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Motion Sickness Mitigation in Road Vehicles with a Triad of Focus on Safety and Sustainability

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Abstract - *Although commonly experienced, the issue of car sickness is still poorly understood. Research towards its alleviation only gained interest in recent years, coinciding with the electric, digital and autonomous transformation of road vehicles. Within these vehicles, a heightened risk of car sickness poses a potential obstacle to their successful integration on public roads. Identifying effective mitigation means for car sickness may not only ensure the acceptability of new transportations means but also have broader benefits in terms of safety, and sustainability. Among others, a solution for car sickness would improve the quality of life for most susceptible individuals, enhance accessibility for people with disabilities, and reduce inequalities to mobility. Addressing car sickness additionally also contribute to vehicle safety by preventing driver distraction and support sustainability by encouraging the use of shared transportation. Such improvements could already be beneficial for current road transportation.*

Keywords: *motion sickness, car sickness, autonomous vehicles, connected cars, future transportation.*

I. INTRODUCTION

Motion sickness refers to a state of illness induced by a prolonged exposition to a physical or visual motion stimulus [1]. The occurrence and severity of this phenomenon increase with time of exposition and magnitude of motion. This condition can persist from few minutes to days depending on individual susceptibility and exposure history.

The onset of motion sickness is due to the uncommon nature of motion environments where the body is unable to adapt [2]. When exposed to a given motion stimulus, the body usually adapts so that the symptoms no longer appear [1], [3]. Such an ability explains why motion sickness occurs when employing new forms of transportations, and may have been discovered along with the adoption of other traveling means than walking [4]. There are different forms of motion sickness, each corresponding to the physical and visual characterization of a provocative motion environment. Most notable forms are

seasickness, airsickness, space-sickness and carsickness, which are respectively induced by particular types of physical motion stimuli. Other forms of motion sickness exist under the notion of visually induced motion sickness [5], [6]. The symptomatology of motion sickness is generally misunderstood: people usually attribute it to moderate to severe symptoms such as hypothermia, nausea and vomiting whereas it also encompasses lighter manifestations such as dizziness, pallor, drowsiness or lethargy [4]. There is a wide variety in autonomic responses and sensitivity to specific motion stimuli between individuals [7], [8], [9], [10], [11].

This paper specifically focuses on car sickness, which is experienced while traveling in road vehicles and characterized by an exposition to unpredictable and low frequency horizontal motion with moderate to high magnitudes [12], [13], [14]. These specific motion stimuli are induced by the vehicle's behaviour on the road, that mainly generates fore-aft and cornering maneuvers. Slight tilts of the car's body also occur due to the combination of accelerations and the vehicle's kinematics [13]. Car sickness is the second most experienced form of motion sickness, with two thirds of the people traveling by car having suffered it once on their life [1], [15], [16].

Although the research community focused on the topic of motion sickness for military purposes in the second half of the 20th century, it is still unclear and discussed through theories. Car manufacturers did poorly consider car sickness occurrence in the design process of automotive vehicles until recently [17], [18]. Yet, motion sickness evolves into a hygiene issue [19], whose addressing is a requirement for the successful introduction of highly automated vehicles (HAVs). This problem motivated further research and development of systems to alleviate car sickness [20], [21].

The next sections aim to help understanding the causes and challenges behind the issue of car sickness. The potential impact of an effective alleviation solution is then discussed in terms of accessibility, safety and sustainability.

II. AETIOLOGY OF CAR SICKNESS

The most accepted hypothesis on the mechanism of motion sickness suggests a sensory discrepancy between expected and real motion forces the body undergoes in a stimulating environment [1]. The body can adapt to provocative motion stimuli by keeping trace of adaptation methods to similar motion patterns that were previously experienced, but in the presence of novel provoking stimuli, the body uses impaired strategies to compensate for the sensory discrepancy, which leads to motion sickness. Another considered hypothesis proposes a relation between motion sickness and postural instability [22]. In a moving car, the postural sway of passengers may be a preceding although not sufficient factor of motion sickness [23], [24].

It has been often noted that susceptible subjects were less sickness-sensitive when driving the vehicle [1], [25]. The reason is that drivers have accurate perception of the vehicle's motion through their steering, clutch and brake inputs. Controllability and predictability are two dimensions that stem from the driving task and are crucial in the mitigation of motion sickness [25], [26], [27]. Such a contrast between drivers and passengers can be observed in their different body reactions to the gravito-inertial forces elicited by the car's motion [28], [29]. This figure supports both the sensory conflict theory and the postural instability theory, as passengers have a reduced perception of motion that results in their use of impaired strategies to stabilize their body.

The low probability of becoming sick as a driver made the issue of car sickness not to be considered in the development of passenger vehicles [30]. However, with the expected widespread of HAVs, this issue may affect passengers' trust and feeling of safety [31], [32]. Such dimensions are crucial for the acceptance of HAVs, and their decline may jeopardize the successful introduction of such vehicles on public roads [17], [33], [34], [35].

III. CAR SICKNESS AND FUTURE TRANSPORTATION

A. Causes of widespread

In the upcoming years, car transportation will undergo technological upheavals such as autonomous, digital, and electric transformations that are likely to increase car sickness prevalence to the point of doubling it [20], [21], [36].

In HAVs, the automation system takes over the driving task, and drivers will evolve into passengers along with a decline of controllability and anticipation, being, as a result, "out-of-the-loop" [37]. The forced reduction of such abilities may increase the likeliness of experiencing motion sickness: the vehicle's driving style may not fit user expectations and the induced motion may feel as unpredictable [38], [39]. Since exposure

history play a role in the development of symptoms [3], [40], [41], some regular drivers may discover themselves as particularly sensitive, and most susceptible individuals might reject this transportation mean [17]. This increase in car sickness prevalence has already been observed with the introduction of vehicles with partial automation and may accentuate with higher levels [21]. By 2050, it is expected that HAVs will constitute a majority of the vehicles on the road [42], which highlights the necessity of dealing with the issue of car sickness.

