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Motion Sickness Mitigation in Autonomous Vehicle: A Mini-Review

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REVIEW ***Open Access***

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Abstract – *An autonomous vehicle is a rapidly evolving technology that received attention from researchers due to its potential benefits. Besides the advantages, there are also non-negligible issues that need to be overcome in the middle of the autonomous vehicle development process. Among all the challenges, one of the important topics that have not gained adequate consideration is motion sickness (MS). This paper reviews the benefit and challenges of autonomous vehicles, MS factors, the quantifying methods of MS, and the mitigation strategies of MS. Considering the importance of minimizing MS, it is concluded that the number of strategies to lessen MS's severity is still lacking; hence, requiring more attention from automotive researchers.*

Keywords: Autonomous vehicle, motion sickness

1.0 INTRODUCTION

The autonomous driving systems can be classified according to the degree of automation outlined by the Society of Automotive Engineers (SAE). The standards for autonomous driving systems ranging from Level 0 (i.e. No automation) to Level 5 (i.e. Full automation) according to SAE J3016-2016 (SAE, 2016). At Level 3 or higher, the driver does not need to control the vehicle and can be considered a passenger.

The transfer of the vehicle control from the human to the autonomous system of the car may bring benefits and challenges to the users. This paper reviews the benefit and challenges of autonomous vehicles. One of the challenges is motion sickness (MS), which will be the focus of this paper. The next sections present an overview of the benefit and challenges, followed by MS factors, MS quantifying methods, and MS mitigation strategies. Lastly, a conclusion is presented in the last section.

2.0 BENEFITS AND CHALLENGES OF AN AUTONOMOUS VEHICLE

A safer transportation mode is one of the potential advantages offered by the advancement in autonomous driving technology (Ge et al., 2018). Distraction and inattention are among the causes of human error in driving that can be avoided by transferring vehicle control from humans to the vehicle (Diels et al., 2017). Hence, leading to reduced traffic collisions resulting from the minimization or elimination of human error (Chan, 2017). Furthermore, integrating advanced sensing, algorithm, and collision avoidance technologies into an autonomous vehicle could improve safety (Seppelt & Victor, 2016; Tian et al., 2017).

Mobility is another advantage offered by autonomous vehicles. Greater mobility freedom would benefit the elderly, disabled, and children, as currently, they are rather excluded from the automobile's mobility (Brenner & Herrmann, 2018; Paden et al., 2016). People who are unable to drive themselves could use autonomous vehicles due to their self-driving capability. Autonomous vehicles could also potentially provide more affordable mobility services (Chan, 2017) by ensuring the realization of shared mobility in the future. The current examples of shared mobility are the Zipcar, Uber, and Lyft services, which offer mobility without owning a private vehicle (Rubin, 2016). Shared mobility is extensively considered crucial for sustainable future transport solutions; concurrently, traffic congestions and parking demand might also be reduced.

Another potential contribution of autonomous vehicles is related to the environmental impact by reducing energy consumption and gas emissions (Offer, 2015; Sarkar & Ward, 2016). The autonomous vehicle can connect with the vehicle's surroundings and collect information regarding the driving environment (Aria et al., 2016). Connectivity and automation technology, such as coordinated vehicle-following, reduces energy-wasting acceleration and deceleration cycles and benefiting the road capacity. Furthermore, vehicle platooning improves aerodynamic effectiveness, significantly reducing vehicle energy consumption and gas emissions on the freeway (Zhai et al., 2019). An autonomous vehicle could increase drivers' productivity during travel time (Brenner & Herrmann, 2018; Chan, 2017). The automation allows them to spend travel time doing other activities, such as relaxing, conversing with other passengers, reading, and texting simultaneously and safely.

