonly mitigated with the use of medicinal drugs (Yates et al., 1998; Shupak and Gordon, 2006; Nachum et al., 2006; Dobie and Dobie, 2019). While drugs are effective at reducing the symptoms of CS, they are associated with significant short- and long-term adverse side effects (Murdin et al., 2011; Golding and Gresty, 2015). Therefore, there remains a need for a viable CS mitigation

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solution that is not only effective but also does not have side effects that negatively impact the passenger's ability to perform tasks or their overall quality of life.

Research shows that in human-driven vehicles, the driver gets less carsick as compared to passengers (Rolnick and Lubow, 1991). Unlike the passenger, the driver is in control of the vehicle and observes the road ahead, allowing them to anticipate the vehicle motions in response to the road and their driving actions as well as their own body motions (Rolnick and Lubow, 1991; Wada et al., 2018). Drivers use this information to take subtle preemptive corrective actions (e.g., move their head or torso, stiffen their neck muscles, activate their core muscles) in anticipation of the vehicle's motion, which leads to lower CS (Rolnick and Lubow, 1991; Wada et al., 2018; Iskander et al., 2019). The passenger, on the other hand, ends up reacting passively to the vehicle's motion and its inertial accelerations, making them more prone to CS (Wada et al., 2012). Previous studies have demonstrated that if the driver's anticipation and associated preemptive action can be recreated for the passenger, it can reduce the passenger's CS (Awtar, 2024; Jalgaonkar et al., 2023; Wada et al., 2012). By leaning the passenger's body and head into the turn (like a driver), the effect of inertial forces is reduced because their head and body are better aligned with the direction of gravito-inertial acceleration, thereby reducing their CS (Wada et al., 2018; Mert and Bles, 2011).

The posture of a vehicle's passenger can be altered either by using a moving seat system that moves the passenger's body (Frechin et al., 2004; Joseph and Griffin, 2007), or by using inflatable bladders on the seat that change the passenger's position (Juffrizal et al., 2021; Konno et al., 2011), or by simply prompting the passenger to lean their head themselves (Wada et al., 2012). A moving seat system can have many different types of motion with respect to the vehicle, including rotations about and translations along vehicle axes (Fig. 1). Specifically, moving seat systems that provide roll motion i.e., tilting seat system (TSS) have been extensively investigated in prior research to reduce CS response (Frechin et al., 2004; Joseph and Griffin, 2007; Juffrizal et al., 2021; Konno et al., 2011; Beard and Griffin, 2014). Prior studies have demonstrated that a preemptively triggered TSS reduced CS response (Joseph and Griffin, 2007; Juffrizal et al., 2021). One study demonstrated that preemptively triggered TSS reduced CS response better than a reactively triggered TSS (Joseph and Griffin, 2007).

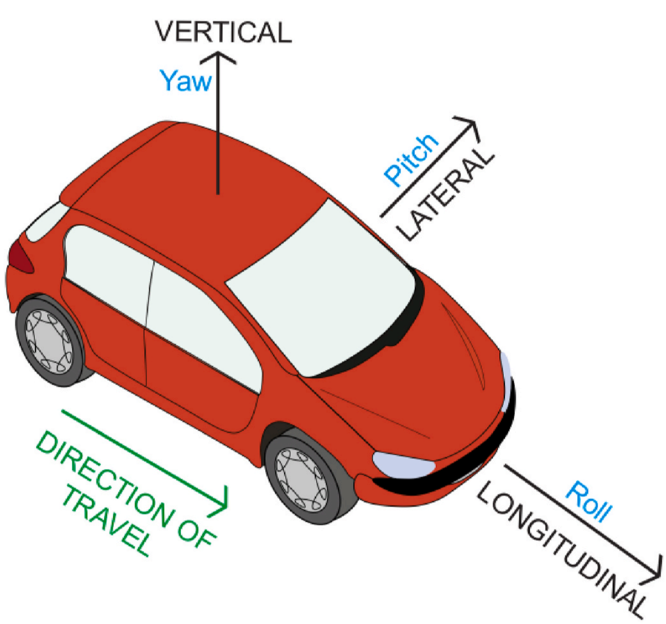

Fig. 1. Vehicle axes (in black) and rotations (blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

However, several critical gaps were identified in the previous research on preemptively triggered TSS (see details in Section II).

Gap 1: Of the studies investigating preemptively triggered TSS (Joseph and Griffin, 2007; Juffrizal et al., 2021), only one study included the passenger performing a productive task, and it provided no analysis of the passenger's task performance (Juffrizal et al., 2021). Without such analysis, any effect of the preemptively triggered TSS on task performance remains unknown.

Gap 2: Of the studies investigating preemptively triggered TSS (Joseph and Griffin, 2007; Juffrizal et al., 2021), only one study was performed under realistic driving conditions (Juffrizal et al., 2021). Another study involved a motion simulator (Joseph and Griffin, 2007), which does not accurately recreate the experience of being a passenger in a real vehicle (Blana, 2001; Wynne et al., 2019) and therefore cannot elicit a realistic CS response.

Gap 3: The prior study of preemptively triggered TSS under realistic driving conditions relied on manual triggering of the TSS (Juffrizal et al., 2021). This manual triggering can lead to variation in preemption time due to human error. Also, no data on precision of preemption time was reported.

The present research paper describes a study (i.e., experiment) that addresses the above gaps in prior research by investigating the efficacy of a preemptively triggered TSS in reducing CS response while the passenger is performing a task, riding a real vehicle under realistic driving conditions. Twenty-nine adults completed their participation in the full study. This paper is organized into five sections. Section II provides a summary of relevant prior research literature and the gaps that have motivated this research study. Section III describes the design of experiment and experimental methods used to conduct the study. Section IV presents the experimental results that include the participants' CS response and task performance. Finally, Section V presents a discussion of the experimental results, study limitations, and recommended future work.