As previously mentioned, HAVs offer their users the possibility to devote travel time to productive, relaxing, or playful NDRAs. To propose an atmosphere that suits the users' needs, future vehicle cockpits may feature numerous screens and interfaces. Their omnipresence may overload the users with incongruent visual stimuli, restrict outside visibility and affect psychology with sensations of overwhelming. As a result, focusing on NDRA visual content may limit the cognitive resource for perceiving the vehicle motion [43] and lead to incongruent visual inputs with the physical motion [44], [45]. Reading and watching screens while traveling proved to increase the occurrence and severity of sickness symptoms [21], [45], [46]. In the context of HAVs, this issue may lead passengers not to be aware of the vehicle's driving. It is expected that 6-10% of adult American passengers of fully automated cars might almost systematically feel carsick [21]. This incidence might be even higher for other populations like Caucasian passengers [47].

Vehicle electrification may also present a higher risk of experiencing car sickness than in combustion engine vehicles: the suppressing of engine sounds (e.g. revving) may decrease audible information on vehicle longitudinal acceleration, which can be an auditory cues on combustion engine cars [48], [49, p. 170]. The high-frequency vibrations of a combustion engine are also suppressed with such motors. Bos (2015) argued that such vibrations could be perceived as soothing and help decrease sickness symptoms [50]. The high torque and reactivity of an electric motor may generate strong and unexpected accelerations. Same applies to the use of regenerative braking, a feature specific to electrified vehicles that has been lamented for its nauseogenic potential.

B. Challenges in solving car sickness

Even if the main motivation for identifying congruent mitigation means is to ensure the acceptability of HAVs, the impact of these findings could go beyond the strategic interests of car manufacturers. Benefits in terms of accessibility, safety and sustainability could be already observed through applications on the currently available vehicles.

1) Accessibility

A minor part of the population (around 10 %) is known to be very sensitive to motion sickness [40]. Some of these individuals have a restrained mobility, as they are so susceptible that they tend to avoid provocative travel means [9]. For such people, alleviating motion sickness symptoms could be perceived as a relief.

An effective solution for car sickness may not only be of public interest in road vehicles but for other passenger transportation means as well: car motion forces can be considered as a “worst case” of motion environment for ground transportation in the way it is characterized by repetitions of multidirectional and low predictable accelerations of high amplitudes. Hence, an efficient countermeasure to this provocative motion may be of great interest for less provocative transportation means like coaches and trains, which could become accessible to most unfortunate subjects.

In the context of future transportation, the identification of such a solution would mainly contribute to increase the acceptance of HAVs. Such vehicles are emphasized to facilitate access to mobility and improve the quality of life for people with disability or a medical condition [51], [52], [53], [54]. In France, a 2019 study showed that 8.4 % of a population aged 16 to 64 surveyed was in a “situation of disability”. These individuals cited more difficult access to mobility with a lack of vehicle equipment as one of the reasons for this disparity [55].

Solving car sickness may help in reducing inequalities to passenger transportation while helping susceptible people in better adapting [7].

2) Safety

In conventional cars as well, car sickness may be a safety issue if one passenger complains about the rise of symptoms or feels the urge to vomit. The driver’s cognitive resources may be altered and represent a potential safety risk if the driving situation is delicate to handle. In cases of incoming emesis for a passenger and the urge to stop the car, the type of driven road or traffic situation may be a dangerous situation for stopping the vehicle. The emergency to stop may also make the driver panic and create a crash while losing concentration when trying to stop the car.

Safety is also an underlying aspect of car sickness when considering HAVs. When considering level 3 and 4, there may be some situations where the vehicle automation surpasses its operational domain and requests the designated driver to regain awareness of the surroundings and take over control within 30 seconds. However, the onset of sickness symptoms, even

unnoticeable, may hinder the designated driver’s capacity to take over these responsibilities [30]. Several studies have reported degraded levels of physical, cognitive and visual performance when under motion sickness symptoms [56], [57], [58], [59], [49, p. 127].

3) Sustainability

As earlier reported, some people tend to reject passenger travel due to their likeliness of becoming sick. Such people may have no other choice than using the car to commute, a case of use that is known harmful for environment and health [60]. With a successful solution, they would hence be able to use shared transportation means. With regards to this hypothesis, the individual carbon footprint could be reduced for such subjects [61]. Considering that, in France, more than 70 % of commuters use individual vehicles, including 9 out of 10 alone in the car [62], solving the issue of carsickness may encourage the use of shared transportation and decrease this proportion.

C. Mitigation approaches and research perspectives

Medication is usually suggested as a reliable countermeasure of motion sickness. However, the efficacy of anti-motion sickness drugs may be counterbalanced by undesirable side effects such as drowsiness [8]. Some of these treatments may even report no improvements in comparison to placebos. Such methods are not compatible with the use of a car, as they could compromise safety and performance. Therefore, the challenge is to identify a universal, non-intrusive and sufficiently effective mitigation technique. Addressing this issue first requires sufficient knowledge on the causes of motion sickness in a car [63]. With the variety of factors to influence car sickness [12], [15], [16], [64], different types of corresponding solution have been elaborated. Recent work proposed clustering these solutions into three respective categories [65].

The first category “Vehicle-Centric Adaptation” clusters solutions to minimize and limit the vehicle dynamics. They involve choosing the most compliant itinerary to follow depending on user requirements (Route Planning) [66], [67], operating a feasible and comfortable trajectory (Motion Planning) [68], [69], [70], [71], and attenuating the motion forces that are generated (Vehicle Dynamic Optimization) [72], [73], [74], [75], [76], [77].

The second category “Cabin Layout” includes design guidelines for vehicle architecture. They mainly propose to maximize outside visibility while considering the position and size of windows (Daylight Opening), seats, and displays [44], [49, Ch. 12], [78], [79].

The third category “Sensory Cueing” involves delivering sensory stimuli to enhance the passenger’s individual perception of the vehicle’s motion or helping in its anticipation. Given that human motion perception is made of sensory integration of visual, vestibular and haptic information mainly, the majority of tested solutions replicated to increase visual [46], [49], [80], [81], [82], vestibular [46], [50], [83] and haptic [84], [85], [86] perception respectively.

