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# SELF-DRIVING CARSICKNESS

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This paper discusses the predicted increase in the occurrence and severity of motion sickness in self-driving cars. Self-driving cars have the potential to lead to significant benefits. From the driver's perspective, the direct benefits of this technology are considered increased comfort and productivity. However, we here show that the envisaged scenarios all lead to an increased risk of motion sickness. As such, the benefits this technology is assumed to bring may not be capitalised on, in particular by those already susceptible to motion sickness. This can negatively affect user acceptance and uptake and, in turn, limit the potential socioeconomic benefits that this emerging technology may provide. Following a discussion on the causes of motion sickness in the context of self-driving cars, we present guidelines to steer the design and development of automated vehicle technologies. The aim is to limit or avoid the impact of motion sickness and ultimately promote the uptake of self-driving cars. Attention is also given to less well known consequences of motion sickness, in particular negative aftereffects such as postural instability, and detrimental effects on task performance and how this may impact the use and design of self-driving cars. We conclude that basic perceptual mechanisms need to be considered in the design process whereby self-driving cars cannot simply be thought of as living rooms, offices, or entertainment venues on wheels.

## 1. Introduction

Maturation, integration and affordability of enabling technologies have turned self-driving cars from science fiction into reality. Whereas automation of the driving task as such is not new, e.g. cruise control was introduced in the late fifties (Akamatsu et al., 2013), the crucial difference is that today's automated vehicle technologies not only control the vehicle, but also monitor, interpret, and act in response to the driving environment without any driver engagement. Google's self-driving car famously has been clocking up thousands of accident-free miles and several countries are now preparing themselves to adapt laws permitting self-driving cars on public roads (BBC news, 2013). At the same time, the car industry seems to have entered a "first to market" race with some manufacturers announcing their intention to introduce self-driving vehicles as early as 2017 (e.g. NBC news, 2014).

Automation is widely regarded as the most significant development within the automotive industry (e.g. Wallace and Sillberg, 2012). This not only relates to the transformation of the concept of the "driving experience", but, more importantly, to its potential societal, environmental, and economic impact (for an overview see Begg, 2014). Given that the vast majority of accidents can be attributed to human error, taking the driver out of the loop may reduce or even eliminate driver error which, in turn, may lead to safer roads. It will also allow for more effective road use with vehicles able to safely drive close together thereby using less road space, reducing congestion and journey times. The optimisation of acceleration profiles enabled by automation will allow energy usage to be optimised leading to reduced pollution and associated emissions.

Further reductions in energy consumption may be achieved by reducing the weight of automated vehicles. In the light of the reduced likelihood and severity of collisions, heavy protective structures may be replaced by structures made out of lighter materials. In particular given our ageing societies, automated vehicles could also improve mobility for those unable or unwilling to take the wheel. Finally, automation may make traveling by car more productive and comfortable. The driver, now passenger, is able to engage in non-driving activities, sit back and relax, have a coffee, check emails, read the morning paper, or swivel the front seat and have a face-to-face conversation with rear passengers.

Yet, if, and to what extent, these potential benefits will materialise, is as yet unclear. In the short term, questions with regard to system reliability, cybersecurity, ethics, and liability will need to be addressed. However, automation raises more fundamental questions, in particular with respect to the interaction between driver and vehicle. To appreciate the nature of this interaction, it is instructive to briefly review the different levels of vehicle automation under consideration.

Automated vehicle technologies have a range of capabilities, from anti-lock brakes and forward collision warning, to adaptive cruise control and lane keeping, to fully automated driving. Following the Society for Automotive Engineers taxonomy (SAE, 2014), we here define 5 levels of vehicle automation. Level 0 indicates the absence of automation, i.e. manual driving. Automation level 1 (*Driver assistance*) refers to the situation where the vehicle technology takes over either longitudinal or lateral control. These automation features have been available within the premium segment for some time in the form of Adaptive Cruise Control and Lane Keeping Assist systems, respectively. Level 2 (*Partial automation*) refers to automation of multiple and integrated control functions, such as adaptive cruise control combined with lane centring. The driver is responsible for monitoring the roadway and expected to be available for control at all times, but under certain conditions can be disengaged from vehicle operation. From level 3 upwards, the driver is no longer required to monitor the environment and is thus able to engage in non-driving tasks under certain conditions. Unlike level 4 and 5, level 3 (*Conditional automation*) would still require the driver to regain manual control if required within a certain time buffer, e.g. within 30 seconds following a warning signal. Level 4 (*High automation*) no longer requires the driver to intervene, but the autonomous mode may not be available on all types of roads. Finally, at level 5 (*Full automation*), the vehicle can perform all driving functions and monitor roadway conditions for an entire trip, and so may operate with occupants who cannot drive, or without human occupants.

