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Yunus, Ilhan; Papaioannou, Georgios; Jerrelind, Jenny; Drugge, Lars

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TOPICAL REVIEW

A Review of Vehicle Dynamics and Control Approaches for Mitigating Motion Sickness in Autonomous Vehicles

ILHAN YUNUS[1,2], **GEORGIOS PAPAIOANNOU**[3], **JENNY JERRELIND**[2], **AND LARS DRUGGE**[2]
[1]Volvo Car Corporation, 405 31 Gothenburg, Sweden
[2]Department of Engineering Mechanics, KTH Royal Institute of Technology, 100 44 Stockholm, Sweden
[3]Cognitive Robotics Department, Delft University of Technology, 2628 CD Delft, The Netherlands

Corresponding author: Ilhan Yunus (ilhan.yunus@volvocars.com)

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ABSTRACT This study highlights the challenge of motion sickness (MS) in autonomous vehicles (AVs), providing a comprehensive review of assessing, predicting, and preventing this issue with a special focus on vehicle dynamics and control-based approaches. Unlike previous studies, this review bridges the gap between MS prediction models and vehicle dynamics-based mitigation strategies by presenting an integrated perspective. Effective mitigation requires accurate and reliable prediction. In this context, motion-based prediction approaches, recognised for their practicality, cost-effectiveness, and promising results, are examined in detail with particular focus on ISO-based methods and sensory conflict theory-based models. The importance of identifying MS triggers and validating these models experimentally is also emphasised, alongside recent trends in customised approaches addressing individual variability in MS susceptibility. The study then investigates mitigation strategies centred on vehicle dynamics and control systems, due to their potential for directly controlling motion triggers, calling for tailored and integrated approaches. Furthermore, the critical role of trajectory planning and tracking algorithms in mitigating MS is reviewed, emphasising their potential through optimal control and the incorporation of MS metrics into cost functions. Additionally, integrating trajectory planning with active chassis systems is identified as a promising direction for reducing MS. The study concludes by underscoring the importance of optimised, personalised, integrated and connected vehicle dynamics and control-based methods to effectively mitigate MS in AVs. Finally, a future horizons approach, supported by a vision roadmap, is introduced as a means to address current challenges, define research directions, and ultimately advance the adoption of AVs with minimum MS.

INDEX TERMS Motion sickness, vehicle dynamics, vehicle control, trajectory planning, trajectory tracking, autonomous driving.

I. INTRODUCTION

Autonomous driving is considered one of the major technological developments in the automotive industry and is expected to change future mobility significantly and will help in addressing transport-related problems [1], [2]. Primary motivators for automated transportation are safety, environmental impacts, and accessibility (e.g., facilitating travel for the elderly and disabled) [3], [4], [5], [6], [7]. However, many challenges exist in implementing autonomous driving, such as the cost of autonomous vehicle platforms, regulations, legislation, certification, security, privacy, and liability issues [8]. Societal acceptability is one of the most crucial factors in the success of any new technology, which is particularly the case for autonomous driving, where safety, trust, and comfort are among the main factors influencing

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public acceptance [9]. An essential element of passenger comfort in autonomous vehicles (AVs) is not suffering from motion sickness (MS) while engaging in non-driving related tasks (NDRTs), such as reading. The term motion sickness (also known as kinetosis) was proposed by Irwin [10] in the late 1800s and is characterised by symptoms such as dizziness, nausea, and vomiting caused by motion. Even though the term is not very precise, it is widely accepted and provides a general collective term for syndromes such as seasickness, train sickness, car sickness and air sickness [11]. Motion sickness is a complex problem that is not fully understood, and the susceptibility to motion sickness varies at an individual level. For instance, gender and age are two of the factors influencing individual susceptibility in the general population, with some findings suggesting that younger individuals and females are more sensitive [12], [13], [14].

In ordinary vehicles, drivers rarely experience motion sickness, whereas passengers are more prone to it [15]. In AVs, shifting from being a driver to a passenger reduces motion predictability and increases MS susceptibility [16], [17]. Moreover, passengers are expected to engage in activities during rides to better use commute time, a major reason for AV adoption [18], [19], [20], [21], [22]. However, engaging in NDRTs, like watching screens [23] or facing rearward [24], further raises MS risk. Figure 1 outlines some of the potential factors for increased risk of motion sickness in AVs. Research indicates that AVs are likely to heighten MS incidence and severity, making it a critical issue [25], [26], [27], [28], [29], and that MS impacts the acceptance of AVs by limiting the effective use of travel time [30]. Therefore, addressing motion comfort, with emphasis on MS, is crucial for the success of AVs and user satisfaction.