Since psychology has a strong influence on the prevalence and development of motion sickness, the present paper proposes including a fourth category “In-Vehicle Atmosphere”, where sensory stimuli with no influence on motion perception are delivered to the user to increase feelings of comfort, wellbeing, promote relaxation and relieve negative feelings. This category includes methods such as olfactory stimuli [87], [88], acupressure [89], [90], [91], pleasant music [92], [93], temperature regulation [94], distraction effects [50] or even the incitation to controlled breathing [93]. Some of these solutions may include placebos, but should be considered given the influence they can have on motion sickness [95].

An overview of these categories can be seen in Figure 1. It is worth noting that each category of solutions addresses a specific cause of motion sickness. Since each category targets to reduce a specific cause of motion sickness, combining solutions from different categories should be considered to yield maximal alleviation effects [96].

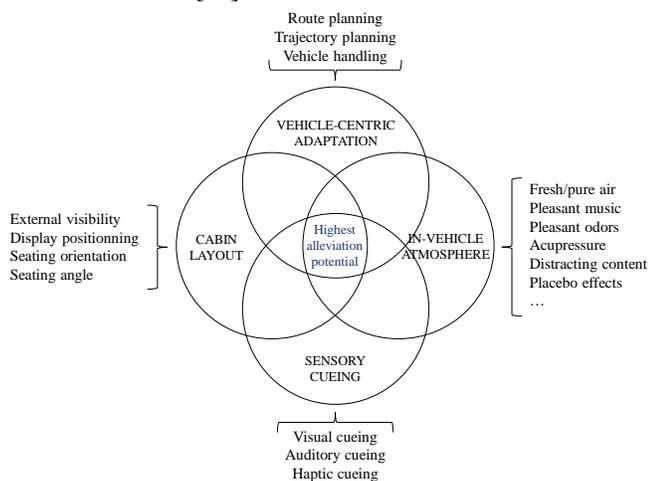


Figure 1. Overview of the different categories of an in-vehicle integrated car sickness mitigation solution.

IV. DISCUSSION

A. A further step towards sustainability... really?

The sustainable aspect of autonomous transportation is to nuance with regards to consumption trends. Identifying a

solution against car sickness may also present a rebound effect: carbon emissions may increase due to a more frequent use of HAVs. A wider adoption of such vehicles may be expected at the expense of “cleaner” mobility systems such as walking or riding a bike, which would be considered as less safe, less comfortable and slower. Some researchers anticipate that the widespread of autonomous transportation may increase the number of individual vehicles on the roads, even crossing the two billion threshold by 2030, even though the one billion mark was crossed in the early 2010s [97]. The use of traveling time as dedication to NDRAs would also increase the average traveled distance of individual vehicles [98], [99, p. 203]. Regarding those predictions, HAVs cannot be considered as sustainable unless promoting softer mobility and using more neutral energies [100].

B. How effective could be motion sickness alleviated in cars?

Motion sickness is a natural phenomenon that developed over millions of years as an adaptive defense mechanism of the body to a provoking motion environment [9], [101]. Yet, it is still poorly understood due to its intricate aetiology and the difference in body reactions from one individual to another [102], [103]. There are several worsening factors of motion sickness as well that may influence the development of symptom when traveling in a car, and designing sufficiently effective countermeasure would first imply identifying all these causes and how to prevent them.

There is a wide inter-individual range in motion sickness susceptibility. The challenge of finding a universal solution is tough, but not impossible if attention is first given to better understand human perception, psychology, sensitivity, and their respective influence [7]. Nevertheless, combining different mitigation systems has been suggested as a promising alternative [63], [65]. While simultaneously considering sensory cueing, dynamic optimization, cockpit design requirements and a wellbeing atmosphere, such a solution would help in limiting the causes, minimizing the severity, and facilitating recovery simultaneously.

V. CONCLUSION AND PERSPECTIVES

Addressing car sickness gained interests within recent years with the purpose of ensuring a good user experience on board future road vehicles that will be electrified, automated, and digitalized. The paper proposed an extended approach to such benefits and discussed further outcomes of safety, accessibility and sustainability. The identification of a universal and effective solution could be already applied in current road vehicles to reduce inequalities to mobility and help in adopting passenger

transportation. In this optic, a sharpened understanding of perception as well as the implication of individual psychology and sensitivity would make it possible to design compelling mitigation means.

