Are you Sitting Comfortably? How Current Self-Driving Car Concepts Overlook Motion Sickness, and the Impact it has on Comfort and Productivity.

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Abstract. A proposed benefit of self-driving cars is that of increased comfort and productivity of the occupants. Self-driving vehicle concepts and published research show the desire for engagement in non-driving related tasks while traveling in such vehicles. Based on survey results and financial productivity estimations, it is likely that completing work activities within such vehicles will be desirable, even expected. These predictions, along with current concepts for self-driving vehicles, fail to consider motion sickness. This paper explores why motion sickness is likely to be a factor in these vehicles, and explicit implications with a range of in-car non-driving related activities is discussed. Through a critique of current concepts, a contrast between that which is advertised, and what may be possible is highlighted and discussed. The importance for inclusivity in future self-driving vehicles considering demographic differences in motion sickness susceptibility is highlighted, and design recommendations for future self-driving vehicles are made.

Keywords: Human Factors · Motion Sickness · Comfort · Self-Driving · Autonomous Vehicles · Productivity

1 Introduction

The introduction of self-driving cars can bring many benefits to society including increased safety, enabling greater mobility for the disabled, and a reduction in congestion, amongst other things. There are many areas of this technology that still need to be addressed before a successful rollout of such vehicles is possible. However, predictions, concepts, and ideas of how they will be used are already fairly well developed. Self-driving and autonomous vehicles have the potential to increase comfort and productivity for occupants where the focus on the packaging of occupants can shift from enabling driving, to increasing comfort and facilitating engagement in non-driving related tasks. Indeed, in a level 5 vehicle ('full automation' as set out by [1]) there is no option for an occupant to physically drive the vehicle, where even in lower levels of automation (including conditional/3 and high/4 automation) there is certainly more freedom to consider non-diving related tasks.

KPMG estimate that "all vehicles produced in the UK by 2027 will have at least L3 technologies" [2], where many vehicle manufactures are hoping to release vehicles with varying levels of autonomy within as little as one year. Regardless of the specifics of timelines and rollout strategies considering automation levels, the end goal for most mainstream vehicle manufacturers is to provide enhanced support for the driver, or even removing them from the driving task altogether. This technology will drastically change road transportation as we currently know it in 2019, and if handled appropriately it could bring immense benefits to many areas. A considerable benefit from a consumer view, and as many manufacturers are promoting, is in relation to increased comfort and productivity. The opportunity for increased comfort is relatively easily understood through considering the lack of need for driving controls and subsequent opportunity for changes to the occupant packaging design that this enables. The concept of increased productivity relates to the ability to complete non-driving related tasks whilst traveling in a car. This could include reading books, watching films, or even working – all very realistic tasks for a level 4/5 vehicle. Considering productivity, the research group at Morgan Stanley have estimated a US$507billion annual increase to the US economy based purely on the increased productivity due to the ability to work within a self-driving car during a commute [3]. They go on to explain how Americans "spend some 75 billion hours a year driving" which, they forecast could be put to better use if traveling in an autonomous vehicle. In this instance, they see the opportunity to transform this wasted commuting driving time into working hours (see [3] p.50 for the full calculation). An idea which is not difficult to imagine considering evidence already showing 40% of train commuters spend their journey attending to work related emails [4], it is even common practice for some commuters to count travel time as paid office hours. Based on this prospect of work-related productivity in a future self-driving car, another report estimates a US$220 billion gain to the economy as drivers become passengers and are able to complete work based activities whilst commuting [5]. All looks very promising for the future of driverless cars, especially with significant financial predictions such as these. However, there is one common oversight in these predictions and current expectations – the propensity for people to become motion sick.

2 An Introduction to Motion Sickness

As suggested by its name motion sickness is a sickness feeling commonly associated with traveling in cars, boats or trains – all scenarios with an element of motion. Sensory conflict theory [6] dictates that when a mismatch between visual, vestibular and/or somatosensory senses occurs, motion sickness can prevail. Where the visual system can detect movement through eye sight, the vestibular system can detect movement through the movement of fluid within the semi-circular canals of the inner ear, and the somatosensory system can detect movement through motion felt through limbs and pressure on parts of the body. This theory is thought to be the most useful at explaining why people become motion sick. The evolutionary hypothesis [7] goes on to explain how sensory conflict 'tricks' the body into assuming a toxin has been ingested, and is to blame for the conflict. This hypothesis provides understanding for the common symptomology of motion sickness of sweating, burping and vomiting as the body attempts to eject the believed toxin. Another theory of motion sickness is the hypothesis of postural instability, which explains that motion sickness is caused by loss of postural control [8]. As such, an underlying contributor to this theory is postural sway – where the human body is understood to be in constant movement through small, multi-axial swaying motions – which are observed in all states, including sitting. This sway helps the brain predict motion through comparing expected variations to swaying against any immediate effects. This theory is somewhat less discussed more recently, where the opinion is now that postural instability is more of a precursor to motion sickness and recent findings show postural instability may not necessarily cause motion sickness, but does precede subjective motion sickness symptoms [9] [10]. However, this theory is still particularly interesting considering seating design and occupant packaging, where seat support is a factor of postural sway and therefore linked to motion sickness