2. Background and motivation

A review of the literature on the efficacy of moving seat systems to mitigate CS identified several relevant prior studies over the last two decades (Mert and Bles, 2011; Frechin et al., 2004; Joseph and Griffin, 2007; Juffrizal et al., 2021; Konno et al., 2011; Beard and Griffin, 2014; Golding et al., 2003; Brietzke et al., 2021). Although these studies differed in experimental methods and tools, an assessment of these previous studies provided several insights that informed the study presented in this paper. The majority of these studies involved a moving seat system with roll or tilting motion (i.e. TSS) (Frechin et al., 2004; Joseph and Griffin, 2007; Juffrizal et al., 2021; Konno et al., 2011; Beard and Griffin, 2014), and three of these studies demonstrated a reduction in CS response (Joseph and Griffin, 2007; Juffrizal et al., 2021; Konno et al., 2011). The majority of these TSS studies involved a reactively triggered TSS (Frechin et al., 2004; Konno et al., 2011; Beard and Griffin, 2014), and only two studies included preemptively triggered TSS (Joseph and Griffin, 2007; Juffrizal et al., 2021). Of these, one study provided evidence that a preemptively triggered TSS reduced CS more than a reactively triggered TSS (Joseph and Griffin, 2007).

The two prior studies with preemptively triggered TSS (Joseph and Griffin, 2007; Juffrizal et al., 2021) had several limitations. Only one of these included the passenger performing a task (Juffrizal et al., 2021), and it did not provide an analysis of the passenger's task performance. This study involved a reading task but provided no justification for this choice. Thus, the research in this present paper aims to address the first major gap in prior studies: a systematic investigation of preemptively triggered TSS and its effects on a passenger performing a representative real-world task.

One of the prior studies with preemptively triggered TSS was

Table 1
Experimental test conditions and variables.

TEST CONDITION	INDEPENDENT VARIABLES		DEPENDENT VARIABLES
	TILTING SEAT SYSTEM (TSS)	TASK	
TC 1	ON	ON	**A. CS Response** • CS scores **B. Task Performance** • Accuracy of responses • Percentage of questions skipped/not answered • Response time of answers
TC 2	OFF	ON	

conducted using a vehicle simulator instead of realistic driving conditions (Joseph and Griffin, 2007). Existing literature indicates that vehicle simulators that are capable of moving the passenger only produce 50%–60% of the accelerations experienced in a real vehicle (Berthoz et al., 2013). Further, validation studies of vehicle simulators have suggested that motion simulators do not accurately capture the entire experience of passenger in a moving vehicle (Blana, 2001; Wynne et al., 2019). The CS response of passengers is closely tied to not only the actual motion of the vehicle, but also the passengers' perception of motion (Koohestani et al., 2019; Huppert et al., 2017; Bertolini and Straumann, 2016). Therefore, the research in the present paper aims to address the second major gap in prior studies: a systematic investigation of preemptively triggered TSS systems conducted under realistic driving conditions to elicit a realistic CS response from passengers.

Lastly, one prior study with preemptively triggered TSS conducted using real vehicles relied on manual triggering of the TSS (Juffrizal et al., 2021). This meant that the researcher onboard the vehicle relied on visual markers in addition to apriori knowledge of the vehicle's path to manually trigger the TSS (Juffrizal et al., 2021). This study did not provide any data regarding the precision of preemptive triggering. Such manual triggering is prone to large variation in the preemption time due to inherent human error. Therefore, the research in the present paper aims to address the third major gap in prior studies: a need for precise preemptive triggering of TSS to assess their efficacy in reducing CS under realistic driving conditions, which the study in this paper also addresses.

This present paper describes a human subject study that was conducted to address the above research gaps using a preemptively triggered TSS. To address the first gap, this study included a representative productive task (and an analysis of task performance data) consisting of several types of questions to emulate the cognitive strain of a passenger performing typical tasks in a moving vehicle such as watching videos, reading, typing, etc. To address the second gap, this study used an instrumented test vehicle on a test path to ensure realistic driving conditions and CS responses. Finally, to address the third gap, carefully designed and engineered software was used to ensure precise preemptive triggering of the TSS, even though the test vehicle is human driven.

3. Experiment design and methods

3.1. Design of experiment

To address the gaps identified in the previous research, this study focused on investigating two specific hypotheses: (1) that preemptively triggered TSS can reduce CS response even when the passenger is performing a task, and (2) that preemptively triggered TSS can help improve task performance of the passenger. The experiment included two independent variables: TSS and representative productive task (or Task). Dependent variables such as CS response and task performance were used to determine the influence of the independent variables on study participants (Table I).

The TSS being ON meant the tilting seat system was operational, whereas OFF meant it was not operational. When the TSS was operational it would move the passenger in anticipation of the vehicle motion. Similarly, Task being ON meant the participant was performing a task during that test condition. An experiment with two test conditions was devised. To investigate the first hypothesis, that preemptively triggered TSS can reduce CS response even when the passenger is performing a task, a comparison of CS response across both test conditions was required. To investigate the second hypothesis, that preemptively triggered TSS can help improve task performance of the passenger, required a comparison task performance across both test conditions.

The TSS OFF and Task OFF (i.e., TC 3) and TSS ON and Task OFF (i.e., TC 4) test conditions were not included in the study. Since prior literature had demonstrated that performing a task exacerbates CS (Isu et al., 2014; Jones et al., 2019), a comparison between TC 2 and TC 3 was not required. Similarly, there was some evidence to suggest that a preemptively triggered TSS can reduce CS response when the passenger is not performing a task (Joseph and Griffin, 2007). Therefore, TC 4 was not required.

A within-subject design was implemented since CS response has a high variation across different individuals, and within-subject studies are ideally suited to overcome this variation (Charness et al., 2012). The order of test conditions was randomized using Latin square randomization to eliminate any order effects, biases, and learned effects due to repeated participation. Test conditions were conducted with a minimum time separation to ensure that any accumulated CS response would not persist from one test condition to the other; a 48-h separation was used based on published guidelines (Jones et al., 2018). All experimental protocols and procedures were evaluated and approved by the University of Michigan Institutional Review Board to ensure the safety and confidentiality of all study participants (HUM00199425).