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REFERENCES

- [1] J. T. Reason and J. J. Brand, *Motion sickness*. in Motion sickness. Oxford, England: Academic Press, 1975, pp. vii, 310.
- [2] J. E. Steele, "The symptomatology of motion sickness," Naval Aerospace Medical Institute, Pensacola, Florida, AMRL-TR-70-86, Sep. 1968.
- [3] J. T. Reason, "Motion Sickness Adaptation: A Neural Mismatch Model," *J. R. Soc. Med.*, vol. 71, no. 11, Art. no. 11, Nov. 1978, doi: 10.1177/014107687807101109.
- [4] J. F. Golding, "Motion sickness," in *Handbook of Clinical Neurology*, vol. 137, J. M. Furman and T. Leöpert, Eds., in Neuro-Otology, vol. 137, Elsevier, 2016, pp. 371–390. doi: 10.1016/B978-0-444-63437-5.00027-3.
- [5] R. S. Kennedy, N. E. Lane, K. S. Berbaum, and M. G. Lilienthal, "Simulator Sickness Questionnaire: An Enhanced Method for Quantifying Simulator Sickness," *Int. J. Aviat. Psychol.*, vol. 3, no. 3, Art. no. 3, Jul. 1993, doi: 10.1207/s15327108ijap0303_3.
- [6] M. E. McCauley and T. J. Sharkey, "Cybersickness: Perception of Self-Motion in Virtual Environments," *Presence Teleoperators Virtual Environ.*, vol. 1, no. 3, pp. 311–318, Jan. 1992, doi: 10.1162/pres.1992.1.3.311.
- [7] T. G. Dobbie, "Motion Sickness," in *Motion Sickness: A Motion Adaptation Syndrome*, 2019.
- [8] A. J. Benson, "Motion Sickness," *Med. Asp. Harsh Environ.*, no. 2, pp. 1048–1083, 2002.
- [9] J. F. Golding, "Motion sickness susceptibility," *Auton. Neurosci. Basic Clin.*, vol. 129, no. 1, Art. no. 1, Oct. 2006, doi: 10.1016/j.autneu.2006.07.019.
- [10] J. M. Mittelstädt, "Individual predictors of the susceptibility for motion-related sickness: A systematic review," *J. Vestib. Res.*, vol. 30, no. 3, pp. 165–193, Jul. 2020, doi: 10.3233/VES-200702.
- [11] P. Matsangas, M. E. McCauley, and W. Becker, "The Effect of Mild Motion Sickness and Sopte Syndrome on Multitasking Cognitive Performance," *Hum. Factors J. Hum. Factors Ergon. Soc.*, vol. 56, no. 6, pp. 1124–1135, Sep. 2014, doi: 10.1177/0018720814522484.
- [12] M. Turner and M. J. Griffin, "Motion sickness in public road transport: the effect of driver, route and vehicle," *Ergonomics*, vol. 42, no. 12, pp. 1646–1664, Dec. 1999, doi: 10.1080/001401399184730.
- [13] M. J. Griffin and M. M. Newman, "An experimental study of low-frequency motion in cars," *Proc. Inst. Mech. Eng. Part J. Automob. Eng.*, vol. 218, no. 11, pp. 1231–1238, Nov. 2004, doi: 10.1243/0954407042580093.
- [14] J. C. Guignard and M. E. McCauley, "The accelerative stimulus for motion sickness," in *Motion and space sickness*, 1990, pp. 123–152.
- [15] M. Turner and M. J. Griffin, "Motion sickness in public road transport: passenger behaviour and susceptibility," *Ergonomics*, vol. 42, no. 3, Art. no. 3, Mar. 1999, doi: 10.1080/001401399185586.
- [16] E. A. Schmidt, O. X. Kuiper, S. Wolter, C. Diels, and J. E. Bos, "An international survey on the incidence and modulating factors of carsickness," *Transp. Res. Part F Traffic Psychol. Behav.*, vol. 71, pp. 76–87, May 2020, doi: 10.1016/j.trf.2020.03.012.
- [17] C. Diels, J. E. Bos, K. Hottelart, and P. Reilhac, "Motion Sickness in Automated Vehicles: The Elephant in the Room," in *Road Vehicle Automation 3*, G. Meyer and S. Beiker, Eds., in Lecture Notes in Mobility, Cham: Springer International Publishing, 2016, pp. 121–129. doi: 10.1007/978-3-319-40503-2_10.
- [18] Z. Htike, G. Papaioannou, E. Siampis, E. Velenis, and S. Longo, "Minimisation of Motion Sickness in Autonomous Vehicles," in *2020 IEEE Intelligent Vehicles Symposium (IV)*, Las Vegas, NV, USA: IEEE, Oct. 2020, pp. 1135–1140. doi: 10.1109/IV47402.2020.9304739.
- [19] C. Diels, P. Dugenetet, J. Webb, A. Brietzke, and R. Pham Xuan, "Designing for wellbeing: Alleviating motion discomfort for rear seat passengers," presented at the CarHMI Europe, Berlin, Germany, 2022.
- [20] C. Diels and J. E. Bos, "Self-driving carsickness," *Appl. Ergon.*, vol. 53, pp. 374–382, Mar. 2016, doi: 10.1016/j.apergo.2015.09.009.
- [21] M. Sivak and B. Schoettle, "Motion sickness in self-driving vehicles," University of Michigan, Ann Arbor, Transportation Research Institute, Technical Report, Apr. 2015. Accessed: Mar. 03, 2022. [Online]. Available: <http://deepblue.lib.umich.edu/handle/2027.42/111747>
- [22] G. E. Riccio and T. A. Stoffregen, "An ecological Theory of Motion Sickness and Postural Instability," *Ecol. Psychol.*, vol. 3, no. 3, Art. no. 3, Sep. 1991, doi: 10.1207/s15326969eco0303_2.
- [23] T. A. Stoffregen and L. J. Smart, "Postural instability precedes motion sickness," *Brain Res. Bull.*, vol. 47, no. 5, pp. 437–448, Nov. 1998, doi: 10.1016/S0361-9230(98)00102-6.
- [24] J. E. Bos, "Nuancing the relationship between motion sickness and postural stability," *Displays*, vol. 32, no. 4, pp. 189–193, Oct. 2011, doi: 10.1016/j.displa.2010.09.005.
- [25] A. Rolnick and R. E. Lubow, "Why is the driver rarely motion sick? The role of controllability in motion sickness," *Ergonomics*, vol. 34, no. 7, pp. 867–879, Jul. 1991, doi: 10.1080/00140139108964831.
- [26] M. E. Levine, R. M. Stern, and K. L. Koch, "Enhanced perceptions of control and predictability reduce motion-induced nausea and gastric dysrhythmia," *Exp. Brain Res.*, vol. 232, no. 8, pp. 2675–2684, Aug. 2014, doi: 10.1007/s00221-014-3950-9.
- [27] O. X. Kuiper, J. E. Bos, E. A. Schmidt, C. Diels, and S. Wolter, "Knowing What's Coming: Unpredictable Motion Causes More Motion Sickness," *Hum. Factors*, vol. 62, no. 8, pp. 1339–1348, Dec. 2020, doi: 10.1177/0018720819876139.
- [28] T. Fukuda, "Postural Behavior and Motion Sickness," *Acta Otolaryngol. (Stockh.)*, vol. 79, no. sup330, Art. no. sup330, 1976, doi: 10.3109/00016487509121271.
- [29] T. Wada, S. Fujisawa, K. Imaizumi, N. Kamiji, and S. Doi, "Effect of Driver's Head Tilt Strategy on Motion Sickness Incidence," *IFAC Proc. Vol.*, vol. 43, no. 13, pp. 192–197, Jan. 2010, doi: 10.3182/20100831-4FR-2021.00035.
- [30] J. Smyth, P. Jennings, A. Mouzakitis, and S. Birrell, "Too Sick to Drive: How Motion Sickness Severity Impacts Human Performance," in *2018 21st International Conference on Intelligent Transportation Systems (ITSC)*, Maui, HI: IEEE, Nov. 2018, pp. 1787–1793. doi: 10.1109/ITSC.2018.8569572.
- [31] M. Elbanhawi, M. Simic, and R. Jazar, "In the Passenger Seat: Investigating Ride Comfort Measures in Autonomous Cars," *IEEE Intell. Transp. Syst. Mag.*, vol. 7, no. 3, pp. 4–17, Jul. 2015, doi: 10.1109/ITMS.2015.2405571.
- [32] C. Peng *et al.*, "Conceptualising user comfort in automated driving: Findings from an expert group workshop," 2023, doi: 10.13140/RG.2.2.14206.87369.
- [33] K. Kaur and G. Rampersad, "Trust in driverless cars: Investigating key factors influencing the adoption of driverless cars," *J. Eng. Technol. Manag.*, vol. 48, pp. 87–96, Apr. 2018, doi: 10.1016/j.jengtecman.2018.04.006.