Nevertheless, despite the potential benefits of autonomous vehicles, several unignorably challenges must be resolved during the autonomous vehicle development stage. Safety is the major issue of autonomous vehicles (Elbanhawi et al., 2015), which can be categorized into road safety and cybersecurity. Although eliminating human error and creating safer transportation are the potential advantages of autonomous vehicles, traffic crashes will not be removed completely (Bagloee et al., 2016). Autonomous vehicle needs to share space and deal with other non-autonomous vehicles and road users, such as pedestrians and cyclists. Moreover, faulty sensors are a possibility that could threaten road safety (Van Brummelen et al., 2018). Also, system hacking is an example of a security issues probability that researchers seriously considered (Cunningham & Regan, 2015; De La Torre et al., 2018). Autonomous vehicle operation is also not spared from cyber threats and could risk its communication ability as a connected vehicle.

Autonomous vehicles bring several implications, of which legal liability is one of the major ones (Elbanhawi et al., 2015a). For instance, when an accident occurred, questions arise regarding who is ultimately held responsible. It is uncertain who has to bear the responsibility, whether the occupants, manufacturers, or mechanics, as a machine cannot be blamed in such cases (Koopman & Wagner, 2017; Sessa et al., 2016). Thus, developing new regulations for autonomous vehicles at this stage may be a challenging task for lawmakers, the government, or related agencies. This would complicate insurance issues and affect how companies handle the transportation business (Lima, 2016).

In order to ensure the public uses autonomous vehicle systems, first and foremost, user acceptance of this self-driving concept is crucial (Cunningham & Regan, 2015), particularly in a high automation condition where a close relationship between comfort and acceptance of the system exists (Bellem et al., 2018). Thus, providing comfortable autonomous driving is imperative so that the system is well accepted by the users, which leads to the next core challenge of autonomous vehicle development, that is, passenger comfort.

The driver has no direct influence on vehicle control in highly autonomous driving. It is the loss of controllability that has become a major factor that challenges the passengers' comfort experience, rendering a direct negative impact on passenger comfort in terms of path naturality and motion sickness (MS) (Elbanhawi, 2015; Sawabe et al., 2016). Natural paths resemble a human-generated path. By using familiar maneuvers, it improves passenger comfort since the feeling of having a robotic operator can be eliminated. In other words, transferring the control from a driver to an autonomous system decrease the path naturality; hence, interrupting passengers' comfort.

Moreover, loss of controllability triggers MS, an uncomfortable sensation that can negatively affect user acceptance of autonomous vehicles (Diels & Bos, 2016). This human factor issue requires a better understanding to ensure the autonomous vehicle can be successfully implemented. Smyth et al. (2018) reported that the issue of MS in autonomous vehicles was overlooked. Jones (2019) also stated that very few studies have been conducted on the factors, quantifying methods, and MS solutions in road vehicles.

Figure 1 summarizes the benefits and challenges of autonomous vehicle development. The grey colored box shows the focus of this study, which is MS.