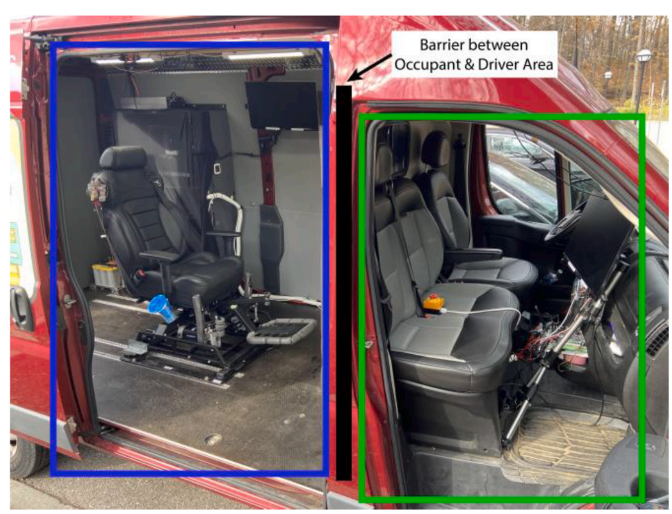

Fig. 2. Test vehicle (passengers' side external view) indicating the physical barrier (black line) separating the Researcher Space (green box) from the Occupant Space (blue box). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.2. Tilting seat system (TSS)

To reduce the engineering development burden, a commercially available TSS, DoF Reality P3 ("Professional Motion Simulator 2), was modified to suit the needs of this study (Fig. 2, TSS shown within the blue box). While the P3 system is capable of multiple rotational motions, it was operated only as a TSS for this study, as explained earlier.

Across the two prior studies with preemptively triggered TSS identified in this paper, preemption times of 0.5 s (Joseph and Griffin, 2007) or 3 s were used (Juffrizal et al., 2021). An optimal preemption time was not reported in any of the studies. However, prior literature on driver perception and response times indicated that a driver can take up to 3 s to perceive and respond to an unexpected situation (Olson, 1989). Since the study in this paper was attempting to recreate the driver's anticipation and preemptive action for the passenger, a preemption time of 3 s was chosen.

A trajectory for the tilting motion of the TSS was designed. The trajectory had to account for the preemption time of 3 s; the TSS would begin tilting 3 s prior to the start of the vehicle motion and the associated lateral acceleration of the vehicle. In addition, since the TSS would tilt the passenger to align their head in the direction of gravito-inertial acceleration, the TSS would hold its tilted position while the vehicle was turning and experiencing peak lateral acceleration. The TSS would return to its starting position as the lateral acceleration of the vehicle approached zero or after zero. Also, the acceleration of the moving seat should be minimal to not contribute to CS.

Based on the above requirements for TSS trajectory, a 5th-order Gaussian curve function was used to design tilt trajectories. Since lateral acceleration of the test vehicle varied as a function of different types of turns (e.g., long sustained turn versus short turn) the vehicle would make, multiple trajectories were defined to suit the requirements of each turn. Fig. 3 shows sample data of the vehicle acceleration and the TSS tilt trajectory associated with that specific left turn. The actual motion of the TSS as measured by sensors (black line, Fig. 3) follows the commanded motion (green line, Fig. 3) with minimal error.

The TSS begins moving from its initial position ($\sim 0^{\circ}$) 3 s prior to the rise in lateral acceleration associated with the vehicle turning. The TSS reaches its peak tilt of 7 degrees of tilt at approximately the same time as the lateral acceleration of the vehicle peaks (Fig. 3). The TSS then briefly holds its position before returning to its initial position just after the lateral acceleration ceases. An analysis of the TSS position data across all participants ($\sim$600 tilts) found the median error in peak TSS tilt was less than 1.2° (17% of peak TSS position).

3.3. Representative productive task

In real-world driving, a vehicle passenger can perform a large variety of productive tasks (Sivak and Schoettle, 2016). Therefore, a representative productive task for study participants must capture this wide spectrum of cognitive engagement to determine if performing a task influences the CS response due to preemptively triggered TSS. The task used in this study was administered as a series of questions that were part of a Qualtrics survey to be answered using a handheld electronic tablet. To emulate a wide spectrum of cognitive engagement, the task consisted of a combination of low and high cognitive loading questions.

Cognitive loading of a question depends on the cognitive functions required to answer it (Wickens, 2002). Low cognitive loading questions relied on lower order cognitive functions, such as sensation, perception, memory, attention, and concentration. Higher cognitive loading questions required a combination of lower order cognitive functions and higher order cognitive functions, such as language and critical reasoning (Wickens, 2002; Sachdev et al., 2014; Harvey, 2019). The task used in this study was based on a similar task used and described in detail in prior CS studies (Jones et al., 2018; Jalgaonkar et al., 2023).

3.4. Test vehicle and path

To ensure realistic driving conditions for the study participants, a custom test vehicle was developed to meet the unique requirements of this human subject study. A 2018 Ram ProMaster van was modified so that participants could be seated and instrumented while being driven on a test track. Since the vehicle was human-driven, the "Wizard of Oz" method (Baltodano et al., 2015; Karjanto et al., 2018) was used to isolate the participant from the vehicle's driver to create an impression of automated driving. A physical barrier (Fig. 2, black line) in the vehicle that split the van into two distinct spaces: the driver and onboard

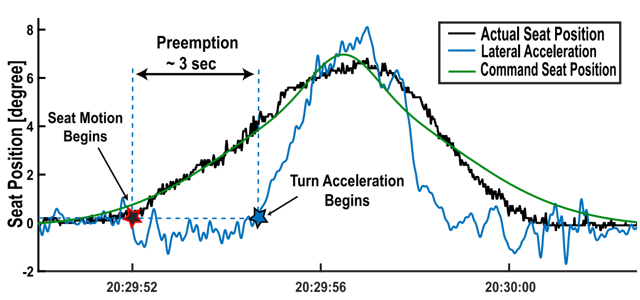

Fig. 3. Sample data of TSS tilt trajectory and lateral acceleration of the vehicle for a left turn.