- [34] D. Paddeu, G. Parkhurst, and I. Shergold, "Passenger comfort and trust on first-time use of a shared autonomous shuttle vehicle," *Transp. Res. Part C Emerg. Technol.*, vol. 115, p. 102604, Jun. 2020, doi: 10.1016/j.trc.2020.02.026.
- [35] P. Liu, L. Wang, and C. Vincent, "Self-driving vehicles against human drivers: Equal safety is far from enough," *J. Exp. Psychol. Appl.*, vol. 26, no. 4, pp. 692–704, Dec. 2020, doi: 10.1037/xap0000267.
- [36] J. Iskander *et al.*, "From car sickness to autonomous car sickness: A review," *Transp. Res. Part F Traffic Psychol. Behav.*, vol. 62, pp. 716–726, Apr. 2019, doi: 10.1016/j.trf.2019.02.020.
- [37] N. Merat *et al.*, "The 'Out-of-the-Loop' concept in automated driving: proposed definition, measures and implications," *Cogn. Technol. Work*, vol. 21, no. 1, pp. 87–98, Feb. 2019, doi: 10.1007/s10111-018-0525-8.
- [38] C. Peng *et al.*, "Drivers' Evaluation of Different Automated Driving Styles: Is It Both Comfortable and Natural?," *Hum. Factors J. Hum. Factors Ergon. Soc.*, p. 001872082211134, Jul. 2022, doi: 10.1177/00187208221113448.
- [39] P. Perrin, A. Lion, G. Bossier, G. Gauchard, and C. Meistelman, "Motion Sickness in Rally Car Co-Drivers," *Aviat. Space Environ. Med.*, vol. 84, no. 5, pp. 473–477, May 2013, doi: 10.3357/ASEM.3523.2013.
- [40] F. Schmääl and W. Stoll, "Kinetosen," *HNO*, vol. 48, no. 5, Art. no. 5, May 2000, doi: 10.1007/s001060050579.
- [41] A. Shupak and C. R. Gordon, "Motion Sickness: Advances in Pathogenesis, Prediction, Prevention, and Treatment," *Aviat. Space Environ. Med.*, vol. 77, no. 12, Art. no. 12, Dec. 2006.
- [42] T. Litman, "Autonomous Vehicle Implementation Predictions: Implications for Transport Planning," Victoria Transport policy Institute, Victoria, British Columbia, Canada, Jan. 2020. [Online]. Available: <https://www.vtpi.org/avip.pdf>
- [43] C. Diels, "Will autonomous vehicles make us sick?," in *Contemporary Ergonomics and Human Factors 2014*, S. Sharples and S. Shorrock, Eds., Southampton, United Kingdom: Taylor and Francis, Oct. 2014, pp. 301–307. doi: 10.13140/RG.2.1.1461.0087.
- [44] S. Salter, C. Diels, P. Herriotts, S. Kanarachos, and D. Thake, "Motion sickness in automated vehicles with forward and rearward facing seating orientations," *Appl. Ergon.*, vol. 78, pp. 54–61, Jul. 2019, doi: 10.1016/j.apergo.2019.02.001.
- [45] A. Morimoto, N. Isu, H. Asano, A. Kawai, and F. Masui, "Effects of reading books and watching movies on inducement of car sickness," presented at the Proceedings of the FISITA 2008 World Automotive Congress, Munich, Germany, Sep. 2008, pp. 14–19. [Online]. Available: https://www.researchgate.net/profile/Fumito-Masui/publication/264843228_Effects_of_Reading_Books_and_Watching_Movies_on_Inducement_of_Car_Sickness/links/542eb6fd0cf27e39fa963cb6/Effects-of-Reading-Books-and-Watching-Movies-on-Inducement-of-Car-Sickness.pdf
- [46] A. Brietzke, R. Pham Xuan, A. Dettmann, and A. C. Bullinger, "Concepts for Vestibular and Visual Stimulation to Mitigate Carsickness in Stop-and-Go-Driving," in *2021 IEEE International Intelligent Transportation Systems Conference (ITSC)*, Indianapolis, IN, USA: IEEE, Sep. 2021, pp. 3909–3916. doi: 10.1109/ITSC48978.2021.9564691.
- [47] R. M. Stern, S. Hu, S. H. J. Uijtdehaage, E. R. Muth, L. H. Xu, and K. L. Koch, "Asian Hypersusceptibility to Motion Sickness," *Hum. Hered.*, vol. 46, no. 1, pp. 7–14, 1996, doi: 10.1159/000154318.
- [48] Y. Sawada *et al.*, "Effects of synchronised engine sound and vibration presentation on visually induced motion sickness," *Sci. Rep.*, vol. 10, no. 1, p. 7553, May 2020, doi: 10.1038/s41598-020-64302-y.
- [49] D. Bohrmann, "Motion Comfort: Physical-Geometric Optimization of the Vehicle Interior to Enable Non-Driving-Related Tasks in Automated Driving Scenarios with the Focus on Motion Sickness Mitigation," PhD Thesis, TUM School of Engineering and Design, Munich, Germany, 2022. [Online]. Available: <http://nbn-resolving.de/urn/resolver.pl?urn:nbn:de:bvb:91-diss-20220309-1615905-1-0>