Taking into account motion sickness in the vehicle development process requires finding reliable ways to detect, predict and evaluate MS. However, objectively determining and monitoring MS poses challenges since it includes single or multiple combinations of different signs and symptoms (i.e., drowsiness, dizziness, eye strain, restlessness, repeated yawning, stomach awareness, nausea, pallor, sweating, headache, disorientation and vomiting) depending on how severe it is [31], [32], [33]. Koohestani et al. [32] explored MS symptoms and physiological behaviours, and compared various methods for measuring MS levels based on physiological parameters. Techniques like Electroencephalography (EEG), Galvanic Skin Response (GSR), and Heart Rate (HR) monitoring were investigated and it was concluded that there may not be a strict correlation between MS and physiological parameters. However, it has been shown that mathematical modelling and data analysis can be used to detect MS using physiological measures [34], [35]. Moreover, combining physiological measures can help in detecting MS, particularly when advanced techniques like machine learning are used [36], [37]. Instead of physiological based approaches, several researchers have also focused on developing different motion based models to predict MS [38],

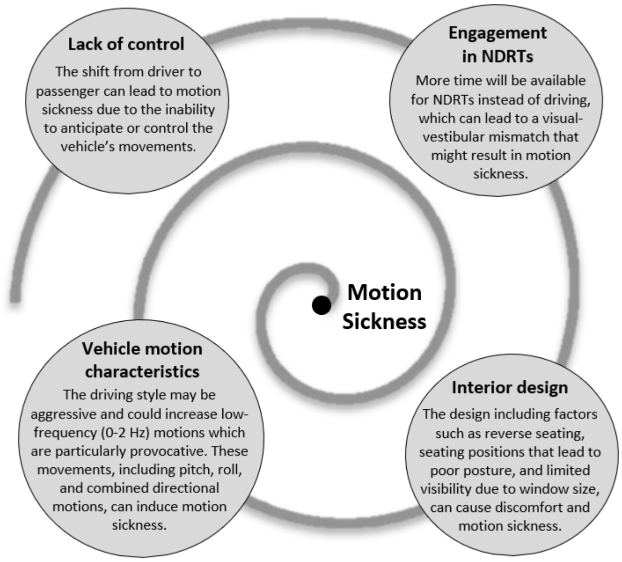

FIGURE 1. Some potential factors that can contribute to increased risk of MS in autonomous vehicles.

[39], [40], which have been investigated and validated by experiments.

There are various hypotheses and theories regarding the mechanisms of motion sickness, which have been reviewed and discussed in [41] and [42]. Evidence shows that the vestibular system plays a central role in MS, and vestibular-induced MS was reviewed by Bertolini and Straumann [31] explaining the sensory signals involved and placing them in the context of current MS theories. According to one of the most accepted theories, the sensory conflict theory [43], [44], [45] (revised version called neural mismatch theory [46]), motion sickness results from a conflict between the current sensory signals related to self-movement and the expected signals based on previous experiences. Therefore, reducing the conflict signal can help alleviate the severity of motion sickness. Such passenger focused mitigation methods involve rearranging and/or presenting additional sensory input to passengers (e.g. visual, auditory and vibrotactile cues), providing neural stimulation to reduce the conflict and decrease MS symptoms. The designed anticipation systems related to upcoming vehicle motion act as modulating factors that are able to regulate MS and can be used to design mitigation strategies [17]. Several test studies have examined anticipatory systems as a means of mitigating MS, including vibrotactile cues [47], [48], flashing LED lights [49] as visual cues, and auditory cues [50], [51]. Different countermeasures to motion sickness have been developed over the years, exhibiting varying levels of success in mitigating MS. Medications [33], [52] can be effective but may have negative side effects such as drowsiness. Non-pharmacological countermeasures also exist, such as training exercises [33], breathing control [52], relief bands for acupressure [33] and active head tilting [53]. Sleeping or remaining awake with the eyes closed [27] can also be useful in reducing MS severity. Although these behavioural methods do not suffer from the side effects of pharmacological countermeasures, they are time-consuming and/or may not be effective enough. Therefore, more reliable solutions are needed to be implemented in the design process of AVs. A comprehensive review was conducted in [52], covering various approaches to mitigate MS in autonomous driving, exploring topics such as vehicle design, better viewing and seating options, head tilting, music, odour, visual and audio cues. Diels and Bos [28] and Iskander et al. [29] stated that improved forward views, active seat adjustment, real-time interior adaptation, including an active infotainment system and using adaptive climate control can help to mitigate motion sickness. The potential use of virtual reality (VR) was also mentioned. Possible interior design solutions were further discussed in [28] and [54], including optimised passenger views [26], seating orientation (rear-or-front-facing) [24] and reclined seating positions [55]. These studies have focused on ergonomics rather than vehicle dynamics, offering a reduction in MS without directly addressing the vehicle's motion, which is one of the primary causes of MS.

