# ZenRide: XR Mindfulness Meditation Support System for Autonomous Vehicles*

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Abstract
This study proposes an XR support system called "ZenRide" to promote mindfulness meditation as a secondary activity within autonomous vehicles. The system supports mindfulness meditation using a motion platform equipped with a hemispherical screen and a seat installed inside the autonomous vehicle. It consists of three main features: first, the immersive meditation environment, which provides relaxing audio-visual stimuli; second, breathing rate guidance, which uses seat tilts to mimic the sensation of deep breathing and enhance concentration; and third, posture control, which counteracts the sensation of vehicle motion through seat adjustments. A prototype implementing the immersive meditation environment and breathing rate guidance was developed, and preliminary experiments were conducted. The results suggest the potential for breath guidance to provide appropriate rhythms to effectively support mindfulness meditation while driving in autonomous vehicles.

**Keywords**
Autonomous vehicle, XR, Mindfulness, Mental health care, Passenger Comfort

## 1. Introduction

The advancement of autonomous driving technologies holds the potential to enhance traffic efficiency and prevent accidents caused by human error [1]. Furthermore, autonomous vehicles can liberate drivers from the task of driving, allowing them to utilize travel time more meaningfully as passengers. Therefore, autonomous vehicles have the potential to serve not only as a means of transportation but also as new living spaces.

In particular, at the Society of Automotive Engineers (SAE) automation level 4, manual driving interventions are no longer required within operational design domains, and at level 5, driving becomes entirely unnecessary [2]. As a result, passengers can engage freely in secondary activities without concern about take-over requests. These secondary activities encompass a variety of options, such as work, entertainment, and sleep, with mindfulness meditation standing out as a noteworthy example [3, 4].

Mindfulness is the practice of focusing attention on moment-by-moment experiences, including the five senses, posture, and mental activities. Numerous studies have demonstrated its effectiveness in reducing stress and promoting mental and physical well-being [5, 6, 7]. Since commute-related stress can negatively impact subsequent work performance, practicing mindfulness meditation within autonomous vehicles offers a promising solution to this issue [4]. Passengers could relax and alleviate stress during transit, thereby improving their performance in post-travel activities.

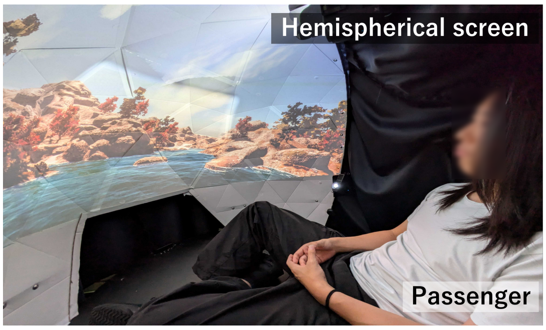


**Figure 1:** A passenger engaging in mindfulness meditation using the ZenRide system within an autonomous vehicle.

However, existing studies have not sufficiently explored the feasibility of comfortable mindfulness meditation inside autonomous vehicles. Sudden accelerations, lane changes, and other driving behaviors can affect passengers' vestibular and somatosensory systems, making it difficult for them to focus on mindfulness practices. Addressing these challenges requires not only improvements to the vehicle's interior environment but also the development of systems that help passengers maintain focus and comfort during the ride.

This study aims to design a support system that facilitates mindfulness meditation for passengers in SAE automation level 4 or higher vehicles. We employ a multimodal XR mobility platform that integrates a motion

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platform with a hemispherical immersive display and seating to achieve this. This paper presents an overview of the mindfulness meditation support system "ZenRide" (see Figure 1) design and reports the preliminary experimental results.

## 2. Related Work

Research on passenger comfort and stress reduction in autonomous vehicles has gained momentum in recent years [8, 9, 10, 11], with particular attention given to the potential of mindfulness during travel [3]. In existing studies, comprehensive models have been proposed to capture the factors influencing passenger comfort in an integrated manner [12, 13, 14]. These models primarily include factors such as the external environment, vehicle functionalities, user activities and characteristics, and system understanding. While these models provide a holistic framework for enhancing the passenger experience within autonomous vehicles, research on factors that directly contribute to improvements in mental health and stress reduction—particularly in the context of secondary activities—remains limited.

In studies focusing on mindfulness within vehicles, P. E. Paredes et al. explored stress reduction through guided breathing techniques, demonstrating that tactile and auditory interventions effectively lowered drivers' breathing rates and alleviated stress [4]. However, this study primarily targeted drivers, leaving the strategies for stress reduction among passengers in autonomous vehicles unexamined. Moreover, virtual reality (VR)-based relaxation experiences have shown that synchronized VR content and vehicle movements can have a calming effect, particularly when simulating underwater diving [15]. These simulations were found to reduce passengers' autonomic arousal during travel. However, the interaction between vehicle dynamics and mindfulness meditation has not been adequately explored, and further research is needed to investigate how vehicle behavior may affect the ability to concentrate during meditation.