From the above taxonomy and definitions, it can be seen that the driver's role changes depending on the level of automation. Starting from an active driver, automation gradually transforms the driver into a system supervisor and ultimately a passenger at automation levels 4 and 5. Not surprisingly, the introduction of automation has raised several classic human factors issues (for a review see Trimble et al., 2014). Of particular immediate concern are the questions that arise at automation level 3, which is widely anticipated to be introduced towards the end of this decade (NBC news, 2014). At this level, the driver is expected to resume vehicle control with a sufficiently comfortable transition time in case the system reaches its performance limits, or because the driver desires to return to manual drive. The safe and comfortable transitioning between in-the-loop and out-of-the-loop behaviours raises several questions. The current human factors research agenda focusses on questions related to control authority, human machine interface design, transition periods and strategies, driver performance over time, safety impact of secondary tasks, situation awareness, driver acceptance and trust, driver training, and system evaluation tools (e.g. NHTSA, 2013; Trimble et al., 2014).

However, there is one human factors issue that appeared to have gone unnoticed and which we would like to draw attention to in this paper, namely motion sickness. As will be argued here, vehicle automation can be predicted to increase the likelihood and severity of motion sickness, or what we refer to as *Self-Driving*

*Carsickness*. The reason for this is that the scenarios envisaged for self-driving cars create conditions that are known to promote the incidence and severity of motion sickness. Furthermore, the issue of motion sickness will be of concern across *all* automation levels.

### 1.1 Scenarios for self-driving cars

Automation creates a new set of design opportunities where the vehicle can be increasingly thought of as a space for living, working and socialising. Recently, several concepts and technology demonstrators have been presented to explore the possibilities that automated driving may offer. The envisaged scenarios can be summarised into three main categories and are illustrated in Figure 1.

- *Transition from an active driver to a passive supervisor or passenger*
  Automation level 2 as already provided by some premium car manufacturers (Forbes, 2013), allows the driver to disengage from the driving task and sit in comfort without the need to control pedals and steering wheel. The transfer of vehicle control and the subsequent lack of vehicle control on behalf of the driver will be a fundamental condition across all automation levels.

- *Engagement of the driver in non-driving tasks*
  Automation levels 3 and higher open up more opportunities and enable the driver, now passenger, not only to relax but also to engage in non-driving activities. Concept vehicles such as Rinspeed's *XchangeE* (Forbes, 2014), *ZOOX* (Digital Trends, 2013), Akka's *Link & Go* (Akka, 2015), and Mercedes-Benz's *Future Truck 2025* and *F015* (Mercedes, 2015) point towards future vehicle designs that may include steering wheels that are stowed away or can slide into the centre of the car, allow the driver's seat to swivel away from the steering wheel, read a book or watch media content on in-vehicle displays, simply relax, or have a face to face conversation with the other passengers.

- *Rearward facing seating arrangements*
  A frequently suggested scenario for self-driving cars is the idea that drivers and front seat passengers are able to swivel their seats. This concept seems to be based around the idea of the vehicle becoming a social space with occupants being able to face each other, e.g. Rinspeed's *XchangeE* (Forbes, 2014), and secondly, to create sufficient space for the driver behind the steering wheel to engage in certain non-driving activities such as the use of nomadic devices such laptops or tablets (e.g. Mercedes-Benz's *Future Truck 2025*).

Figure 1. Illustration of the three main scenarios for automated vehicles: From active driver to passive supervisor / passenger (left); Engagement in non-driving tasks (middle); Rearward facing seating arrangements (right)

The argument we put forward in this paper is that these scenarios can be expected to significantly increase the likelihood of motion sickness in self-driving cars, or self-driving carsickness. Here, motion sickness refers to a condition in which people get sick due to motion. Although there is still debate about the actual origin thereof, the most widely accepted theory assumes motion sickness to be correlated with, and likely caused by, an error signal in the control of self-motion, like pain is correlated with heat when touching a stove, for example.

As further elaborated on below, anticipation is of particular interest, and taking away lateral and longitudinal vehicle control transforms the driver's role from an active to a passive passenger. It is widely known that the absence of control renders individuals more susceptible to motion sickness due to the inability to predict the future motion trajectory with sufficient accuracy. Secondly, engagement in non-driving tasks which preclude a view of the outside world, can easily lead to conflicting motion information provided by the visual and vestibular system, and is a classic example of the sensory conflict underlying the causation of motion sickness as explained further below. Furthermore, the absence of a clear view of the road ahead also means that the ability to predict the future motion path on the basis of visual information may be compromised as explained below as well. Finally, a rearward facing seating arrangement creates a condition that amalgamates the issues identified in the previous ones. That is, not only is the "driver" not in control, he or she is also unable to anticipate the future motion trajectory based on visual information, whilst in addition, the view inside the vehicle cabin may lead to a visual-vestibular conflict.