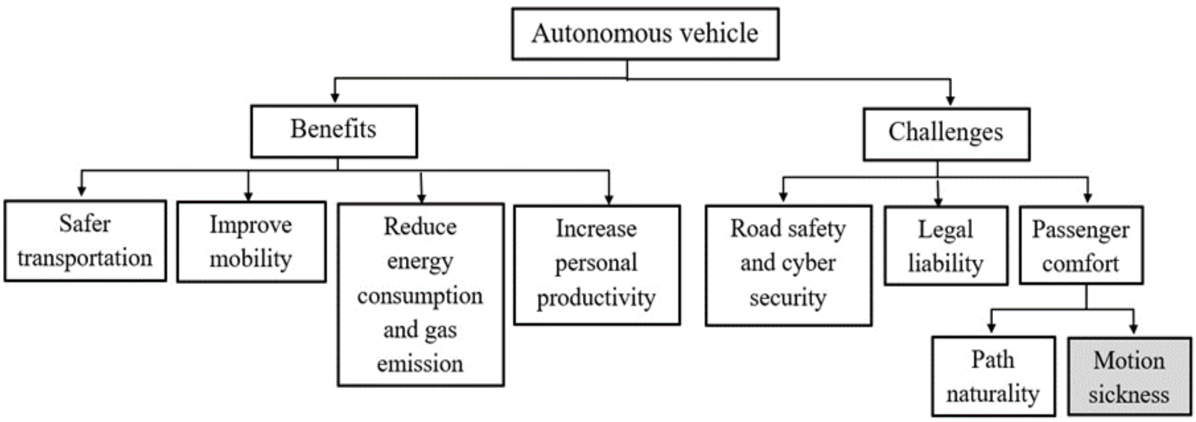

Figure 1: Benefits and challenges of autonomous vehicle development

3.0 MOTION SICKNESS

3.1 MS Factors

In this study, the MS factors are categorized into two different perspectives: occupant's behavior and vehicle dynamics behavior. First, in terms of occupant's behavior, MS occurrence is due to the existence of sensory conflict (Reason & Brand, 1975). The sensory conflict theory is the most widely accepted in MS studies (Zhang et al., 2015). Based on the theory, MS is developed when there is a mismatch between sensory input information from the visual (eyes) and vestibular systems. The vestibular system consists of semi-circular canals and otolith organs, in which each of them distinguishes neck rotational and translational motion (Iskander et al., 2019). The high autonomous vehicle allows both passengers and drivers to engage with non-driving activities, such as reading, playing games, and chatting. Engagement in such activities contributes to the sensory conflict, leading to the increment of the MS level (Diels & Bos, 2016).

Another well-known theory is that MS is preceded by postural instability (Riccio & Stoffregen, 1991). Occupants who have degraded control of the body, such as stance and locomotion, will experience MS (Koslucher et al., 2016). One of the causes of unstable posture is abnormal or non-smooth vehicle movement (Green, 2016). This theory explains the importance of the vestibular system in minimizing swaying and maintaining a stable posture during traveling to avoid MS. Dong and Stoffregen (2010) proved that those consistent in movement over time were less likely to experience MS compared to those who exhibited movement variation.

The third aetiology of MS is the reduced ability to predict the course of vehicle movement (Golding & Gresty, 2005). The expectation of future trajectory reduces when the driver's control is shifted to autonomous driving (Diels & Bos, 2015). In regards to interior design, it is assumed that an autonomous vehicle will improve occupants' social interactions. Researchers suggested a flexible interior with a rotatable seat concept in autonomous vehicles, whereby this arrangement allows the seats of the driver and front passenger to rotate and face backward. However, facing backward will lead to the inability to anticipate the future path direction (Diels, 2014). Furthermore, windows are not required by the passengers to look at the outside view because they do not control the vehicle (Kuiper et al., 2018). Thus, such restriction of visual input affects the passengers' ability to predict the vehicle's movement (Sivak & Schoettle, 2015).

While driving on curvy roads, the direction of the head tilt movement, concerning the direction of lateral acceleration, has a strong influence on MS susceptibility (Wada et al., 2018; Wada et al., 2013; Wada et al., 2012). Passengers experienced a higher severity level of MS compared to the drivers because passengers tend to tilt their heads in the same direction with the lateral acceleration when the vehicle turned into a corner. In contrast, under similar conditions, drivers normally tilt their heads to the opposite of the lateral acceleration direction. It has been proven that a correlation existed between the head tilt movement and lateral acceleration. The head tilt is measured by observing the response of the head roll angle. The degree of head roll angle affects the level of MS. Based on the relationship between head roll angle, lateral acceleration, and MS level, it is deduced that MS will increase if the head roll angle towards lateral acceleration is large and decreases, and vice versa.

The Subjective Vertical Conflict (SVC) theory also explains the cause of MS (Bles et al., 1998). SVC theory hypothesizes that the occurrence of MS is due to the accumulation of conflict between the sensed vertical by the vestibular system and the estimated vertical by the internal model in the cerebellum. Besides the above reasons, it is also believed that MS occurrence is due to individual physiological and genetic (Zhang et al., 2015). Odors inside the vehicle and food consumed during a drive might lead to MS as well (Turner & Griffin, 1999a).

Based on the perspective of vehicle dynamics, MS occurs in a low frequency of vertical oscillation, fore-and-aft oscillation, and lateral oscillation environments (Donohew & Griffin, 2009; Joseph & Griffin, 2007). On the other hand, pure roll oscillation does not trigger MS. Vertical oscillation causes MS, particularly in a sea voyage, while the fore-and-aft and lateral oscillations are responsible for MS when traveling on the road (Donohew & Griffin, 2004). Turner and Griffin (1999b) stated that the MS factor was the low frequency of lateral oscillation caused by the steering. The frequency was between 0.1Hz until 0.5Hz. The same author proved the correlation between lateral acceleration and MS level. The lateral acceleration, which resulted from the driver's turning method, is the main cause of MS. Therefore, it can be concluded that a bigger lateral acceleration will lead to a higher level of MS.