- [50] J. E. Bos, "Less sickness with more motion and/or mental distraction," *J. Vestib. Res.*, vol. 25, no. 1, pp. 23–33, Mar. 2015, doi: 10.3233/VES-150541.
- [51] J. Hwang, W. Li, L. Stough, C. Lee, and K. Turnbull, "A focus group study on the potential of autonomous vehicles as a viable transportation option: Perspectives from people with disabilities and public transit agencies," *Transp. Res. Part F Traffic Psychol. Behav.*, vol. 70, pp. 260–274, Apr. 2020, doi: 10.1016/j.trf.2020.03.007.
- [52] C. D. Harper, C. T. Hendrickson, S. Mangones, and C. Samaras, "Estimating potential increases in travel with autonomous vehicles for the non-driving, elderly and people with travel-restrictive medical conditions," *Transp. Res. Part C Emerg. Technol.*, vol. 72, pp. 1–9, Nov. 2016, doi: 10.1016/j.trc.2016.09.003.
- [53] M. Sivak and B. Schoettle, "Influence of Current Nondrivers on the Amount of Travel and Trip Patterns with Self-Driving Vehicles," University of Michigan, Dec. 2015. [Online]. Available: <http://www.umich.edu/~umtriswt/PDF/UMTRI-2015-39.pdf>
- [54] R. N. Brewer and V. Kameswaran, "Understanding the Power of Control in Autonomous Vehicles for People with Vision Impairment," in *Proceedings of the 20th International ACM SIGACCESS Conference on Computers and Accessibility*, Galway Ireland: ACM, Oct. 2018, pp. 185–197. doi: 10.1145/3234695.3236347.
- [55] "Les pratiques de mobilité des personnes en situation de handicap," *Statistiques.developpement-durable.gouv.fr*. Accessed: Dec. 28, 2023. [Online]. Available: <https://www.statistiques.developpement-durable.gouv.fr/les-pratiques-de-mobilite-des-personnes-en-situation-de-handicap?rubrique=&dossier=1345>
- [56] J. Smyth, S. Birrell, A. Mouzakitis, and P. Jennings, "Motion Sickness and Human Performance – Exploring the Impact of Driving Simulator User Trials," in *Advances in Human Aspects of Transportation*, vol. 786, N. Stanton, Ed., in *Advances in Intelligent Systems and Computing*, vol. 786. Cham: Springer International Publishing, 2019, pp. 445–457. doi: 10.1007/978-3-319-93885-1_40.
- [57] N. Md. Yusof, J. Karjanto, M. Z. Hassan, J. Terken, F. Delbressine, and M. Rauterberg, "Reading During Fully Automated Driving: A Study of the Effect of Peripheral Visual and Haptic Information on Situation Awareness and Mental Workload," *IEEE Trans. Intell. Transp. Syst.*, vol. 23, no. 10, pp. 19136–19144, Oct. 2022, doi: 10.1109/TITS.2022.3165192.
- [58] K. M. T. Pöhlmann *et al.*, "I think I don't feel sick: Exploring the Relationship Between Cognitive Demand and Cybersickness in Virtual Reality using fNIRS," in *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*, Hamburg Germany: ACM, Apr. 2023, pp. 1–16. doi: 10.1145/3544548.3581063.
- [59] J. F. Golding and M. Kerguelen, "A comparison of the nauseogenic potential of low-frequency vertical versus horizontal linear oscillation," *Aviat. Space Environ. Med.*, vol. 63, no. 6, pp. 491–497, Jun. 1992.
- [60] C. Johansson *et al.*, "Impacts on air pollution and health by changing commuting from car to bicycle," *Sci. Total Environ.*, vol. 584–585, pp. 55–63, Apr. 2017, doi: 10.1016/j.scitotenv.2017.01.145.
- [61] M. Migliore, G. D'Orso, and D. Caminiti, "The environmental benefits of carsharing: the case study of Palermo," *Transp. Res. Procedia*, vol. 48, pp. 2127–2139, 2020, doi: 10.1016/j.trpro.2020.08.271.
- [62] "Résultats détaillés de l'enquête mobilité des personnes de 2019," *Statistiques.developpement-durable.gouv.fr*. Accessed: Dec. 28, 2023. [Online]. Available: <https://www.statistiques.developpement-durable.gouv.fr/resultats-detailles-de-lenquete-mobilite-des-personnes-de-2019?rubrique=&dossier=1345>
- [63] A. Dam and M. Jeon, "A Review of Motion Sickness in Automated Vehicles," in *13th International Conference on Automotive User*