The aim of this article is to provide a better understanding of the conditions that may promote motion sickness in self-driving cars and provide guidelines to minimise the severity and occurrence of self-driving carsickness in future vehicles and applications. The relevance of self-driving carsickness lies in the fact that its occurrence may hamper the successful introduction of vehicle automation. Signs and symptoms of motion sickness may prevent the driver from activating the automation or engage in non-driving tasks. As such, the advantages of vehicle automation in terms of comfort and productivity may not be realised, reducing the perceived benefits and subsequent user acceptance of this emerging technology. In addition, self-driving carsickness may negatively impact an individual's task performance which, in turn, may compromise his or her ability to effectively and safely switch back from automated to manual vehicle control. Thirdly, following the use of self-driving cars, aftereffects may negatively affect an individual's ability to engage in subsequent safety critical activities. Finally, self-driving carsickness may prevent the anticipated increase in road capacity if automated vehicle-control algorithms need to be tuned to avoid self-driving carsickness.

In the below, we discuss the causes of motion sickness and its contributing factors in the context of self-driving cars in more detail. This will be followed by a discussion on future research requirements, implications for the implementation of automated vehicle technologies, and design guidelines for automated vehicles.

## 2. Motion Sickness in Self-Driving Cars

### 2.1 Motion Sickness

Although the ultimate manifestation of motion sickness is vomiting, this is typically preceded initially by signs and symptoms such as (cold) sweating, pallor, flatulence, burping, salivation, apathy, and finally by nausea and retching (Reason & Brand, 1975; Bos et al., 2005). These symptoms may vary considerably between people regarding their (order of) occurrence, and degree. Depending on the origin and type of motion, the all-embracing term motion sickness can be split up into physically induced forms like carsickness, seasickness, airsickness, and space sickness, and visually induced forms like cinerama sickness (i.e., in movie theatres, especially those with a large image format like IMAX), cybersickness, and simulator sickness. About 2/3 of all people have ever suffered specifically from carsickness, of which about half have even vomited (Reason & Brand, 1975; Griffin, 1990). Incongruences between what we feel and what we see typically aggravates symptoms (such as below deck at sea, or when reading a book in a car), whereas looking at the Earth-fixed horizon, even when this is presented artificially, may be beneficial (Bos et al., 2008a; Feenstra et al., 2011; Tal et al., 2012). Yet, functioning organs of balance within our inner ears, also referred to as vestibular end organs, are crucial; people without do not suffer from any kind of motion sickness. In the 19th century, for example, it was observed already that totally deaf people were immune to seasickness (Irwin, 1881; James, 1882), and this has been confirmed many times since, with different kinds of motion (Reason & Brand, 1975; Kennedy et al., 1968; Money, 1970). Interestingly, these so called labyrinthine defective patients also do not suffer from visually induced motion sickness in the absence of physical self-motion (Cheung et al., 1991; Cheung et al., 1989; Johnson et al., 1999). Blind people, on the other hand, do suffer (Graybiel, 1970). Motion sickness should therefore not be considered a disease but a common phenomenon, a natural response to an unnatural environment. Although there are other factors at issue, such as mood, smells, and food, motion is the common factor, where sickness severity shows a remarkable trend with its amplitude and frequency (see more below).

### 2.2 Visual-vestibular conflict

Automation levels 3 and upwards will allow the driver to engage in non-driving activities. It is likely that popular activities will include reading, responding to emails, or engaging otherwise with nomadic or integrated infotainment systems such as in-vehicle displays, laptops, gaming consoles, or tablets. Increased comfort and the ability to use the driving time more productive, is frequently being put forward as the main customer advantage (e.g. CNN, 2013). As alluded to already, engagement in such activities can be expected to lead to an increase in carsickness. Similar to reading a map or book whilst driving, the (static or dynamic) image displayed on displays will not correspond to the motion of the vehicle, which ultimately may lead to carsickness. The essential point here is that our central nervous system (CNS) integrates visual and vestibular signals normally caused by congruent motion inputs as expected. Watching a scene showing different motion than felt by our organs of balance is not what we expect, which has been shown to be a plausible cause of visually induced motion sickness in particular (Bos et al., 2008), and may as well explain the key issue with respect to the current paper. Indeed, previous research has already shown that the use of in-vehicle entertainment systems can increase the incidence and severity of carsickness. Cowings et al. (1999), for example, reported a negative impact on crew performance and health when subjects attended to displays while the vehicle was moving. More recently, in a study by Kato and Kitazaki (2008), participants were driven around whilst sitting in the backseat either watching the road ahead, or a rear-seat display showing written text.

As expected from a sensory conflict perspective, watching the in-car display led to significantly higher levels of carsickness.