Cause(s) aside, the symptoms of motion sickness are well understood in a subjective sense, where many people have had personal experiences with motion sickness. Sweating, burping and vomiting (as previously mentioned) are known symptoms of motion sickness, but other symptoms can include cold sweats, fatigue, stomach awareness, temperature change, nausea, disorientation, and oculomotor issues/strain amongst others. Such symptoms have been explained and discussed (in terms of grading the severity) within reports from [11]. It is important to understand motion sickness is not a binary state, where even with mild motion sickness, symptoms can begin to show – making even mild motion sickness an undesirable experience. More recent research looks beyond just subjective comfort, and highlighted the effect of motion sickness on human performance [12]. This research has shown how motion sickness can significantly negatively affect various areas of fundamental performance, including cognitive and physical ability. Other research, looking specifically at occupational skills found that motion sickness affected the ability to complete work-related cognitive tasks [13]. Where further work highlighted similar performance degradation during a seasickness trial [14].

The literature evidences how motion sickness has undesirable effects for people considering both their comfort and their performance. Further, it is known how motion sickness susceptibility and severity is not uniform across the population where there are many differences between a variety of demographics including ethnicity [15] age, [16], and perhaps most interestingly (considering the size of the demographic proportions) gender. It is reported in almost all studies looking at motion sickness that females are more susceptible than males to motion sickness (for example [17]). This gender difference was shown to be true in previous simulator sickness studies [18] as well as other dedicated gender focused studies [19]. Such demographic differences mean that motion sickness and its effects are not uniformly problematic across the population, where for some people onset frequency and severity is much worse than for others.

3 Why Self-Driving and Autonomous Vehicles will Increase Incidences of Motion Sickness

Considering motion sickness, it is understood that ‘around 60% of the population has experienced some nausea from car travel, whereas about a third has vomited in cars before the age of 12’ [20]. These figures are however considering traditional vehicles. When considering future autonomous vehicles – such as those with conditional, high or full automation – the consideration of motion sickness is of much greater importance. It is expected that self-driving vehicles are likely to significantly increase motion sickness onset frequency and severity. One paper [21] has summarized the reasons for increased motion sickness in autonomous driving into three areas: "First, automation alters the driver's function from an active to a passive, monitoring one. Secondly, occupants are assumed to engage in non-driving tasks taking the eyes off the road ahead. Finally, flexible seating arrangements may involve rearward facing seats" [21] (p. 303). Addressing the first point, it is almost unheard of that a driver of a traditional vehicle will become motion sick, as they are physically inputting directional controls including lateral and longitudinal accelerations. However, when the role changes to merely observing movement within a vehicle (as a passenger might currently, and a self-driving vehicle occupant will) there can be a lack of anticipation of motion which can contribute to motion sickness. This phenomenon has previously been explored and summarized [22] where the effect is described as a 'profound helplessness reaction' (also commonly referred to as 'loss of control theory').

Fig. 1. Example of sensory conflict in an Autonomous Vehicle (AV)

Figure 1 illustrates how when driving traditionally the majority of the field of vison is on the road, and thus with the anticipated vehicle movement and flow of traffic. However, if reading a book, or engaging in other non-driving related activities as levels 4 and 5 automated vehicles may allow, the majority of the field of vision is static while movement is still detected by the inner ear and somatosensory system. Thus in this second instance, sensory conflict can occur and motion sickness is likely. The final point made by [21] discusses flexible seating arrangements. It is understood that rearward-facing seats will compound the lack of motion cues and anticipation of future motions – increasing the opportunity for sensory conflict and postural instability, therefore increasing the likelihood of motion sickness onset.