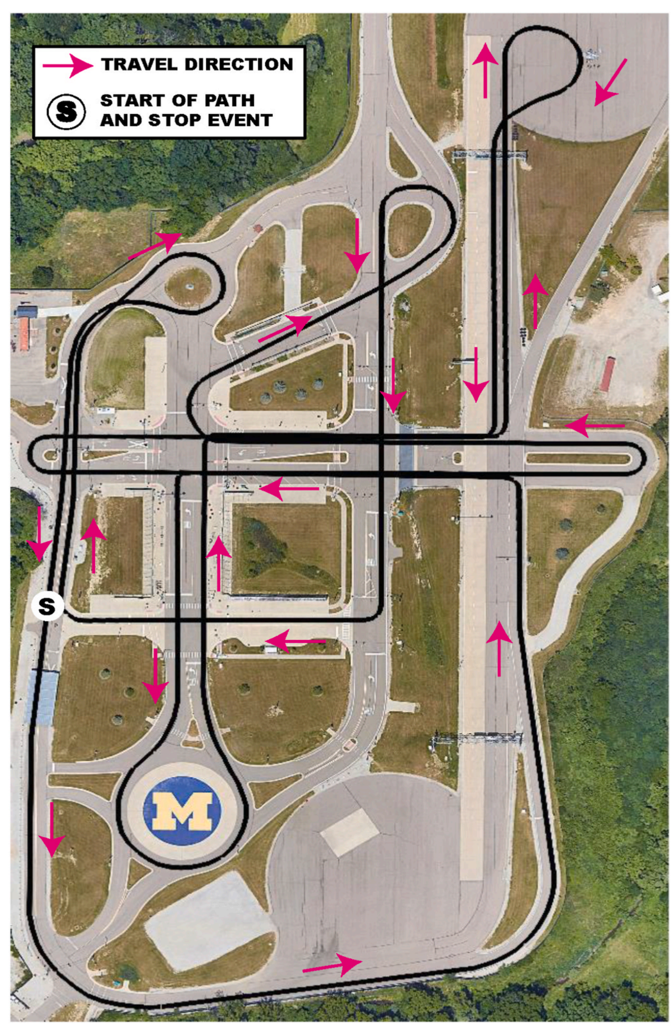

Fig. 4. Test path at the Mcity Test Track.

researcher were seated in the researcher space (green box, Fig. 2), and the participant was seated on the TSS in the occupant space (blue box, Fig. 2). The onboard researcher monitored the well-being and safety of the onboard participant.

The occupant space was designed without windows. Limiting the onboard participant's view of the outside environment reduced bias in multiple ways. Since individuals process visual information about the vehicle's immediate surroundings differently, obstructing this view prevented any variable influence on the participants' CS response (Baltodano et al., 2015). In addition, since participants were asked to repeat test conditions, limiting the view of the outside environment prevented participants from learning the test path used for the study and prevented bias due to learned effects. Additional information regarding the test vehicle can be found in prior publications (Awtar, 2024; Jalgaonkar et al., 2023; Jalgaonkar, 2024).

The test vehicle was driven at the University of Michigan Mcity Test Track for all test conditions (Fig. 4). A test path was designed to ensure that the participants experienced a range of vehicle motion representative of realistic driving, such as short versus long right turns. The path was limited to different types of turns since the TSS was restricted to tilting motion only, and stops would require additional motion such as pitch rotation to reduce CS response. The peak lateral acceleration associated with the path was 6 m/s^2, which was typical of everyday driving conditions (Jones et al., 2018). To ensure sufficient time for the participant to experience CS due to a variety of turns, each test condition included 3 loops of the designed path, with each loop consisting of 9 left turns and 7 right turns that was also representative of naturalistic driving as determined from large scale driving datasets (Jones et al., 2018). To emulate the variability in naturalistic driving, the time between turns varied between 3 s to as much as 10 s. A minimum separation of 3 s ensured sufficient time for preemptive triggering of the TSS. Each loop of the path took less than 7 min to complete, for a total time of ~20 min for all 3 loops.

Since the van was human driven, emulating the consistency of autonomous driving required extensive driver training. Drivers practiced and memorized the path used ahead of the study. In addition, acceleration data from their driving practice was analyzed and used to provide feedback to drivers to reduce variance in their driving. An analysis of vehicle acceleration data from over 60 rides throughout the study demonstrated that the mean deviation in both lateral and longitudinal acceleration was limited to less than 0.6 m/s^2. This deviation is comparable to prior studies on CS response using real vehicles (Jones et al., 2018).

3.5. Carsickness (CS) response assessment

Since there is no direct measurement of CS, we adopted a multi-pronged approach to assess the CS response of the study participants based on subjective assessments. Two self-reported subjective assessments of CS response were included – a quantitative Motion Sickness Scale and a qualitative Questionnaire.

This study used a numerical motion sickness reporting scale based on the previously developed University of Michigan Transportation Research Institute (UMTRI) Motion Sickness Scale (MSS) (Jones et al., 2019; Jones et al., 2018) because prior research has demonstrated that it is capable of capturing progression of CS symptoms (Jones et al., 2019). Since CS response varies from person to person, unlike other scales such as the Misery Scale which links specific symptoms to the numerical values on the scale (de et al., 2022), the UMTRI MSS gives the participant the flexibility to report changes in their CS response, which are unique to them. This scale is similar to the Fast MS Scale (FMS), which also does not link specific symptoms to numerical scores and has been used widely in prior literature (Keshavarz and Hecht, 2011).

Like the UMTRI MSS, the scale used in this study also goes from 0 to 10, with 0 being no motion sickness and 10 being such high motion sickness that the person would like the vehicle to come to an immediate stop (Jones et al., 2019). The numbers on the scale are not linked to specific CS symptoms. The researcher onboard the vehicle prompted the participants to score their CS response using the Motion Sickness Scale every 90 s. Unlike the UMTRI MSS, the participants were not asked to report their symptoms along with their CS score, to avoid causing distraction during task performance. A reduction in the CS score was used as one indicator of CS response reduction in the participants.

In addition to the quantitative CS scores, the participant's qualitative responses were used to assess their CS response using a qualitative Questionnaire. This qualitative Questionnaire was designed to provide yet another independent assessment of CS response resulting from preemptive TSS. The qualitative Questionnaire consisted of various open- and close-ended questions to determine the quality of the participants' experience during the test condition with regards to their CS response. For example, participants were asked if they had a preference for the TSS with the goal of determining the influence of TSS on CS response of participants, independent of their CS score.