Additional studies have also examined the potential of mindfulness interventions during commutes, involving exercises and breathing-based techniques. For example, interventions combining vibrotactile patterns with simple movements have been proposed to reduce commuter stress [3]. However, these studies again focus primarily on drivers rather than passengers.

While these prior studies have contributed to understanding stress reduction and mindfulness in autonomous driving environments, most discussions center around drivers or VR content, with limited attention to mindfulness meditation specifically tailored for passengers. This study seeks to address these gaps by providing an environment that allows passengers to engage in mindfulness meditation without disrupting vehicle movements in SAE automation level 4 or higher vehicles. By employing a motion platform with a hemispherical immersive display and seating, the proposed system aims to support mindfulness meditation, thereby reducing passenger stress and enhancing comfort during travel. The significance of this study lies not only in offering new technical and design approaches for facilitating comfortable mindfulness meditation within autonomous vehicles but also in promoting the idea that secondary activities during travel should be designed to provide benefits beyond merely making efficient use of travel time, positively influencing passengers' post-travel experiences as well.

## 3. Proposed System: ZenRide

ZenRide is an XR system designed to support mindfulness meditation within autonomous vehicles. Since vehicle movements during autonomous driving may cause discomfort and anxiety in passengers, this system aims to enhance comfort and facilitate meditation through audiovisual stimuli and posture control.

Autonomous vehicles can use onboard sensors and route-planning algorithms to calculate and predict the somatic and vestibular stimuli that passengers may experience during travel. Based on these predictions, the system tilts the seat accordingly to minimize the impact of vehicle dynamics and reduce passenger anxiety. As a result, passengers are provided with an environment conducive to immersive and deeper mindfulness meditation. This system is only feasible in fully autonomous driving. Vehicle behavior depends on moment-to-moment decisions with human drivers, introducing unpredictability that makes preemptive control difficult, unlike autonomous driving.

Passengers meditate while seated on a motion platform within the vehicle. This system offers three key functions to enhance the meditation experience.

### 3.1. Immersive Meditation Environment

This function creates an immersive meditation environment through visual content projected onto a hemispherical screen and auditory stimuli provided via headphones. To further enhance immersion and focus, the system employs noise-canceling headphones to eliminate external sounds, including road noise and any noise generated by seat adjustments.

### 3.2. Breathing Rate Guidance

This function controls the seat's tilt to regulate the passenger's posture, stimulating both somatic and vestibular sensation. By mimicking the natural movements of deep breathing—where the upper body reclines during inhalation and returns to its original position during exhalation—the system facilitates a natural deep breathing experience for passengers.

### 3.3. Posture Control

This function manages the motion platform based on the vehicle's driving route and acceleration or deceleration patterns, reducing the sense of vehicle motion caused by vehicle dynamics. By minimizing stress from movement sensations and alleviating anxiety related to external driving conditions, the system allows passengers to relax and engage more deeply in meditation.

## 4. System Overview

Figure 2 illustrates the overview of this system, and the following sections describe the hardware and software details.

### 4.1. Hardware Architectures

The autonomous vehicle utilized is the "RoboCar Mini Van" by ZMP Inc. To accommodate the motion platform and hemispherical display, the two rear rows of seats have been removed.

The motion platform is powered by linear actuators from Koncy (ASIN: B09B4SS6P3). They offer a 150 mm range, a speed of 15 mm/s, and a load capacity of 800 N. The actuators are controlled by an Arduino Leonardo (microcontroller based on the ATmega32u4).

Passengers sit on the motion platform and view content through a custom-made hemispherical display (with an inner diameter of 1.24 m, height of 1.00 m, and depth of 0.62 m). Three projectors display immersive 360-degree visuals, enhancing the sense of presence. The display tilts in sync with the seat, allowing passengers to enjoy the visuals seamlessly without being distracted by the seat's movement. Additionally, Bose Noise Cancelling Headphones 700 block out noises from the vehicle and the motion platform, further improving the immersive experience.

### 4.2. Software Architectures

The autonomous driving system perceives the surrounding environment and the vehicle's position, plans the route, and controls acceleration, braking, and steering. The system employs the open-source Autoware.AI platform, which uses LiDAR data to generate maps of the surroundings and estimate the current position. Based on this information, the system generates a route that the vehicle follows. The CAN bus collects and controls vehicle data such as speed, acceleration, and steering angles.