One of the most significant factors influencing motion sickness is low frequency linear motions, which is particularly important for vehicle transportation [31]. Driving style and road conditions affect horizontal motions and influence MS [56], [57], which are crucial considerations for the design of AVs. Existing MS evaluation methods (e.g., ISO 2631 [58]) primarily consider vertical (z) accelerations, underlining the need for improved models [17]. As vehicle motion is the basis for MS, optimising vehicle dynamics, for example by using active chassis control systems that regulate vehicle body motion, offers various possibilities for enhancing the comfort of AV platforms and can therefore help reduce MS symptoms [17], [59]. A brief review of MS reduction methods, including examples of vehicle dynamics based strategies that can be used to minimise MS are presented in [60], without providing details on how these systems would be developed considering MS.

Several studies have emphasised the importance of defining metrics and new design requirements for autonomous vehicles in order to ensure a comfortable driving style [61], [62]. In this context, path planning has emerged as a potential solution for enhancing passenger comfort in autonomous driving [63], [64], as developing a smooth lateral control system can reduce lateral acceleration, thereby improving comfort and mitigating motion sickness. Additionally, trajectory planning [65], [66] and tracking [67] have been considered as promising solutions for addressing MS in autonomous driving. However, one issue that might arise is that resulting excessive velocity reductions, which a trajectory planner might impose, could substantially affect users' acceptance and satisfaction as journey times might increase considerably [68]. Therefore, additional approaches to enhancing comfort and mitigating motion sickness should be considered that would not affect the journey time. Such

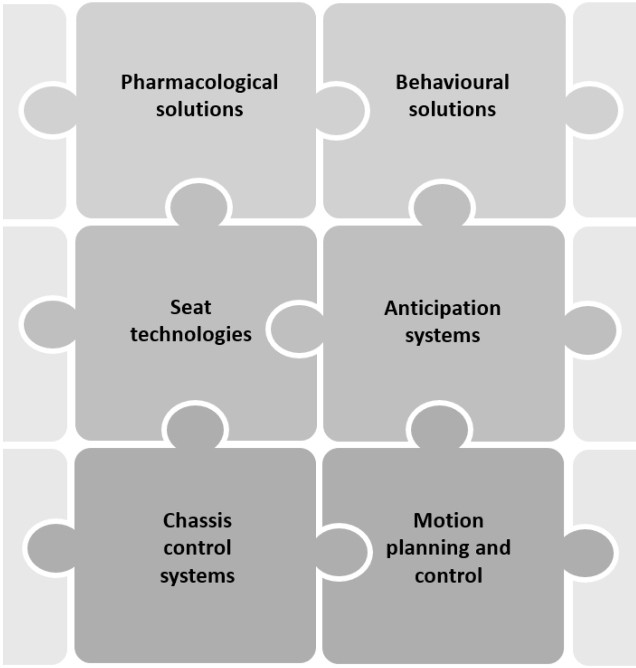

FIGURE 2. Examples of motion sickness mitigation methods.

approaches could be vehicle dynamics oriented solutions, for example active suspension [69], [70], seat suspension designs [71] and other chassis control systems like torque vectoring, rear-wheel steering and active anti-roll bars [59].

This introduction outlines several established mitigation approaches in the literature for minimising the severity of motion sickness. Figure 2 illustrates examples of methods for mitigating MS, while Table 1 summarises these methods and their potential benefits in reducing MS. Existing review papers such as [72], [73], [74], and [75] provide limited focus on vehicle dynamics based solutions and their potential integration into autonomous vehicle systems, including trajectory planning and control methods for mitigating MS. This study aims to fill this gap by reviewing existing approaches and proposing potential solutions within vehicle dynamics and control to address motion sickness in AVs. Additionally, existing studies predominantly focus on ergonomics (e.g., seating adjustments, visual displays) or attempt to reduce MS by tuning standalone vehicle control systems, rather than adopting a combined approach. This study emphasises the importance of a combined strategy, incorporating the development of vehicle dynamics based mitigation methods and a design process focused on reducing MS. Furthermore, by integrating motion sickness prediction models with vehicle dynamics-based mitigation methods, this review brings together two traditionally separate research areas within a unified framework, offering new insights into data-driven, real-time, personalised, adaptive, and optimised approaches for MS mitigation. In addition, the study analyses the existing testing methods and standards, notes their current limitations, and introduces the need for multi-directional and

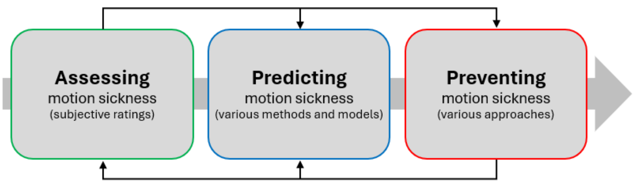

FIGURE 3. Flowchart of motion sickness management.

real-world testing to more effectively design motion sickness mitigation strategies. Figure 3 illustrates the flowchart of the main steps involved in managing motion sickness: assessment using questionnaires and subjective/self-ratings (reviewed in [59], [74], and [75]), prediction with models and methods, and prevention through various approaches. Adopting an iterative and repetitive process can enhance the effectiveness of MS mitigation. A more detailed overview of MS estimation and assessment, as well as mitigation strategies in AVs is shown graphically in Figure 4.