The Questionnaire also helped identify if any factors other than their CS response affected the participant's experience. For example, the participant was asked if factors such as temperature or lighting in the vehicle during the test condition had any impact on their experience. Additional open-ended questions were used to determine if any uncontrolled factors had influenced the participants experience during a test condition. Hence, the Questionnaire not only provided qualitative insights into a participant's CS response but also shed light on the influence of any other factors in the study that may have influenced the participant's experience.

3.6. Precise preemptive TSS triggering software

To ensure precise and accurate triggering of the TSS, a real-time global positioning system (GPS)-based triggering software was developed. The software relied on apriori knowledge of the vehicle path and vehicle data collected from driver training. The software ensured that the average error in preemptive trigger times throughout the study was as low as 150 ms with a median error of less than 100 ms (Fig. 5). Across all the data (i.e., over 1200 data points), 8% (<100 data points) of the preemption times are outliers with large errors (error >0.3 s). Prior work on preemptively triggered TSS has not provided any data regarding the precision of their triggering. This is the first study to establish a precision benchmark for using preemptively triggered TSS.

3.7. Study participants

The study design required recruitment of an equal number of male and female participants to balance any effects due to participant

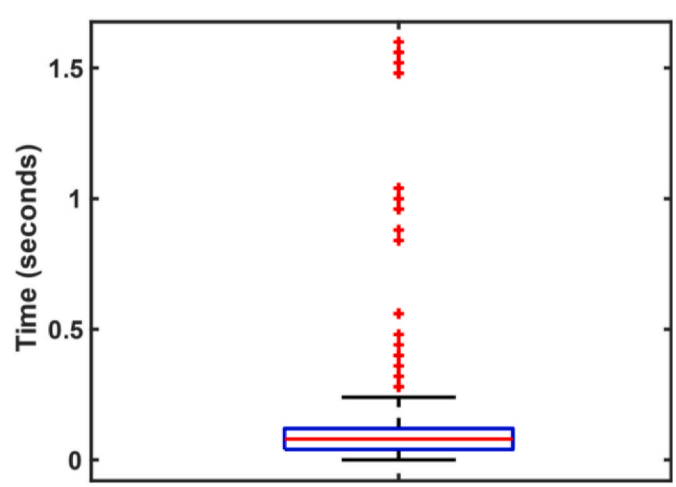

Fig. 5. Boxplot of error in preemptive trigger times.

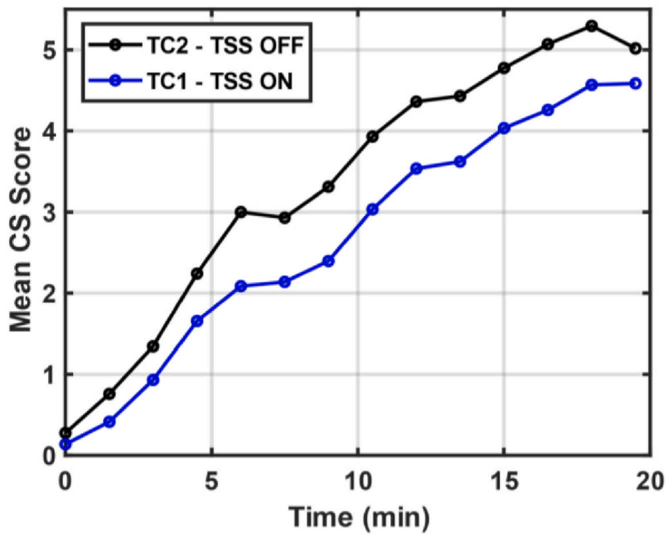

Fig. 6. Mean CS scores across 29 study participants.

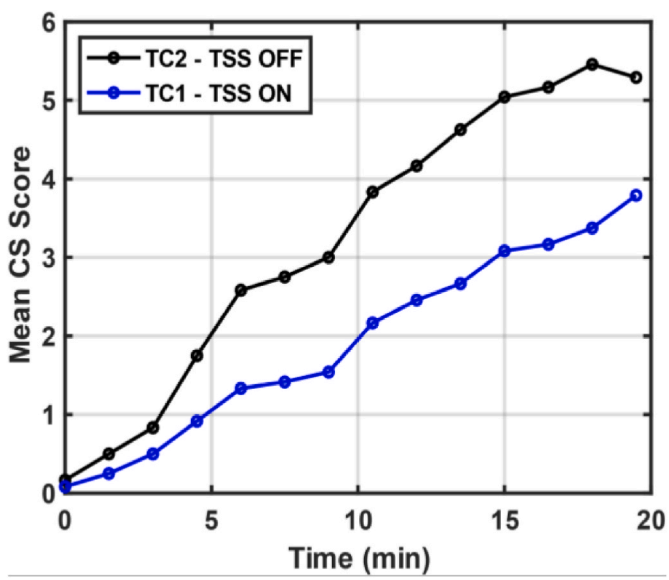

Fig. 7. Mean CS scores for all male study participants.

biological sex. Also, participant age was restricted to less than 35 years as prior work has shown that CS response is reduced for participants with greater age (Jones et al., 2019). To ensure a large enough sample of participants to achieve statistically significant outcomes, nearly 40 participants were recruited for the study.

Of those participants, 29 participants completed their participation in the full study (i.e., all test conditions). Of these 29 participants, 12 were male and 17 were female. The average age of the male participants was 25 years (25yrs ± 4yrs), and the average age of the female participants was also 25 years (25yrs ± 4.5yrs). Based on their self-reported motion sickness susceptibility and frequency, participants were grouped into one of three categories: low, moderate, and high motion sickness susceptibility. Ten participants (5 females and 5 males) were categorized as low motion sickness susceptibility, 18 participants (11 females and 7 males) were categorized as moderate motion sickness susceptibility, and one participant (1 female) was categorized as high motion sickness susceptibility.