- Interfaces and Interactive Vehicular Applications*, Leeds United Kingdom: ACM, Sep. 2021, pp. 39–48. doi: 10.1145/3409118.3475146.
- [64] M. Turner and M. J. Griffin, “Motion sickness in public road transport: The relative importance of motion, vision and individual differences,” *Br. J. Psychol.*, vol. 90, no. 4, pp. 519–530, Nov. 1999, doi: 10.1348/000712699161594.
- [65] E. Pereira *et al.*, “Motion Sickness Countermeasures for Autonomous Driving: Trends and Future Directions,” *Transp. Eng.*, Dec. 2023, doi: 10.1016/j.treng.2023.100220.
- [66] D. L. Larner and J. S. Russell, “Method and system for determining and dynamically updating a route and driving style for passenger comfort,” US10107635B2, Oct. 23, 2018 [Online]. Available: <https://patents.google.com/patent/US10107635B2/en>
- [67] Z. Li, I. V. Kolmanovsky, E. M. Atkins, J. Lu, D. P. Filev, and Y. Bai, “Road Disturbance Estimation and Cloud-Aided Comfort-Based Route Planning,” *IEEE Trans. Cybern.*, vol. 47, no. 11, pp. 3879–3891, Nov. 2017, doi: 10.1109/TCYB.2016.2587673.
- [68] N. Rajesh, Y. Zheng, and B. Shyrokau, “Comfort-Oriented Motion Planning for Automated Vehicles Using Deep Reinforcement Learning,” *IEEE Open J. Intell. Transp. Syst.*, vol. 4, pp. 348–359, 2023, doi: 10.1109/OJITS.2023.3275275.
- [69] Y. Zheng, B. Shyrokau, and T. Keviczky, “Mitigating Motion Sickness with Optimization-based Motion Planning,” *ArXiv Prepr. ArXiv230107977*, 2023, doi: 10.48550/ARXIV.2301.07977.
- [70] Z. Htike, G. Papaioannou, E. Siampis, E. Velenis, and S. Longo, “Fundamentals of Motion Planning for Mitigating Motion Sickness in Automated Vehicles,” *IEEE Trans. Veh. Technol.*, vol. 71, no. 3, pp. 2375–2384, Mar. 2022, doi: 10.1109/TVT.2021.3138722.
- [71] D. Li and J. Hu, “Mitigating Motion Sickness in Automated Vehicles With Frequency-Shaping Approach to Motion Planning,” *IEEE Robot. Autom. Lett.*, vol. 6, no. 4, pp. 7714–7720, Oct. 2021, doi: 10.1109/LRA.2021.3101050.
- [72] A. Ananthkrishnan, J. Moeller, and D. Schilberg, “The analysis of the influence of suspension parameters in reducing motion sickness in vehicles,” in *2020 21st International Conference on Research and Education in Mechatronics (REM)*, Cracow, Poland: IEEE, Dec. 2020, pp. 1–5. doi: 10.1109/REM49740.2020.9313898.
- [73] G. Papaioannou, J. Jerrelind, L. Drugge, and B. Shyrokau, “Assessment of optimal passive suspensions regarding motion sickness mitigation in different road profiles and sitting conditions,” in *2021 IEEE International Intelligent Transportation Systems Conference (ITSC)*, Indianapolis, IN, USA: IEEE, Sep. 2021, pp. 3896–3902. doi: 10.1109/ITSC48978.2021.9564474.
- [74] D. D. Stamenković, V. M. Popović, M. A. Tirović, and I. A. Blagojević, “Effects of lateral vehicle dynamics parameters on motion sickness,” presented at the Proceedings of the XXI International Conference MHCL’15, 2015. [Online]. Available: https://www.researchgate.net/profile/Dragan-Stamenkovic-2/publication/319746942_Effects_of_Lateral_Vehicle_Dynamics_Parameters_on_Motion_Sickness/links/5b1403d30f7e9b49810855ed/Effects-of-Lateral-Vehicle-Dynamics-Parameters-on-Motion-Sickness.pdf
- [75] P. DiZio *et al.*, “An Active Suspension System for Mitigating Motion Sickness and Enabling Reading in a Car,” *Aerosp. Med. Hum. Perform.*, vol. 89, no. 9, pp. 822–829, Sep. 2018, doi: 10.3357/AMHP.5012.2018.
- [76] J. Ekchian *et al.*, *A High-Bandwidth Active Suspension for Motion Sickness Mitigation in Autonomous Vehicles*. 2016. doi: 10.4271/2016-01-1555.
- [77] M. Jurisch, C. Holzapfel, and C. Buck, “The influence of active suspension systems on motion sickness of vehicle occupants,” in *2020 IEEE 23rd International Conference on Intelligent Transportation Systems (ITSC)*, Sep. 2020, pp. 1–6. doi: 10.1109/ITSC45102.2020.9294311.
- [78] C. Diels and J. E. Bos, “User interface considerations to prevent self-driving carsickness,” presented at the 7th International Conference on Automotive User Interfaces and Interactive Vehicular Applications, Nottingham, United Kingdom, Sep. 2015, pp. 17–19. doi: 10.1145/2809730.2809754.
- [79] O. X. Kuiper, J. E. Bos, and C. Diels, “Looking forward: In-vehicle auxiliary display positioning affects carsickness,” *Appl. Ergon.*, vol. 68, pp. 169–175, Apr. 2018, doi: 10.1016/j.apergo.2017.11.002.
- [80] A. Meschtscherjakov, S. Strumegger, and S. Trösterer, “Bubble Margin: Motion Sickness Prevention While Reading on Smartphones in Vehicles,” in *Human-Computer Interaction – INTERACT 2019*, vol. 11747, D. Lamas, F. Loizides, L. Nacke, H. Petrie, M. Winckler, and P. Zaphiris, Eds., in Lecture Notes in Computer Science, vol. 11747, Cham: Springer International Publishing, 2019, pp. 660–677. doi: 10.1007/978-3-030-29384-0_39.
- [81] K. M. T. Pöhlmann, M. S. K. Auf Der Heyde, G. Li, F. Verstraten, S. A. Brewster, and M. McGill, “Can Visual Motion Presented in a VR Headset Reduce Motion Sickness for Vehicle Passengers?,” in *14th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, Seoul Republic of Korea: ACM, Sep. 2022, pp. 114–118. doi: 10.1145/3544999.3552488.
- [82] K. Kato and S. Kitazaki, “A Study for Understanding Carsickness Based on the Sensory Conflict Theory,” *SAE Tech. Pap.*, Apr. 2006, doi: 10.4271/2006-01-0096.
- [83] S. Salter, C. Diels, S. Kanarachos, D. Thake, P. Herriotts, and D. A. Depireux, “Increased bone conducted vibration reduces motion sickness in automated vehicles,” *Int. J. Hum. Factors Ergon.*, vol. 6, no. 4, p. 299, 2019, doi: 10.1504/IJHFE.2019.105358.
- [84] J. Karjanto, N. M. Yusof, M. Z. Hassan, J. Terken, F. Delbressine, and M. Rauterberg, “An On-Road Study in Mitigating Motion Sickness When Reading in Automated Driving,” *J. Human Univ. Nat. Sci.*, vol. 48, no. 3, Art. no. 3, 2021, Accessed: Jun. 17, 2022. [Online]. Available: <http://jonuns.com/index.php/journal/article/view/536>
- [85] N. Md. Yusof, J. Karjanto, J. M. B. Terken, F. L. M. Delbressine, and G. W. M. Rauterberg, “Gaining Situation Awareness through a Vibrotactile Display to Mitigate Motion Sickness in Fully-Automated Driving Cars,” *Int. J. Automot. Mech. Eng.*, vol. 17, no. 1, pp. 7771–7783, Apr. 2020, doi: 10.15282/ijame.17.1.2020.23.0578.
- [86] M. Tomzig *et al.*, “How to Make Reading in Fully Automated Vehicles a Better Experience? Effects of Active Seat Belt Retractions and a 2-Step Driving Profile on Subjective Motion Sickness, Ride Comfort and Acceptance,” in *Proceedings of the 15th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, Ingolstadt Germany: ACM, Sep. 2023, pp. 11–21. doi: 10.1145/3580585.3607160.
- [87] A. C. Paillard *et al.*, “Is there a relationship between odors and motion sickness?,” *Neurosci. Lett.*, vol. 566, pp. 326–330, Apr. 2014, doi: 10.1016/j.neulet.2014.02.049.
- [88] A. C. Paillard, L. Jacquot, and J.-L. Millot, “Olfactory perception and motion sickness,” presented at the XXth Congress of European Chemoreception Research Organization, ECRO-2010, Avignon, France, Sep. 2010. [Online]. Available: <https://ualresearchonline.arts.ac.uk/id/eprint/10442/>
- [89] F. Schmääl, “Neuronal Mechanisms and the Treatment of Motion Sickness,” *Pharmacology*, vol. 91, no. 3–4, Art. no. 3–4, 2013, doi: 10.1159/000350185.
- [90] P. Bertalanffy *et al.*, “Korean hand acupressure for motion sickness in prehospital trauma care: a prospective, randomized, double-blinded trial in a geriatric population,” *Anesth. Analg.*, vol. 98, no. 1, pp. 220–223, Jan. 2004, doi: 10.1213/01.ANE.0000093252.56986.29.
- [91] O. Fydanaki, P. Kousoulis, E. Dardiotis, I. Bizakis, and I. Hajioannou, “Electroacupuncture Could Reduce Motion Sickness Susceptibility in