**2.3 Motion profiles**

Motion sickness typically occurs when we are exposed to motion that, from an evolutionary perspective, we are not used to, such as low frequency oscillating motion (O'Hanlon & McCauley, 1974), or to altered, i.e., hypo- and hyper-gravity levels (Nooij et al., 2007). Sea and airsickness are mainly caused by slowly oscillating vertical motion. Carsickness, on the other hand, is mainly associated with horizontal accelerations caused by accelerating, braking, and cornering (Guignard & McCauley, 1990; Turner & Griffin, 1999ab). An aggressive driving style involving plenty of accelerating and braking is therefore more likely to result in carsickness. Using a vertical motion simulator, O'Hanlon and McCauley (1974) oscillated over 500 subjects with different frequencies and amplitudes, up to two hours each, or less when they vomited. As a result, they were able to show that sickness not only increases with motion amplitude, but also that the average sickness incidence peaks at a frequency of 0.16 Hz. This observation has thereafter been confirmed repeatedly, also for other degrees of freedom, and no matter whether the motion was induced physically (Dai et al., 2010; Donohew & Griffin, 2004; Golding et al., 2001; Griffin & Mills, 2002; Howarth & Griffin, 2003; Lawther & Griffin, 1987) or visually (Diels & Howarth, 2013; Golding et al., 2013). The fact that physical motions with a frequency content above 1 Hz are hardly or not sickening at all, has furthermore been shown to be even beneficial when added to low frequency motion, the combination being less sickening than the low frequency motion alone (Bos, 2015). Talking about comfort, by the way, this also nuances the car industry's pursuit to reduce vibration levels to the technically lowest feasible limits.

The actual motion profile, i.e., the driving scenario and associated vehicle dynamics, is also of relevance to self-driving carsickness in the context of the above visual-vestibular conflict. Then, the motion sensed by the visual system does not agree with that sensed by the vestibular system. Our organs of balance are in essence biological accelerometers, and this means that they are sensitive to accelerations only, i.e., to changes in velocity (Howard, 1982). As a corollary, sensory conflict, and hence the likelihood of carsickness from occurring, is significantly reduced when traveling at constant speed. The organs of balance signal the body to be stationary, and any stationary scene as sensed by our eyes will therefore be perceived as congruent. Under conditions of constant motion, i.e. no lateral or longitudinal accelerations, carsickness is therefore less likely to occur when reading or using in-car displays.

Importantly, however, this is predicated on the assumption that the display itself does not induce a visually induced perception of self-motion, also known as vection (see Hettinger et al., 2014 for an overview). Several self-driving vehicle concepts, such as Rinspeed's *XchangeE* (Forbes, 2014)) and Akka's *Link & Go* (Akka, 2014), suggest occupants to view media content on large in-vehicle displays while in autonomous mode. Most recently, Mercedes-Benz proposed the idea of occupants donned with Head Mounted Displays (HMD) to enjoy their own personal media content whilst being driven (Mercedes, 2015). When traveling at constant speed, with the vestibular system subsequently signalling the body to be stationary, viewing a large field of view display with dynamic content (i.e. optic flow) may result in a different type of visual-vestibular conflict. In this case, the moving images displayed are incongruent with the (stationary) motion information provided by the vestibular system. From a sensory perspective, this situation is indistinguishable from that occurring in fixed-based driving simulators for example. As such, motion sickness occurring under these conditions should technically be referred to as *Visually Induced Motion Sickness* (VIMS) rather than self-driving carsickness. The prospect of using large field of view displays showing dynamic content in self-driving and driverless cars will therefore create similar challenges with regard to the occurrence of motion sickness as observed in simulators and other virtual environments. In that respect it is telling that 50% drop-out in simulated car driving scenarios due to simulator sickness is not an exception (Reed et al., 2008). As can be inferred from the above, the most trivial solutions are to either reduce image size (or Field of View) or to add information on the veridical motion (see below). Moreover, it has been suggested that the critical visual-vestibular conflict as referred to above will increase with increasing image reality (Bos, 2013). The latter thus implies a paradox, i.e., the likelihood of (self-driving) carsickness will most probably increase with improving image quality of on-board displays, rather than decrease. In that respect it is also telling that the incidence of simulator sickness seems to increase in the course of time rather than to decrease (Reed et al., 2008), irrespective the increase of knowledge thereabout.