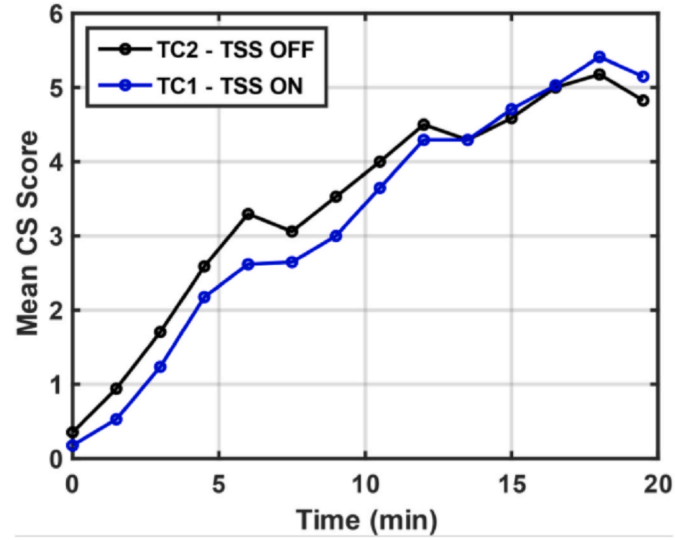

Fig. 8. Mean CS scores across all female study participants.

4. Experiment results

4.1. Carsickness (CS) scores

In Fig. 6, the mean CS scores for all 29 participants across both test conditions is plotted as a function of time. Initially the CS score is similar across both test conditions, before 5 min. The difference in the rate of accumulation of CS is most apparent between 5 min and 15 min. The rate of CS accumulation is highest for TC 2 (i.e., TSS OFF), and lowest for TC 1 (i.e., TSS ON). Also, the final mean CS score, at 19.5 min, was lower for TC 1 as compared to TC 2. This CS score data supports the first hypothesis that preemptively triggered TSS reduces CS response while the participants perform productive tasks.

A further analysis of the final mean CS score for all participants shows that for 15 out of 29 participants (7 females + 8 males, 52%) the final mean CS score is higher for TC 2 as compared to TC 1. Of the remaining 14 participants, 7 participants (4 females + 3 males) have the same final mean CS score across both test conditions, and 7 participants (6 females + 1 male) have a higher final mean CS score for TC 1 as compared to TC 2. These results indicate a disparity in the CS score of female and male participants, motivating further analysis of CS score

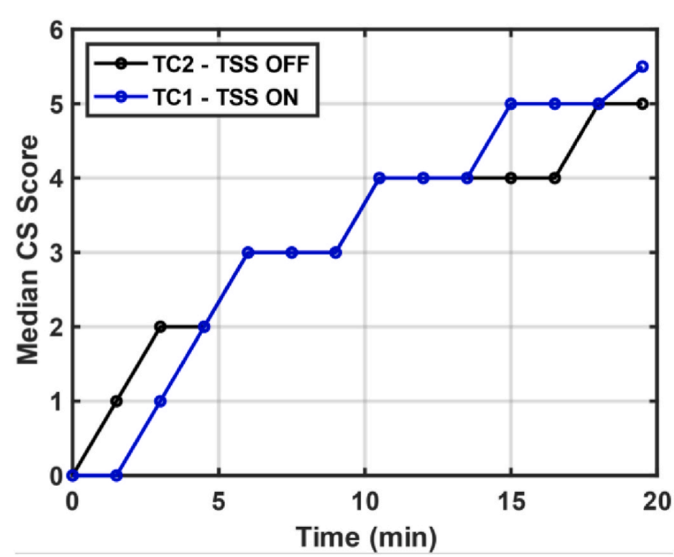

Fig. 9. Median CS scores across all female study participants.

Table 2
Linear mixed modeling results – male participants.

LINEAR MIXED MODEL RESULTS OVER 0 MINS TO 19.5 MINS			
FIXED EFFECT COEFFICIENT	ESTIMATE	STANDARD ERROR	P-VALUE
Intercept of TC 2	0.448	0.248	7.15 e−2
Δ Intercept TC 1 w.r.t. TC 2	−0.343	0.189	7.04 e−2
Slope of TC 2	0.287	0.029	1.18 e−20
Δ Slope TC 1 w.r.t. TC 2	−0.093	0.017	3.73 e−8
LINEAR MIXED MODEL RESULTS OVER 0 MINS TO 12 MINS			
Intercept of TC 2	0.087	0.195	6.56 e−1
Δ Intercept TC 1 w.r.t. TC 2	−0.091	0.190	6.34 e−1
Slope of TC 2	0.348	0.037	1.86 e−17
Δ Slope TC 1 w.r.t. TC 2	−0.150	0.027	5.66 e−8

Table 3
Linear mixed modeling results – female participants.

LINEAR MIXED MODEL RESULTS OVER 0 MINS TO 19.5 MINS			
FIXED EFFECT COEFFICIENT	ESTIMATE	STANDARD ERROR	P-VALUE
Intercept of TC 2	1.159	0.287	6.36 E−5
Δ Intercept TC 1 w.r.t. TC 2	−0.582	0.193	2.77 E−3
Slope of TC 2	0.232	0.037	7.27 E−10
Δ Slope TC 1 w.r.t. TC 2	0.038	0.017	2.42 E−2
LINEAR MIXED MODEL RESULTS OVER 0 MINS TO 12 MINS			
Intercept of TC 2	0.671	0.238	5.15 E−3
Δ Intercept TC 1 w.r.t. TC 2	−0.401	0.203	4.86 E−2
Slope of TC 2	0.332	0.041	1.36 E−14
Δ Slope TC 1 w.r.t. TC 2	−0.001	0.028	9.82 E−1

data by the biological sex of the participant.

Figs. 7 and 8 show the mean CS scores over time for all 12 male participants and all 17 female participants, respectively, across both test conditions. A comparison of mean CS scores by biological sex of participants reveals that the TSS causes a significant reduction in the CS scores for male participants, while it has almost no effect on the CS scores of female participants. A further analysis of the female CS score data reveals that the trend in mean CS scores was consistent across most female participants and is not skewed by outlier data. This was confirmed by analyzing median CS score data for all female participants that showed no difference in median CS score across test conditions (Fig. 9). Statistical modeling is used to ensure that these trends in CS score were statistically significant.

Linear mixed modeling (LMM) with random intercept and slope is used to statistically model the CS score data across all participants over the entire length of the experiment (up to 19.5 min). Linear modeling is sufficient since the deviation between the linear model and experimental data was minimal. Additional modeling using experimental data up to 12 min was also conducted since the modeling error was nearly half as much as when data up to 19.5 min was used. The fixed effects for the model included test conditions (i.e., TC 1, TC 2) and time (i.e., 0 min, 1.5 min … 19.5 min).