Figure 2 summarizes the MS factors in terms of occupant's behavior and vehicle's dynamic behavior. In terms of occupant's behavior, this study found that the head tilt movement towards lateral acceleration direction is the simplest and most straightforward reason for the MS occurrence, which is easy to understand. This is related to one of the MS factors in the vehicle dynamics perspective studied by Turner and Griffin (1999b). As per the earlier discussion, the authors proved that the high lateral acceleration from excessive wheel turning is the primary cause of MS. Combining the two factors of MS occurrence, that is, the occupant's and the vehicle's dynamic perspectives, it can be concluded that the turning of the wheel, lateral acceleration, head tilt movement, and MS level are intercorrelated. An excessive turning of the wheel will produce a higher lateral acceleration, causing a larger head roll angle towards the lateral acceleration direction. Hence, increasing the level of MS.

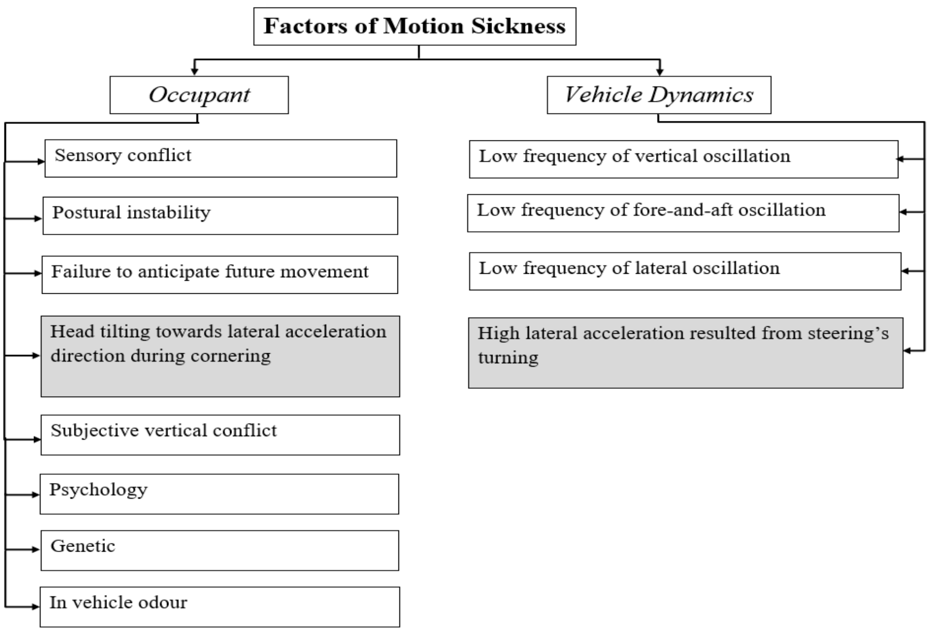

Figure 2: Factors of MS

3.2 MS Quantifying Methods

The questionnaire methods have been used by numerous studies to scale MS. One of the earliest types of the questionnaire is Pensacola Motion Sickness Questionnaire (MSQ) (Kellogg et al., 1965). In the MSQ evaluation, participants rate the presence of 20 to 30 MS symptoms based on a scale ranging from no symptom to emesis. In 1993, Kennedy et al. (1993) developed the Simulator Sickness Questionnaire (SSQ), which is intended to scale the simulator sickness; however, it has been used more generally for all types of MS. SSQ usage examples can be found in Smyth et al. (2018) and Treleaven et al. (2015). Over time, more simplified rating systems were developed and have been widely used in various experiments, such as the Motion Sickness Susceptibility Questionnaire (MSSQ), Motion Sickness Assessment Questionnaire (MSAQ), and Misery Scale (MISC) (Karjanto et al., 2018; Kuiper et al., 2018; Md. Yusof et al., 2017). However, the questionnaires' major drawback is the inability to administer data collection during the running motion stimulus because the occupants might be distracted (Keshavarz & Hecht, 2011). Also, a lengthy questionnaire will take more time to assess the participants' MS level.