**2.4 Anticipation**

One of the most striking issues with respect to carsickness concerns the observation that, different from passengers, drivers rarely get sick (Rolnick & Lubow, 1991; Stanney & Hash, 1998). Here, anticipation seems to be a key issue. The difference can be understood by assuming our central nervous system not only reckons sensed motion, but also makes a prediction about self-motion based on previous experiences (Oman, 1982; Bles, et al., 1998; Bos & Bles, 1998, Bos & Bles, 2002; Bos et al., 2008a). This makes sense because sensory imperfections, neural delays, and the fact that our organs of balance cannot make a distinction between inertial and gravitational accelerations prevent our CNS to adequately control body motion and attitude (Bos & Bles, 2002; Einstein, 1907; Mayne, 1974). The latter refers to our orientation with respect to gravity, which seems of particular interest with respect to motion sickness. A discrepancy or conflict between integrated sensory afferents indicative for specifically attitude, and a prediction thereof by a so called internal model or neural store, is assumed responsible for generating motion sickness (Bles et al., 1998; Oman, 1982; Reason & Brand, 1975). A mathematical model of this concept has been able to explain the origin of the peak in sickness incidence about 0.16 Hz (Bos and Bles, 1998, 2002). This, although not proving, does suggest that our CNS may indeed apply a mechanism as suggested. If, within this frame of mind, the driver of a car is then familiar with the transfer from pedals and steer to actual motion of that car, he or she can make an additional prediction, i.e., anticipate motorically about future motion, thus minimising the sickening conflict. Even different from a forward looking passenger who can see a curve ahead, only the diver knows whether this curve will be taken wide or sharp, thus having optimal information about self-motion, resulting in the smallest possible conflict. Braking and accelerating will likewise cause a difference in conflict and hence a difference in sickness.

Importantly, this anticipatory mechanism may not only be at play when individuals are able to *motorically* anticipate incoming sensory cues, but also on the basis of *visual* information alone. Although with a reduced level of accuracy, a clear view of the road ahead will allow for the prediction of the future motion path and a subsequent reduction in sensory conflict. Recently, the effectiveness of anticipation on the basis of visual information was demonstrated by Feenstra et al. (2011), who showed a fourfold reduction in motion sickness when a visual track to be travelled was presented in a motion simulator. The importance of anticipatory visual information is furthermore suggested by the anecdotal evidence that backward looking passengers suffer more from car sickness than forward looking passengers, the former only seeing the trajectory that has been followed, the latter seeing the trajectory that will be followed. The importance of visual information per se is furthermore demonstrated by the fact that rear seat passengers are particularly prone to car sickness under conditions where external visual views are limited (Turner & Griffin, 1999ab).

From the above, it becomes apparent that all the scenarios envisaged for self-driving cars have consequences for the occupants' ability to anticipate the future motion trajectory and, as such, the lack thereof may prove to be one of the most important factors in the development of self-driving carsickness. When traveling in autonomous mode, the absence of vehicle control, facing away from the direction of travel or even traveling backwards, or not having a clear view of the road ahead due to it being obscured by displays or internal structures otherwise, will all increase the likelihood of occupants experiencing motion sickness.

### 2.5 Accumulation and habituation

The time course typical for motion sickness in general and carsickness in particular, is another factor to be considered. The onset time of signs and symptoms can vary considerably but is normally of the order of ten to twenty minutes (O'Hanlon & McCauley, 1974). Here, it is thought that signals from the organs of balance and the eyes are integrated by the CNS and relayed to the gastro-intestinal system in some, not yet fully understood way, except that it takes time for sickness to appear (Money, 1970; Reason and Brand, 1975; Oman, 1982). After that, or likely effective already from motion onset onwards, habituation is at play. Although less evident in carsickness, especially seasickness is known to diminish after a couple of hours already, a process that typically continues over the next days at sea. We assume this habituation to be less evident in cars than at sea, just because there is ample opportunity to interrupt the motion, allowing for recovery on the road, but not at sea. As with physical motion, the effect of interruptions in motion exposure has also been observed in experiments on visually induced motion sickness (Van Emmerik et al., 2011). Here too, the CNS plays a crucial role, assumed to minimise the difference between integrated sensory information about self-motion and the prediction thereof as referred to above.

In the context of self-driving cars, the above raises the question whether people habituate to sickness in self-driving cars in a similar way compared to manually driven cars. Alternatively, users of self-driving cars may be less inclined to interrupt their journey in response to the onset of signs and symptoms and habituate sooner as a consequence.

### 2.6 Performance

On the one hand, carsickness may be considered a luxury issue. By that we mean that in passengers, carsickness does not cause a serious health or safety issue. When performing certain physical and cognitive tasks on the other hand, it has been shown to be a risk (Bos 2004; Colwell, 2004; Stevens & Parson, 2002). Where about 5% of tasks performed by professionals doing different kinds of tasks at sea did not result in the desired outcome within the time set for that task when not feeling sick at all, this increased to about 60% in case of at least one vomiting incident during the time interval at issue (Bos, 2004). Interestingly, the data also suggested that even when not feeling nauseated yet, "sickness" (i.e., all other symptoms) resulted in about 20% of task failures. Another effect concerns the observation that our visual acuity, i.e., our ability to differentiate (small) objects from one another decreases as well when feeling sick (Bos et al., 2008b). Although these data concerned seasickness, there is no reason to assume these will differ with respect to carsickness.