Considering consumer expectations, a survey conducted by insurance company StateFarm in 2016 [23] looked to understand what people want to do within a self-driving car, given the premise that self-driving technology would free up their time to engage in other activities. They reported 45% of people would be more willing to read texts, 36% would be more willing to access the internet, 21% would be more willing to watch movies and 19% would be more willing to read a book. These figures would be expected to increase as trust and familiarity with the technology increase, with research showing that the development of trust is a dynamic process and needs to be calibrated to the correct levels [24]. Further, considering the productivity benefits that have been predicted [3] [5], it is becoming likely that employers may expect their staff to work in these vehicles. Considering these activities discussed, it has been theorized that "all envisaged use cases can be predicted to increase the risk of motion sickness" [25] and with an understanding of the physiological causes of motion sickness it is clearer to see why self-driving vehicles have this increased potential to exacerbate motion sickness onset. To this end, one paper looking at motion sickness likelihood of adults riding as passengers in self-driving cars found that, of the people surveyed, 37% of Americans, 40% of Chinese, 53% of Indian people would "experience an increase in the frequency and severity of motion sickness" [26] (p.5). However, they also added that the "actual frequency and severity of motion sickness in self-driving vehicles might be greater than calculated" (p.9), mainly due to this great variation in activities passengers could engage in, and the potential design changes in self-driving vehicles. In [26], the state of motion sickness is presumed to be severe motion sickness, where they did not report on more mild motion sickness. This is significant as it was found that even mild motion sickness (although less subjectively uncomfortable) can be just as detrimental for human performance as severe motion sickness [18]. Further, these figures look at just an 'increase' of motion sickness, where they do not capture the current motion sickness statistics for traditional vehicles, which we know already affects a significant proportion of the population. Considering these points, the aforementioned statistics are considered relatively conservative, where it is likely motion sickness would be a factor for a larger percentage of the population under many circumstances. For the most part, estimating the percentage of the population likely to experience motion sickness in a self-driving car will be depended on five defined areas as presented in Table 1 below:

Table 1 – Categorizing Areas of Motion Sickness Management

Category	Explanation/ Examples
1 – Occupant characteristics	i.e., a person's natural susceptibility to motion sickness - including demographic differentiation, habituation, clothing, etc.
2 – Interior design	i.e., the design of the cabin including seating, displays, interfaces, windows, climate control and features, etc.
3 – Vehicle design	i.e., size, height, vehicle dynamics, suspension etc.
4– Activity	i.e., the activity of the person inside the vehicle such as working, reading, looking out the window etc.
5 – Driving	i.e., the driving style, speed, route motion path of the vehicle etc.

Occupant characteristics (point 1) are fairly well documented in the literature considering demographic trends, and with an understanding of the thermoregulation aspect of motion sickness, the importance for cool, light and non-sweat restrictive clothing is also understood. Habituation is a key area and is relatively under researched however. Points 2, 3, 4 and 5 are difficult to report on empirically as there are no full automation vehicles on the road currently on which to collect data, nor are there any finalized designs for such vehicles. However, it is possible to assess self-driving vehicle concepts to understand how these factors are likely going to affect motion sickness.

4 Current Self-Driving and Autonomous Concepts

This paper has previously discussed the many productivity gains forecast on the premise of the introduction of self-driving vehicles. However, it is argued that unless motion sickness is taken into consideration in the design of such vehicles, and expectations of what is possible for some people is addressed, these forecasts may not be realized. As an example of some of these challenging concepts for self-driving vehicles, three concepts from three separate sources are presented. For the purpose of this review, points 1, 2 and 4 will be the primary focus as they relate to factors understandable through imagery.

The purpose of this analysis is not to discourage or criticize the efforts made in these designs, but rather highlight the factor of motion sickness and therefore challenge the feasibility of such concepts – especially considering the productivity forecasts. At the end of the exploration presented in this paper, design recommendations are given.

Fig. 2. Mercedes Benz Autonomous Vehicle Prototype. [27]

Figure 2 shows a concept made by Mercedes-Benz, where occupants are engaging together in work based tasks. In this example much of the view of the outside world is not visible, where the windows are limited and all visual fixation points are below the window line – with interfaces on the door or center table. This design would not allow for appropriate visual motion cues in either a direct line of sight or peripheral sight. The probability of sensory conflict for all occupants is high, and the ability to understand current motion and/or predict upcoming motion is further limited. The seat designs appear unsupportive, hence the ability to manage postural sway would also be problematic. With a lack of support from the seats, it is likely the effectiveness of the somatosensory (perceived movement) system will be limited due to the lack of contact with the static seats. With rearward facing seating the motion experienced would be unfamiliar for someone used to traveling forwards, again leading to a disconnect between motion cues. Statistically speaking, the female occupant is more likely to become motion sick than the males, where comfort and performance degradation may be more severe for the female compared to her male colleagues - illustrating a lack of inclusivity. Overall, this concept, although visually appealing, has given little consideration to motion sickness and the expectation of productivity is an unlikely scenario for many who would travel in such a vehicle.