The results of the LMM model of male participants are summarized in Table II and female participants are summarized in Table III. The intercept refers to the CS score at time 0 min (i.e., beginning of the test condition). For all models, the CS score intercept across all participants is close to 0. This is expected as the experiment was designed to ensure that participants have the same baseline CS at the beginning of all the test conditions. The slope refers to the rate of accumulation of CS over time. The difference in slope across test conditions for male participants is statistically significant, with the TSS reducing the slope by over 40% between TC 2 and TC 1 for data up to 12 min and over 30% for data up to 19.5 min.

There is no statistically significant difference in slope across test conditions noted for female participants.

4.2. Task performance

Task performance was quantified using the following parameters: (a) accuracy of responses, (b) percentage of skipped questions, and (c) response time for answering questions. Accuracy of responses was defined as the ratio between the number of questions answered correctly and the total number of questions viewed (including answered or skipped) by the participant.

Of the 29 participants, task performance data for five participants was corrupted or lost due to technical errors. Of these five participants, one participant was a moderate susceptibility female, one participant was a low susceptibility female, one participant was a low susceptibility male, and remaining two participants were moderate susceptibility males. Therefore, task performance data analysis is only performed on data from 24 participants.

Since the task performance data is a continuous paired non-parametric dataset, Wilcoxon Signed-Rank analysis was used to statistically model task performance to determine significance (Rosner et al., 2006). Initially, task performance data was aggregated across all 24 participants and shows no statistically significant difference across test conditions. Since the CS scores differed by participant biological sex, further analysis of the task data as a function of participant biological sex was also conducted. Task performance data for 9 male participants is summarized in Table IV and for 15 female participants is summarized in Table V. There is no statistically significant difference in task performance parameters for male participants across both test conditions.

There is no statistically significant difference in the task performance parameters for female participants across both test conditions, except for the accuracy of high cognitive loading questions. The data showed that female participants have a statistically significant slightly higher accuracy of high cognitive loading questions in TC 1 as compared to TC 2. Therefore, while the preemptively triggered TSS has no effect on the task performance of male participants, it had a small positive effect on the task performance of female participants.

Table 4
Statistical analysis of task performance male participants only.

PARAMETER	TC 2 – TSS OFF	TC 1 – TSS ON	Δ TC 1 & TC 2
Mean Accuracy across all questions	83% ± 7%	84% ± 10%	TC 1 ~ TC 2 *p-value > 0.05*
Mean Accuracy of only low cognitive questions	85% ± 8%	88% ± 6%	TC 1 ~ TC 2 *p-value > 0.05*
Mean Accuracy of only high cognitive questions	81% ± 11%	79% ± 16%	TC 1 ~ TC 2 *p-value > 0.05*
Mean Percentage of skipped questions	1% ± 1%	1% ± 0%	TC 1 ~ TC 2 *p-value > 0.05*
Mean Response time across all questions	26s ± 7s	32s ± 17s	TC 1 ~ TC 2 *p-value > 0.05*
Mean Response time across only low cognitive questions	24s ± 6s	26s ± 15s	TC 1 ~ TC 2 *p-value > 0.05*
Mean Response time across only high cognitive questions	30s ± 11s	38s ± 29s	TC 1 ~ TC 2 *p-value > 0.05*

Table 5
Statistical analysis of task performance female participants only.

PARAMETER	TC 2 – TSS OFF	TC 1 – TSS ON	Δ TC 1 & TC 2
Mean Accuracy across all questions	84% ± 8%	86% ± 8%	TC 1 ~ TC 2 *p-value* > *0.05*
Mean Accuracy of only low cognitive questions	91% ± 8%	87% ± 6%	TC 1 ~ TC 2 *p-value* > *0.05*
Mean Accuracy of only high cognitive questions	78% ± 12%	85% ± 10%	TC 1 > TC 2 *p-value* < *0.05*
Mean Percentage of skipped questions	2% ± 2%	2% ± 1%	TC 1 ~ TC 2 *p-value* > *0.05*
Mean Response time across all questions	27s ± 9s	25s ± 6s	TC 1 ~ TC 2 *p-value* > *0.05*
Mean Response time across only low cognitive questions	24s ± 8s	26s ± 11s	TC 1 ~ TC 2 *p-value* > *0.05*
Mean Response time across only high cognitive questions	30s ± 16s	24s ± 8s	TC 1 ~ TC 2 *p-value* > *0.05*

4.3. Subjective qualitative questionnaire

Using the qualitative Questionnaire described previously, each participant was interviewed after each test condition and asked to describe their experience qualitatively. When asked if they noticed the motion of the TSS, 23 out of the 29 participants (12 of 17 females, 11 of 12 males) indicated that the motion of the TSS was neither noticeable nor bothersome. The remaining six participants found the TSS motion to be noticeable, especially during sharp turns, but did not find it to be bothersome.

After participants had successfully completed participation in both test conditions, they were also asked if they would prefer to have a TSS system, similar to what they experienced in the study, in a vehicle as a passenger. Of the 29 participants, 20 participants (9 of 17 females, 11 of 12 males) reported a positive preference for the TSS, stating that the TSS seemed to be helping reduce their CS response and/or helping improve their comfort in the vehicle. Three of those nine female participants also felt that the TSS helped them perform the task better.

The remaining 9 participants who did not report a positive preference for the TSS indicated that they felt the TSS made it harder to focus on the productive task, but no corresponding difference in task performance data was observed. One of the nine participants felt that the TSS was exacerbating their CS response, even though there was no observable difference in this participant's CS score. Therefore, participant responses to the Questionnaire provided additional insights regarding participant CS response which were not observed in their CS score data. To the authors' knowledge, this is the first study to leverage both quantitative CS Scores and Questionnaires to assess participant CS responses. This is also the first study to report qualitative data indicating a strong subjective preference for a TSS that helped reduce participant CS response.