With regard to self-driving cars, of particular interest here is the question to what extent the occurrence of self-driving carsickness affects the performance of a passive and sick driver who has to take over vehicle control in response to an emergency situation. Although the ultimate scenario would involve a passive driver vomiting at the moment his or her interaction is required as a driver, more subtle effects may include effects on situation awareness and response times.

### 2.7 Posture

It has been observed that people susceptible to motion sickness also show more postural instability (Cobb, 1999; Faugloire et al., 2007; Fukuda, 1975; Smart et al., 1998; Takahashi et al., 1992; Van Emmerik et al., 2005; Yokota et al., 2005). Yet, negative or lacking correlations have been observed too (Reed-Jones et al., 2008; Stoffregen et al., 2008; Warwick-Evans et al., 1991; Golding et al., 2009). The difference may be explained by the fact that most of these data concern visually induced motion sickness. With repeated exposure, people then seem to habituate in terms of sickness during exposure when physical and visual motion does not match. After return to the natural condition, they then show more postural instability due to the re-adaptation to the condition in which physical and visual motion are matching again (Gower et al., 1987; Kennedy & Stanney, 1996; Bos, 2011, 2014). The essential point here is that a visual-vestibular conflict induced by watching, e.g., in-vehicle entertainment, may cause an *after-effect* impeding the proper control of self-motion, be it directly or indirectly by means of vehicle motion. As already mentioned, several self-driving vehicle concepts suggest occupants to view media content on large field of view in-vehicle displays or even Head Mounted Displays (HMD) while in autonomous mode. Hence, it may be anticipated that comparable effects will happen due to this type of displays, the effects thereof possibly being aggravated by even larger visual-vestibular conflicts due to the fact that the visual motion shown will likely be farther away from the real vehicle motion than from sitting still as in most Virtual Environments. Questioned carefully, if the effect of incongruent visual and vestibular motion cues on posture does show that our CNS can render itself in a state inappropriate for the control of self-motion, why would this not hold alike for the control of vehicle motion? As such, this situation may pose a health and safety issue both during intermittent driving in self-driving cars as well as following a journey.

### 2.8 Age and gender

On average, females seem to suffer more from sickness than males do (Cheung & Hofer, 2002; Dobie et al., 2001; Flanagan et al., 2005; Jokerst et al., 1999; Klosterhalfen et al., 2005, 2006; Lenzt & Collins, 1977; Park & Hu, 1999). The difference, however, may be due to cultural issues, females being more open about their feelings than (macho) males. This may be substantiated by the observation that most studies on this issue concern self-reports on wellbeing, and there seems to be a lack of evidence when it comes to the ultimate objective measure of motions sickness, i.e. vomiting. An effect of the menstrual cycle has been suggested in addition, which issue, however, remains unsettled (Cheung et al., 2001; Golding et al., 2005; Grunfeeld & Gresty, 1998). Age has been shown to be at issue as well (Bos et al., 2007; Dobie et al., 2001; Lawther & Griffin, 1988; Lentz & Collins, 1977; Turner & Griffin, 1999ab). Below the age of two, typically before the first attempts to stand up, we seem to be immune, while susceptibility seems to peek between the age of 16 and 20. At the age of 80, susceptibility to seasickness has been shown to be only one quarter of that at the age of 20 (Bos et al., 2007). Despite these data do concern seasickness, here again there is no reason to assume these will differ with respect to carsickness. In that case, especially the youngest and highest susceptible group of drivers will be at extra risk in self-driving cars. Of all drivers they are the least experienced as may be exemplified by them being nearly three times more likely to be involved in a fatal crash than drivers above the age of 20 (IIHS, 2012), and might then be at extra risk because of a self-driving carsickness induced performance reduction. Apart from this risk, these age and gender effects may also suggest that user acceptance may be lower amongst females and the younger age group as a consequence of experiencing elevated levels of motion sickness.

### 2.9 Anti-motion sickness drugs

In order to make use of the advantages that self-driving cars can provide regarding comfort and productivity, susceptible individuals in particular may reach for anti-motion sickness drugs, including antimuscarinics (e.g. scopolamine) and by far the most popular group of H1 anti-histamines (e.g. dimenhydrinate). Whereas these may be effective in avoiding individuals from experiencing signs and symptoms, they also tend to produce unwanted side effects such as drowsiness (Cowings et al., 2000; Nicholson et al., 2002; Spinks et al., 2004).

Although this may be beneficial in transporting nagging kids over longer distances at the backseat of a car, this causes a serious risk for the driver, irrespective the possibility of the act of driving being performed only intermittently.