Fig. 3. Rinspeed XchangE Autonomous Vehicle Prototype [28]

Figure 3 exhibts a similar cause for concern for motion sickness sufferers. In this scene the rearward facing seats are limiting the ability to predict future motion, the windows are again limited in size – reducing visual indication(s) of motion, and the fixation point for occupants is a large display screen. In this example not only is the inability to predict oncoming motion and the lack of visual motion cues likley to induce motion sickness, but sensory conflict may be compounded where the visual system may be exposed to conflicting motion cues if the dispaly screen is showing moving images.

Fig. 4. Volvo Autonomous Vehicle Prototype [29]

The scene presented in Figure 4 also raises concerns for motion sickness onset. The main work surface and interface is a table, which requires occupants to be looking with their heads down – a known issue for sensory conflict and perhaps the worst head position for motion sickness management. Further, the window is being utilized as a display screen, which limits views of outside motion and therefore impacts the ability to understand current and predict future motion – limiting the ability to receive coherent sensory cues. The panoramic roof and wide windscreen would be beneficial however, and this is a good example of how to decrease sensory conflict. The bench style seat is undesirable, where without the ability to anticipate future motion it is likely that the occupant will not be well supported. The literature surrounding demographic changes in motion sickness variation is fairly comprehensive, where not only is there a gender difference, but also ethnicity bias – where this example highlights the possibility for lack of inclusivity for such designs.

In summary, looking at the designs presented, it is clear that the possibility for increased motion sickness is likely in all scenarios. The issues raised in this paper surpass the physical designs showcased in these concepts, and questions the very use cases they propose. Such use cases are clearly desirable for many people and organizations, based on the opportunity for increased productivity and the statistics previously presented support these ideas. However, these scenarios as they are currently envisaged and conceived highlight a disconnect between what is desired, and what is possible for many people. Along with design and use case(s), personal susceptibility (including demographic factors) will play a critical role in the further development of such vehicles. If commuters in the future are expected to use time spent traveling as working hours, and it is known how certain people are more likely to be motion sick than others, the ability – or expectation – to work is not uniformly accessible, hence a new area for inclusive design is highlighted. Current productivity estimates do not differentiate between demographics or consider individual accessibility. With the concepts presented, there is a significant productivity benefit bias towards those who are less susceptible to motion sickness. Therefore, due to lack of consideration for motion sickness, many demographics are being designed out of much of the benefits these vehicles aim to bring and it is therefore possible that the productivity estimates are vastly over optimistic, and importantly not inclusive for all populations.

4 Recommendations for the Management of Motion Sickness in Future Autonomous and Self-Driving Vehicles.

There is growing amounts of information in the literature highlighting the causes of motion sickness and, more recently, how such motion sickness may affect productivity and comfort. There is however, a comparative lack of proven methods to reduce or eliminate motion sickness. Considering the five areas highlighted in Table 1, and in reflection of the above concepts, some design recommendations can be summarized, and areas for further research can be highlighted. In all recommendations, the execution is likely as important as the theory itself, testing and development will be needed to understand the most effective way of reducing motion sickness and implementing these solutions.

1. Occupant characteristics

- Habituation is known to be the best way to manage motion sickness, where repeat exposure to motion-challenging environments can reduce susceptibility over time (see [30]). People should be aware of their own susceptibility and they can aim to reduce it though repeat exposures, whereas avoiding motion sickness inducing scenarios will slow habituation. Further, motion sickness medication can reduce habituation, so for long term benefit, medication should be avoided [31] (p.628). Other methods for aiding/expediting habituation should be explored, such as simulation, exposure time/frequencies etc.
- Scarfs, heavy jackets and restrictive clothing should be avoided to aid in thermoregulation and allow participants to cool, as it is known that improving the ability to loose heat through evaporative heat loss and vasodilation are beneficial for reducing motion sickness discomfort and severity [32] [33].

- An awareness of personal susceptibility will aid in understanding what tasks should be avoided, and where counter measures can be self-initiated, such as taking breaks from non-driving related activities.