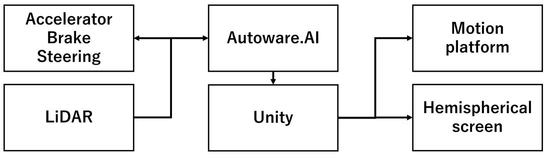


**Figure 2:** The system overview of our proposed system.

LiDAR data and vehicle position information are transmitted to Unity, where virtual scenes (e.g., flowing clouds) are generated and projected onto the screen. In the breathing rate guidance function, signals are sent from Unity to the motion platform every four seconds to tilt the seat forward and backward, aligning with the breathing rhythm.

## 5. Preliminary Experiment

### 5.1. Overview

This section details the preliminary experiment using a prototype implementing two functions of the ZenRide system: the "immersive meditation environment" and "breathing rate guidance." Notably, this experiment did not include the posture control function, meaning that participants directly experienced the sense of vehicle motion caused by vehicle dynamics. As a result, discrepancies between the perceived sense of vehicle motion and the visual information displayed on the screen could induce motion sickness. To address this, the visual content was designed to align the flow of clouds—representing the surrounding scenery—with the direction of movement experienced by the participants. Figure 3 shows the visual content projected onto the hemispherical screen during the experiment.

Since VR visuals aligned with the direction of the vehicle's movement are effective for mindfulness experiences [15], this experiment used the immersive meditation environment function as a baseline and focused on the breathing rate guidance function. Therefore, this preliminary experiment evaluated the effectiveness of the breathing rate guidance function in facilitating mindfulness meditation within an autonomous vehicle, focusing on ease of practice and its subjective effect on users. Figure 4 shows the driving route.

### 5.2. Experimental Conditions

This experiment employed a within-participants design. Participants first experienced the breathing rate guidance (w/ BRG) condition to get used to the system. To

**Figure 3:** Audiovisual content for the immersive meditation environment.

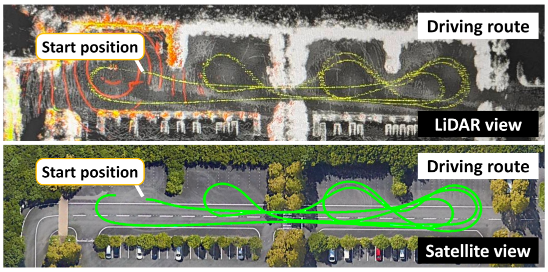


**Figure 4:** Driving route of the autonomous vehicle.

account for order effects, all participants subsequently experienced the two conditions in different sequences:

- With breathing rate guidance function (w/ BRG)
- Without breathing rate guidance function (w/o BRG)

### 5.3. Participants

The experiment involved eight Japanese undergraduate and graduate students (six males and two females, mean age = 21.0, standard deviation (SD) = 1.07).

### 5.4. Measurements

Participants completed two subjective questionnaires to assess their impressions during the experiment:

- Emotion Questionnaire: We used the Affect Grid [16] to assess emotions along two axes. In this study, we defined them as valence and arousal. Participants were instructed to rate each question on a nine-point scale, ranging from one (negative, passive) to nine (positive, active). Additionally, to evaluate focus levels during the experiment, participants were asked, following a similar study [4], to rate their level of focus on an 11-point scale, ranging from zero (low focus) to ten (high focus).
- Workload Questionnaire: National Aeronautics and Space Administration Task Load Index (NASA-TLX) [17] was used to assess participants' workload.

Additionally, to evaluate the extent of motion sickness induced by the system, the Simulator Sickness Questionnaire (SSQ) [18] was administered.

### 5.5. Procedure

The study was approved by the ethics committee of the Nara Institute of Science and Technology (approval number: 2024-I-9) and conducted in accordance with the institution's ethical guidelines. Before the experiment, participants were briefed on its objectives and procedures.

Participants first boarded the autonomous vehicle, fastened their seatbelts, and put on headphones. They then completed a pre-experiment SSQ questionnaire. To familiarize themselves with the autonomous driving experience, participants first underwent the breathing rate guidance (w/ BRG) condition, which served as the baseline for the overall experience assessment.

Next, participants experienced both conditions in a randomized sequence, answering the same questionnaires after each condition. Finally, they completed the SSQ once more and participated in an oral interview, during which they elaborated on their impressions of the overall experience.

## 6. Results

Figure 5 presents the questionnaire scores under the two conditions: with breathing rate guidance (w/ BRG) and without breathing rate guidance (w/o BRG).