## 3. Design considerations for self-driving cars

On the basis of our theoretical understanding as well as previous research into motion sickness, it can be expected that automation will increase the likelihood of motion sickness amongst drivers, now passengers, in particular amongst those already susceptible to motion sickness. Even if people do not experience full blown symptoms of motion sickness, mild and subtle symptoms may negatively affect the user experience. Thus, a significant proportion of drivers may be unable or unwilling to take advantage of the new scenarios afforded by self-driving cars due to the occurrence of motion sickness. The development of measures to minimise the severity of motion sickness, or avoiding its occurrence altogether, can therefore be expected to become an important line of automotive research to ensure the uptake and acceptance of self-driving cars. Moreover, this issue can be especially relevant during the introductory period of these cars, in which the general public may be hypercritical, the least publically known failure easily leading to unwanted delays.

### 3.1 Anticipation of motion trajectory

A central guiding principle that may lead to potential design solutions is the fact that the moderating effect of control on motion sickness is related to the ability to anticipate the future motion path as discussed in section 2.4. This anticipatory mechanism may not only be at play when individuals are able to *motorically* anticipate incoming sensory cues but also on the basis of *visual* information. From a design perspective, the most critical consideration is that the occupant should be provided with sufficient visual information about the conditions ahead, such as to be able to anticipate the future motion path. Although it currently is an open question as to what is sufficient, forward and sideway visibility should be maximised to provide occupants with a clear view of the road ahead. The vehicle design should therefore aim for:

- Maximum window surface areas (also known as Day Light Openings (DLO))
- Minimal obstruction by A-pillars, low belt or shoulder lines
- Seats of sufficient height to ensure passengers are able to look out of the vehicle

The latter, of course, already holds for children sitting at the backseat irrespective the car being self-driven or not. Note that, in part due to increasing safety demands, some of these recommendations are in direct contrast to current automotive design trends, which show relatively high belt lines, and subsequent reduced window surface areas, as well as obstructed forward views due to the width of A-pillars.

Besides a clear view of the road ahead, additional visual information provided via artificial enhancement of the visual scene (i.e. augmented reality) may prove a promising approach. Feenstra et al. (2011), for example, demonstrated a fourfold reduction in airsickness when a visual track to be travelled (i.e. future motion trajectory) was presented (see Figure 2, left). In this simulator study, passive participants were exposed to turbulent physical aircraft motion (1) without visual cues (interior cabin only), (2) with a display showing an Earth-fixed star field moving opposite the simulator cabin, or (3) with the same star field augmented by anticipatory information by means of a rollercoaster like track showing the future trajectory. Results showed a dramatic effect on the occurrence of airsickness. Provision of the Earth-fixed visual frame reduced sickness by a factor 1.6, whereas the addition of the anticipatory information led to a reduction by a factor of no less than 4.2. Although it has yet to be determined whether this approach can be successfully applied within an automotive context, in theory, we would predict a similar approach to reduce or prevent self-driving carsickness.

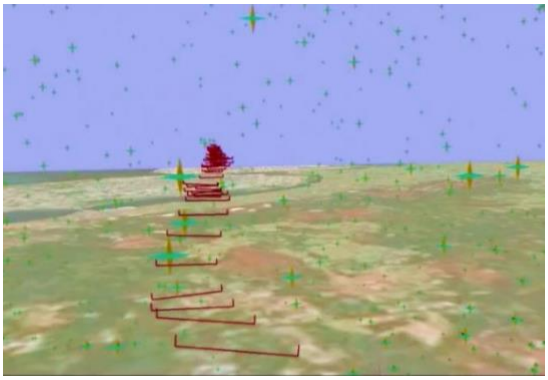


Figure 2. Anticipatory motion visualized by a stylistic rollercoaster track (Feenstra et al. 2011) (*left*) and contact analogue HUD trajectory (Weissgerber et al. 2012) (*right*).

Incidentally, in a recent study by Weissgerber et al. (2012) a similar anticipatory approach has been suggested albeit with a different goal. In this study, a contact-analogue Head-Up Display (HUD) was used to provide the driver an augmented view of the road ahead indicating, amongst other things, the vehicle's future trajectory (see Figure 2, right). The simulation required drivers to take over vehicle control due to the system reaching its limits. Results showed that the additional visual information improved driver's ability to create a correct mental model and representation of the driving situation and automated vehicle system as reflected in reduced response times and higher technology acceptance. Taken together, these studies suggest that the use of Augmented Reality (AR) to display advanced system status such as the future motion trajectory may have multiple advantages.

### 3.2 Design for non-driving tasks

As discussed in section 2.2 and 2.3, engagement in non-driving tasks such as reading or interacting with nomadic or integrated displays may result in visual-vestibular conflict. Whether these interactions are likely to result in motion sickness will depend on several factors.