2. Interior design

- Some very useful recommendations in this area have already been made where lay-out of vehicle cabin features have been considered as well as some user interface aspects [25] and building upon these points:
- Window areas should be maximized [25] to ensure visual motion cues for current and upcoming motion.
- Seats should be positioned to allow for views of the outside [25] (including height adjustable for shorter occupants), and in the direction of travel (i.e., avoid rearward facing seats).
- HVAC systems should be adaptable if flexible seating is required, to enable ventila-tion and cooling at any seat angle to aid in thermoregulation.
- Seats should be supportive for cornering and changes in accelerations – providing adequate bolsters to help the management of postural sway.
- Methods for communicating future motion through cockpit or HMI design should be considered – including cues for braking, accelerating and cornering. Methods could include audible motion cues such as navigation directions, indictor sound for corners, sounds for acceleration/braking etc. Tactile motion cues such as using the HVAC system to simulator motion through air movement. Dynamic cues such as a preemptive small turn before the main corner. Visual motion cues such as using lighting inside the vehicle to simulate motion, or artificial horizons within HMI's to allow motion to be inferred.
- Alternative thermo-comfort management systems should be considered such as cool-ing seats to allow for management of body temperature and sweat.
- Location of working stations or displays should be in the line of sight of the outside world so that motion can be inferred through peripheral vision [25].
- Tables and workstations that require head-down posture should be avoided.
- Objects obstructing the view of the outside world should be reduced (e.g. large dis-plays should be avoided, seats not in use could be folded, and sun visors should be up when not in use).

3. Vehicle design

- Suspension should be optimized to manage unnecessary motions through accelera-tions (including corners and braking).
- Suspension to reduce low frequency vibration should be used where frequencies of 0.08 to 0.4 Hz are particularly sickness inducing [34].
- Vehicle ride height should be considered where greater distance from the road will increase pitch/roll in accelerations, but may increase outside visibility.

4. Activity

- Any task requiring looking down should be avoided, where looking straight forward, out of a window is the ideal position.

- “avoid dynamic or static display content in constant or varying velocity driving scenarios, respectively” [25]
- Tasks should be interruptible at any time (e.g. limit use of scrolling text or timeouts due to inactivity for any task).
- Tasks should be designed with breaks and rest points – avoiding fixation for extended periods and encouraging brakes to look out the window.
- Devices requiring physical interaction should be in an area which can aid in supporting the upper body e.g. in armrests or other fixed supports so that limbs are not self-supported and thus postural instability/sway can be managed.
- Visual tasks should be in line of sight of the outside world, where displays could be presented on transparent displays (such as heads up display) to enable processing of visual motion cues.

5. Driving

- Route type could be chosen based on motion sickness susceptibility of occupants, where for example slower speed cities are more preferable than highways for most people [35]. Route could also be chosen based on occupant activity expectancy e.g. avoid bending roads and roundabouts if the occupant will be working.
- Constant speeds are preferable rather than braking and acceleration – avoiding areas with high stop/start traffic light density and similar will be beneficial.
- Driving style should be consistent where braking / acceleration rates could be predefined and uniform across instances - allowing for better understanding of motion paths and habituation to driving due to increased predictability of motion(s).
- Minimize steering corrections and adjustments by planning optimal cornering paths for the road.
- Changes in velocity whilst cornering should be avoided where possible, to reduce compound motion cues.

5 Conclusion

Self-driving and autonomous vehicles are likely to induce motion sickness for a considerable percentage of the population, with motion sickness being further exacerbated through the engagement in non-driving related activities. Current predictions of the benefits of such vehicles have overlooked the factor of motion sickness, and productivity predictions are unlikely to be achieved without further consideration of how to reduce, or manage motion sickness. Motion sickness causes significant subjective discomfort – leading to a likely reduction in willingness to engage in many tasks, and even if those tasks are completed, actual performance has been shown to be significantly affected. Further to this, through understanding demographic differences in motion sickness susceptibility it is clear to see a lack of inclusivity in these current designs, where without methods of managing motion sickness some users will be much more affected than others. This paper has highlighted some key concerns for such future vehicles, and through the exploration of the literature and in reflection of some current self-driving vehicle concepts, a series of design recommendations have been made across five areas of self-driving vehicle design. Many of these recommendations are theory-based where there is a current lack of proven methods to manage motion sickness through physical vehicle design, and given the variation in many vehicle designs, the implementation of recommendations will be dependent of the characteristics of individual vehicles. It is hoped that vehicle manufacturers will consider these motion sickness design solutions presented for future self-driving and autonomous vehicles so that everyone can benefit from the many comfort and productivity gains that have been predicted.

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