### 6.1. Emotion Questionnaire

The emotion questionnaire results present scores for valence and arousal. According to the Affect Grid, under the w/ BRG condition, the mean scores ± SD were 6.86 ± 2.10 for valence and 5.13 ± 2.36 for arousal. In contrast, under the w/o BRG condition, the mean scores ± SD were 6.25 ± 2.05 for valence and 5.00 ± 2.51 for arousal. We conducted wilcoxon signed-rank test and we did not find significant differences: $W = 3.5$, $p = 0.258$ for valence, $W = 10.0$, $p = 0.915$ for arousal.

The results of the questionnaire on focus levels during the experience indicate that, under the w/ BRG condition, the mean score ± SD was 7.00 ± 1.31. Under the w/o BRG condition, the mean score ± SD was 6.13 ± 1.81. We conducted wilcoxon signed-rank test and we did not find significant differences: $W = 7.5$, $p = 0.268$.

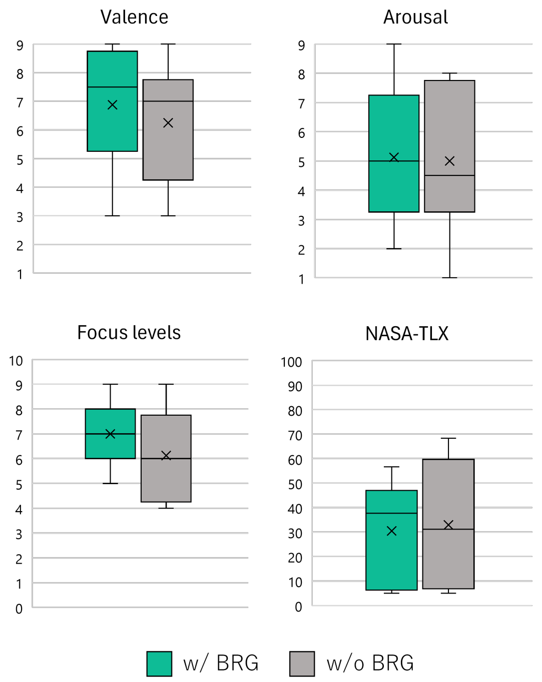


**Figure 5:** Box-and-whisker plot of each questionnaire result.

### 6.2. Workload Questionnaire

The NASA-TLX scores for workload during the experiment indicate that, under the w/ BRG condition, the mean score ± SD was 30.5 ± 20.7. Under the w/o BRG condition, the mean score ± SD was 32.9 ± 25.5. We conducted wilcoxon signed-rank test and we did not find significant differences: W = 13.0, p = 0.866.

### 6.3. SSQ

Motion sickness in the vehicle was evaluated using SSQ before and after the experiment. Before the experiment, the mean scores ± SD were 13.1 ± 19.04 for Nausea, 11.4 ± 21.44 for Oculomotor, 8.7 ± 16.53 for Disorientation, and 124.1 ± 181.63 for the Total Score. After the experiment, the mean scores were 11.9 ± 13.24 for Nausea, 10.4 ± 12.11 for Oculomotor, 15.7 ± 20.29 for Disorientation, and 142.1 ± 161.41 for the Total Score.

## 7. Discussion

In this study, we examined how breathing rate guidance through seat tilting supports mindfulness meditation in an autonomous vehicle, where visual influence from the external driving environment was blocked using a hemispherical screen. Although no significant differences were found due to the small number of participants, the distribution of scores suggested the potential for the breathing rate guidance function to provide passengers with an appropriate breathing rhythm, facilitating their engagement in meditation.

This research demonstrates the potential of autonomous driving technology to offer novel relaxation experiences, contributing to the future design of vehicle well-being environments. However, several limitations must be acknowledged. In future work, we plan to implement the posture control function to counteract the sense of vehicle motion and make it easier for passengers to engage in meditation. Additionally, to evaluate the effectiveness of ZenRide not only subjectively but also objectively, it will be essential to conduct large-scale evaluation experiments utilizing biometric sensors.

## 8. Conclusion

In this study, we proposed an XR mindfulness meditation support system called "ZenRide" for practicing mindfulness meditation as a secondary activity within autonomous vehicles. ZenRide integrates immersive audiovisual content and posture control, utilizing a motion platform equipped with a hemispherical screen and a seat to create an immersive meditation environment conducive to mindfulness meditation. A prototype implementing the immersive environment and breathing guidance was developed. The results of preliminary experiments suggested the potential of the breathing rate guidance function to support meditation by offering appropriate rhythms. Future research will focus on implementing posture control and real-time biometric feedback systems to improve focus, reduce stress, and create personalized meditation environments. ZenRide aims to enhance both in-vehicle comfort and passenger well-being, not only facilitating meaningful use of travel time but also improving post-travel performance. This system provides a foundation for achieving relaxation and well-being in next-generation mobility.

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