5. Discussion and conclusions

5.1. Discussion of study limitations & future work

The results from this study provide supporting evidence for the first hypothesis, that a preemptively triggered TSS reduces CS response even when the participant performs a task (using two CS assessment tools). Although the TSS showed a significant reduction in the CS scores of male participants, it has no effect on the self-reported CS scores of female participants. While some prior literature has indicated that motion sickness response can vary as a function of biological sex, such as females are more prone to motion sickness as men (Lawther and Griffin, 1986; Lawther and Griffin, 1988; Koslucher et al., 2016; Turner and Griffin, 1999), other published work has found no correlation between motion sickness and participant sex (Jones et al., 2019; Klosterhalfen et al., 2006). Some past research studies have also found that (postural) precursors to motion sickness differ by participant sex (Curry et al., 2020; Munafo et al., 2017). Therefore, it is possible that the observed disparity in CS scores between the sexes reported in the study presented in this paper may be due to an implicit difference in the CS response of the two sexes. Future research with a larger sample size of participants may provide more definitive insights regarding the influence of TSS on CS response as a function of participant sex.

Even though there was no observable effect of the preemptively triggered TSS on the CS scores of female participants (one of the two CS assessment tools), over half of all females indicated a positive preference for the TSS in their Qualitative Questionnaire. Those female participants with a positive preference for the TSS also reported that they felt that the TSS was having a positive effect on their CS response. Also, some female participants indicated that they felt the TSS helped them perform the task better. Therefore, it is unlikely that the positive preference for TSS of female participants is correlated with other factors e.g. such as finding the motion of the seat enjoyable.

Based on the Questionnaire responses of these female participants, 7 of the 9 female participants indicating a positive preference for the TSS did not find the motion of the TSS to be noticeable or bothersome. It is unlikely that they would find the TSS enjoyable if they did not notice its motion. Similarly, since the same seat and seat cushions were used in both test conditions, it is unlikely that the participants would find the seat (and not the motion of the TSS) more comfortable in one test condition as compared to the other. It is possible that the positive benefit of the TSS on the CS response of female participants was not observed in their self-reported CS scores but was captured in their responses to the Questionnaire. This underscores the importance of using both CS assessment methods in conjunction to assess participant CS response.

To the authors' knowledge, the study presented in this paper is the first to include two self-reported subjective assessments of CS response of participants. These two subjective assessments of CS include both the **quantitative** Motion Sickness Scale and the **qualitative** Questionnaire. In this study, the data for male participants from both assessments was strongly aligned, indicating a reduction in CS score due to TSS and positive preference for TSS. However, the data for female participants from both CS response assessments was weakly aligned. While more than half of the female participants indicated a positive preference for TSS, there was no corresponding reduction in their CS score. Given that both these assessments are subjective, it is challenging to explain the differences between the quantitative and qualitative responses of female participants. It is recommended that the physiological and kinematic data collected in the study presented in this paper be used for future research efforts to develop an objective assessment of CS response. A combination of self-reported subjective CS assessment and sensor-measured objective CS assessment should lead to an even more complete assessment of participant CS response.

Despite reasonable efforts to recruit an equal number of male and female participants, this study was constrained by an imbalance in participant biological sex. In addition, there was only one participant who had a high self-reported susceptibility to motion sickness. Future research which addresses this participant recruitment constraint can provide additional data on efficacy of preemptively triggered TSS in reducing CS for high motion sickness susceptibility participants.

Another avenue of future research is the design of the trajectory for preemptively triggered TSS systems. The TSS trajectory in this research was constrained by the 3 s preemption time and the requirement of minimal acceleration of the participant's head so that the motion of the TSS would not be noticeable for the participants. While most participants (23 out of 29) did not find the motion of the TSS in this study to be bothersome, the optimal trajectory for a TSS to maximize CS response reduction and productive task performance remains unknown.

While the results from this study are significant, this study had some practical limitations**.** While using a commercially available TSS reduced the engineering development burden, it limited the maximum range of motion to 7 degrees of tilting. Depending on the lateral acceleration of the vehicle, a tilt beyond 7° may be required to better align the passenger's head with the direction of gravito-inertial acceleration (Frechin et al., 2004). Furthermore, the center of rotation of the TSS was fixed and located under the participant. As the TSS rotates, the farther the participant's head is from the center of rotation the more linear acceleration (due to rotation of the TSS) will be experienced by the participant. Some prior research has proposed that collocating the center of rotation of the moving seat with the passenger's head may be more effective at reducing CS (Frechin et al., 2004; Beard and Griffin, 2014). Therefore, further systematic investigations are required to determine the optimal TSS design, with regard to the range of motion of the seat and location of its center of rotation.

5.2. Conclusions

Despite the constraints and limitations, the findings from this study are significant. The results from this study demonstrate that a preemptively triggered TSS reduces CS response of male participants, as observed by the reduction of their self-reported CS scores and in their strong positive preference for the TSS indicated in their Questionnaire responses. In addition, the results show that male participants benefit from CS reduction due to the preemptive TSS without any negative side effects on their ability to perform productive tasks.

The results from this study also demonstrate that a preemptively triggered TSS had a small positive effect on the CS response of female participants as while the TSS did not affect their self-reported CS scores but half the female participants still indicated a positive preference for the TSS. In addition, the TSS also has a small positive effect on the female passengers' ability to perform tasks.

This was the first TSS study to use both CS scores and Questionnaires to gauge the participants' CS response and overall experience while participating in the study. Through the Questionnaire responses, this study demonstrated a strong preference for TSS among the majority of the participants (both male and female), even amongst those participants who did not show a reduction in their CS scores. This systematic study could pave the path to the long-term development of novel real-world CS mitigation technologies based on preemptive interventions (Awtar et al., 2020)

CRediT authorship contribution statement

Nishant Jalgaonkar: Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Daniel Sousa Schulman:** Project administration, Methodology, Investigation. **Ming Shao:** Methodology. **Saharsh Jaisankar:** Visualization, Resources, Methodology. **Brandon Tarter:** Visualization, Resources, Project administration, Methodology. **Nikitha MV:** Visualization, Project administration. **Jacqueline Buford:** Visualization, Methodology. **Sarah Chan:** Visualization, Methodology. **Michael Wachsman:** Visualization, Methodology. **Shorya Awtar:** Writing – review & editing, Writing – original draft, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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