First, *compromising the occupant's view of the road ahead*, or line of sight, may prevent the ability to anticipate the future motion path and subsequently increase the likelihood of motion sickness. As discussed, this situation is currently of relevance to passengers reading a newspaper or using an infotainment display (e.g. tablet, laptop) located at a downward angle requiring the user to look inside the vehicle interior. Similarly, depending on the occupant's height, a rear seat passenger's view may be blocked by front seats or head rests which furthermore may be fitted with a rear-seat display. With the introduction of self-driving cars, driving in automated mode allows the driver to engage in similar activities and subsequently, the same issues are at play.

Thus, from a design perspective, it is important to consider that both the *size* and *location* of any display, for instrumentation or entertainment, will determine the extent to which the occupant is able to use visual information to anticipate the future motion path. Therefore, in principle, it is recommended to:

- Locate displays near the line of sight out of the window. This will enable the passenger to view the content of the display with their central vision, whilst using peripheral vision to gather information on the direction of travel.
- Limit the size of the display to allow for sufficient peripheral visual information.

If, and to what extent this approach will be successful in avoiding motion sickness, is yet to be determined. For example, future research will be required to understand the degree of peripheral vision required to allow occupants to anticipate the motion trajectory with sufficient accuracy to avoid motion sickness. Possible design solutions may involve the integration of displays in the vehicle interior (e.g. door cards, floor) presenting congruent motion information.

As an alternative design solution, the use of see-through and augmented reality displays, i.e. displays in which display content is superimposed on the view of the road ahead, seems promising. This type of arrangement may provide the user the required visual information indicating the direction of travel, whilst at the same time showing display content. Whereas this can be expected to avoid the abovementioned visual-vestibular conflict, depending on display media content, it may introduce a new type of sensory conflict as discussed in more detail below. Apart from this additional complicating matter, it furthermore remains to be seen to what extent either of the above design solutions would be comfortable and acceptable to the user.

The second major factor that will determine whether any of the non-driving tasks will lead to self-driving carsickness is the *display content* relative to the *vehicle motion profile* (see section 2.3). The level of congruence between the motion depicted on a display (static or dynamic) and the motion sensed by the vestibular system determines the level of sensory conflict. Regarding the relevance of motion profiles, levels of self-driving carsickness may be manageable provided the automation is not applied under traffic conditions that involve high levels of accelerations as typically observed in urban or rush hour motorway traffic. When velocity is relatively constant, sensory conflict is minimised since the static image on a display will correspond to the perceived motion of the vehicle.

On the other hand, the use of large field of view displays showing dynamic content while driving at constant velocity will lead to visually induced motion sickness. As such, this will create similar challenges with regard to the occurrence of motion sickness as seen in simulators and other virtual environments. The two most important parameters to take into account here are the screen size or *Field Of View* (FOV) and the *visual motion profile*. In general, larger displays have the potential to provide a stronger sense of self-motion and subsequent sensory conflict (Hettinger et al., 2014, Van Emmerik et al., 2011), whereby motion profiles around 0.2Hz are more provocative than others (e.g. Diels & Howarth, 2006, 2013). Whereas media content, and subsequent motion profiles, will be largely out of the designer’s control, display size and position are the two considerations to be taken into account in the design for non-driving tasks in self-driving cars.

The vehicle’s motion profile also plays an important role in the context of self-driving carsickness in a different way. Automation of the driving task in theory allows for less aggressive and smoother motion profiles. Given the existing knowledge on the relationship between acceleration and sickness, the manoeuvring algorithm of the autonomous vehicle could also be optimised in such a way as to minimise the likelihood of carsickness from occurring. Ironically, however, it has been estimated that if automated vehicle-control algorithms would be tuned in such a way, one of the major socioeconomic benefits of automation, i.e. increased road capacity, may not be achieved (Le Vine et al., 2015).

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## 4. Conclusions

Vehicle automation has the potential to provide significant benefits to not only the driver but also society at large. However, current concepts and scenarios put forward for self-driving cars fail to take into account basic perceptual mechanisms and run the risk of causing occupant discomfort, i.e. self-driving carsickness. As such, this may prevent the driver from activating the automation or engage in non-driving tasks. Consequently, the benefits of this technology may not be capitalised on, which may negatively affect user acceptance, technology uptake, and ultimately, the assumed positive socioeconomic impact. This paper provided research questions and design guidelines to aid the design of future automated vehicle technology and avoid the occurrence of self-driving carsickness and associated negative side effects to facilitate its successful introduction. In short, self-driving cars cannot be thought of as living rooms, offices, or entertainment venues on wheels and require careful consideration of the impact of a moving environment.

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