MS can also be quantified using a mathematical expression. Motion Sickness Dose Value (MSDV) is an approach that can objectify MS rating or known as illness rating (IR) (Aykent et al., 2014). The equation of MSDV was introduced as the square root of the integral of squared frequency weighted acceleration over time (Wiederkehr & Altpeter, 2013). IR is 1/50 of the MSDV value. The scale of IR ranges from 0 to 3. This evaluation method is best suited for the MS prediction, of which the dominant stimuli is vertical acceleration (Lewkowicz, 2017).

Motion Sickness Incidence (MSI) is commonly used for assessing the possible occurrence of the sickness (Cepowski, 2015). MSI is defined as the percentage of people who would become ill when exposed to certain motion characteristics in a given time interval (Misra, 2015). In 1998, Bosetal [110] introduced a mathematical model to calculate the MSI based on the SVC theory. Later, Kamiji et al. (2007) expanded the model to a six-degree-of-freedom (6-DOF) motion in three-dimensional (3D) space motion. They include the semicircular canal and the canal-otolith interaction to allow the model application to analyze head tilt motion. Later, Wada et al. (2010) proposed a revised version of the 6-DOF SVC model based on the research by Kamiji et al. (2007). The model can predict MSI using the accelerations' information of the vehicle and the orientation of the individual head rotation. Wada et al. (2018, 2013, 2012) demonstrated lateral acceleration and head roll angle to calculate MSI. The same authors also successfully proved the correlation between those two variables. Meanwhile, Green (2016) classified the 6-DOF SVC model as a contemporary MS model.

Using sensors is another alternative method to quantify MS. Rapid advances in neuroimaging technology enable the device, such as electroencephalography (EEG), to be part of the MS evaluation system. EEG estimates MS based on the responses from the brain area (Lin et al., 2013). The capability of EEG to detect MS in an early stage is beneficial in preventing the occurrence of uncomfortable symptoms (Ko et al., 2011). EEG could detect one's MS, even if the MS level is mild (Lin et al., 2012). MS can also be evaluated by electromyography (EMG). EMG evaluates MS by assessing the abdominal and back muscles activities while in motion (Shafeie et al., 2013). EMG application is suitable in MS studies related to postural behavior. Other examples of devices that could measure MS are heart rate variability (HRV) and electrogastrogram (EGG) monitoring sensors (Zhang et al., 2015). They are useful for assessing cardiac sympathovagal interactions and gastric motility.

Based on the above arguments, it can be concluded that a questionnaire is a widely used method. It is also cost-effective because it does not need any device. However, since it cannot be performed during the running motion stimulus, it will take time to assess the individual MS susceptibility. Contrary to the questionnaire, using a mathematical equation to find MSDV is less time-consuming as it is doable without the need to cease driving. It is also easy to determine someone's MS level because the IR scale that can be calculated based on the MSDV value is fixed. Moreover, it is expected that the usage of the 6-DOF SVC model will be widely used by MS researchers in the future, especially for those who study the relation of vehicle motion and the human factor. Meanwhile, evaluating MS is much easier using sensors. MS can be evaluated just by monitoring the signal or response from a person's body part. However, it is impractical to attach sensors to the vehicle occupants in real-time. Table 1 shows the summary of the MS quantifying methods.

Table 1: Summary of the MS quantifying methods

Method	Example	Description	Comment
Questionnaire	MSQ, SSQ, MSSQ, MSAQ, MISC	Participants rate their illness in scale	1. Widely used. 2. Cost-effective. 3. Take time to assess the individual MS susceptibility because cannot administer data collection during running motion stimulus.
Mathematical equation	MSDV	Determine MS using formula	1. Less time-consuming. 2. Easy to determine MS level because the formula is fixed.
Mathematical model	1-DOF SVC, 6-DOF SVC	Calculate MSI in 1-DOF (vertical) and 6-DOF	1. Have potential to become a widely used method by MS researchers, especially for those who study the relation of vehicle motion and human factor.
Sensor	EEG, EMG, HRV, EGG	Monitor the signal or response from a person's body part	1. Easy to evaluate the MS. 2. Impractical to attach devices on the participants in real situation.