- Healthy Male Adults: A Double-Blinded Study,” *Med. Acupunct.*, vol. 29, no. 6, pp. 377–382, Dec. 2017, doi: 10.1089/acu.2017.1246.
- [92] B. Keshavarz and H. Hecht, “Pleasant music as a countermeasure against visually induced motion sickness,” *Appl. Ergon.*, vol. 45, no. 3, Art. no. 3, May 2014, doi: 10.1016/j.apergo.2013.07.009.
- [93] F. D. Yen Pik Sang, J. P. Billar, J. F. Golding, and M. A. Gresty, “Behavioral Methods of Alleviating Motion Sickness: Effectiveness of Controlled Breathing and a Music Audiotape,” *J. Travel Med.*, vol. 10, no. 2, pp. 108–111, Mar. 2003, doi: 10.2310/7060.2003.31768.
- [94] E. Igoshina, F. A. Russo, B. Haycock, and B. Keshavarz, “Comparing the Effect of Airflow Direction on Simulator Sickness and User Comfort in a High-Fidelity Driving Simulator,” in *Virtual, Augmented and Mixed Reality: Applications in Education, Aviation and Industry*, vol. 13318, J. Y. C. Chen and G. Fragomeni, Eds., in Lecture Notes in Computer Science, vol. 13318, Cham: Springer International Publishing, 2022, pp. 208–220. doi: 10.1007/978-3-031-06015-1_15.
- [95] I. B. McIntosh, “Motion sickness—questions and answers,” *J. Travel Med.*, vol. 5, no. 2, pp. 89–91, Jun. 1998, doi: 10.1111/j.1708-8305.1998.tb00470.x.
- [96] C. Diels, P. Dugenet, A. Brietzke, and R. P. Xuan, “Design Strategies to Alleviate Motion Sickness in Rear Seat Passengers - A Test Track Study,” in *2023 IEEE 26th International Conference on Intelligent Transportation Systems (ITSC)*, Bilbao, Spain: IEEE, Sep. 2023, pp. 5254–5258. doi: 10.1109/ITSC57777.2023.10421968.
- [97] D. Sperling and D. Gordon, *Two Billion Cars: Driving Toward Sustainability*. University of California, Davis: Oxford University Press, 2010.
- [98] E. Papa and A. Ferreira, “Sustainable Accessibility and the Implementation of Automated Vehicles: Identifying Critical Decisions,” *Urban Sci.*, vol. 2, no. 1, p. 5, Jan. 2018, doi: 10.3390/urbansci2010005.
- [99] A. Bigo, “Les transports face au défi de la transition énergétique. Explorations entre passé et avenir, technologie et sobriété, accélération et ralentissement.,” Institut polytechnique de Paris, 2020. [Online]. Available: <https://www.theses.fr/2020IPPAX068/abes>
- [100] M. Martínez-Díaz, F. Soriguera, and I. Pérez, “Autonomous driving: a bird’s eye view,” *IET Intell. Transp. Syst.*, vol. 13, no. 4, pp. 563–579, Apr. 2019, doi: 10.1049/iet-its.2018.5061.
- [101] M. Treisman, “Motion Sickness: An Evolutionary Hypothesis,” *Science*, vol. 197, no. 4302, pp. 493–495, Jul. 1977, doi: 10.1126/science.301659.
- [102] R. Tan *et al.*, “Motion Sickness Detection for Intelligent Vehicles: A Wearable-Device-Based Approach,” in *2022 IEEE 25th International Conference on Intelligent Transportation Systems (ITSC)*, Macau, China: IEEE, Oct. 2022, pp. 4355–4362. doi: 10.1109/ITSC55140.2022.9922392.
- [103] A. Koohestani *et al.*, “A Knowledge Discovery in Motion Sickness: A Comprehensive Literature Review,” *IEEE Access*, vol. 7, pp. 85755–85770, 2019, doi: 10.1109/ACCESS.2019.2922993.