3.3 MS Mitigation Strategies

The development of measures for reducing and avoiding the severity of MS is expected to become an important and relevant issue in automotive research to ensure public acceptance of automated vehicles. Md. Yusof et al. (2017) introduced a haptic feedback device attached to the passenger's forearms. This device provides information about the direction of the vehicle, either right or left, to the passengers so that they will be aware of the situation.

Wiederkehr and Altpeter (2013) stated that the increase in lateral acceleration would also increase the MS. In other words, MS can be minimized if lateral acceleration is reduced. In conventional vehicles, drivers can enhance their driving skills through practice and experience. However, for the autonomous vehicle, the application of an MS mitigation system is necessary to avoid excessive turns; hence, preventing the production of high lateral acceleration. One of the methods to achieve smooth cornering is by integrating the vehicle lateral control system with the longitudinal control system. In general, longitudinal control involved the acceleration and the deceleration of the vehicle system or the speed control system. For example, Wada (2016) proposed a velocity profile based on expert drivers' profiles for the autonomous vehicle to be used in curve driving to mitigate MS.

Elbanhawi et al. (2015a) suggested a smooth lateral control strategy that could be one of the MS solutions. The authors added that modifications of the vehicle interior design are required to improve passengers' views and reduce lateral acceleration. The reduction of lateral acceleration can be achieved by integrating the path tracking system with a continuous curvature path planning algorithm. The same authors proved that the combination of a pure pursuit controller and continuous path planner could reduce lateral acceleration; hence, improving the passengers' level of comfort (Elbanhawi et al., 2015b).

Based on the correlation between head tilting movements and lateral acceleration direction effect on MS. Konno et al. (2011) and Fujisawa et al. (2012) developed a posture control device to minimize passengers' MS by inducing the passengers' head movement towards the drivers. They proved that by controlling the changes in passengers' head tilt movement against the lateral acceleration direction, the MS effect would decrease. Although it was tested in a conventional vehicle, the device and the concept of reducing passengers' head tilt towards lateral acceleration direction can be applied in an autonomous vehicle.

Studies by Konno et al. (2011) and Fujisawa et al. (2012) suggested that the general idea to overcome the severity of MS in an automated vehicle is to reduce passengers' head tilting movement towards lateral acceleration direction during curve driving. It can be realized by decreasing the lateral acceleration when cornering. More recently, Saruchi et al. (2020a, 2020b, 2020c) implemented the correlation of head tilting movements, lateral acceleration direction, and MS level to propose a novel MS mitigation control strategy in an autonomous vehicle. The author proposed the head roll angle as the new controlled variable in the vehicle's active steering system. However, the effectiveness of the control strategy is not verified in a real autonomous vehicle.

Currently, MS can be minimized by using devices, modification of the interior design, and control system. The application of devices was proven to be useful in reducing MS levels. There is potential to install such devices in an autonomous vehicle in the future. The idea of modifying in-vehicle interior design is expected to be one of the effective ways to minimize MS. On the other hand, the idea of mitigation MS using control system strategy requires more validation tests in a real-time situation. Despite all the existing methods, it is believed that the numbers of MS mitigating strategies are still lacking. Thus, it is encouraged to have more studies on MS mitigation strategies in the future.

4.0 CONCLUSION

The autonomous vehicle performance can be further improved by enhancing its level of comfort. One of the issues that can negatively affect the user's comfort is the occurrence of MS. However, given the existing MS mitigation strategies, it is safe to say that MS's issue has not received enough attention. The solution of MS can enhance the user acceptance of autonomous vehicles. Considering the importance of minimizing MS, it concluded that the number of strategies to lessen MS's severity is still inadequate, which necessitates more attention, particularly from automotive researchers. Therefore, more research on MS issues should be encouraged.

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