The structure of this paper is as follows: Section II provides a summary of motion based motion sickness prediction methods and models, Section III reviews active chassis systems and control strategies, and Section IV surveys trajectory planning and tracking methods, all with a particular focus on motion sickness, including how these systems can be developed, as well as their potential implementation and validation through testing. Section V outlines future research directions and a roadmap for mitigating motion sickness using vehicle dynamics based methods in AVs, and finally Section VI presents discussions and conclusions.

II. MOTION BASED MOTION SICKNESS PREDICTION METHODS AND MODELS

To enhance the understanding of how specific motion characteristics contribute to motion sickness and to develop effective mitigation strategies, prediction methods and models for motion sickness in moving vehicles are needed. In the literature, both empirical and theoretical approaches have been employed for modelling motion sickness. Various motion based MS models used for objective assessment are summarised in [76] including their strengths and weaknesses. Such motion sickness models can also be used as tools during the development of vehicle dynamics and control based solutions to mitigate MS and can be integrated into the development process of autonomous vehicles, providing valuable insights for assessing various design options. In this study, the focus is on motion sickness models that utilise physical motion measures as inputs (e.g., acceleration and exposure time) due to their practical applicability and potential for integration into vehicle dynamics based mitigation systems. This section provides an overview of the existing literature concerning MS prediction methods and models that identify the relationship between motion characteristics and MS, with a particular focus on ISO 2631-based and MS mechanism theory-based models. Furthermore, their advantages and limitations are discussed, offering insights into potential directions for future improvements. Figure 5 summarises methods and models for predicting MS, including relevant literature, as well as notes about their features and challenges.

A. ISO 2631-BASED METHODS

Researchers use laboratory motion simulators to provoke, assess and evaluate participants' subjective responses by employing pre-specified motion stimuli in controlled conditions. These assessment tests aim to identify the presence of motion sickness, its triggers, and to evaluate its severity level. Experimental studies show that low-frequency vertical motions, particularly around the 0.2 Hz frequency range, are a significant trigger of motion sickness [58], [77], [78], [79]. One of the experimentally developed empirical methods, which only considers the vertical motion as proposed in ISO 2631 [58] and in [77], determines a frequency weighting filter describing the human motion sickness sensitivity to vertical accelerations. This determination is used to calculate a widely used metric for assessing MS known as the Motion Sickness Dose Value (MSDV) [58]. However, other directions of motion can also significantly affect motion sickness susceptibility. Some people might be more sensitive to certain directions or their combinations of motion than others, for example, longitudinal (forward-backward) and lateral (side-to-side) motions may induce a stronger sense of MS compared to vertical motions. Therefore, additional weighting filters for both horizontal and rotational vibrations have been developed to enhance the precision of predictions. Griffin and Mills [80] examined the design of a longitudinal (x) acceleration weighting filter and Donohew and Griffin [81] studied a weighting filter for lateral (y) acceleration, while Howarth and Griffin [82] investigated a rotational vibration weighting filter, based on their own experimental studies. Roll and pitch motions are not highly provocative on their own [83], [84], [85]; however, when combined with motions like lateral acceleration, they can intensify motion sickness, although this increase is not always linear [83], [84]. The effects of roll and lateral acceleration can be reduced by tilting the head, aligning the body with the gravito-inertial acceleration (GIA) vector, thereby minimising sensed lateral acceleration and mitigating motion sickness [86]. Some studies [87], [88], [89] have proposed that by multiplying each filtered acceleration component by a specific factor and then adding them together, the overall MSDV can be calculated for motion sickness estimation, which is similar to the calculation of the vibration total value defined in ISO 2631. Their approach still needs to be further investigated to define possible non-linear effects of the combined motions on MS. Another limitation is that ISO 2631 proposes a cumulative mathematical formulation based on filtered acceleration to calculate the MSDV for predicting motion sickness. However, since the value increases monotonically as long as the motion continues, it may not accurately represent the severity of motion

TABLE 1. Examples of motion sickness mitigation methods and their potential benefits.

Category	Mitigation method	Short description	Potential benefits for MS mitigation
Pharmacological solutions	Medications and supplements [33], [52]	Use of medications and supplements (e.g., antihistamines) to counteract MS symptoms.	Provides rapid symptom relief; ideal for short-term use and acute situations.
Behavioural solutions	Training exercises [33]	Exercises that help improve motion adaptation, reducing sensitivity to MS.	Provides long-term relief; no pharmacological related side effects.
	Active head tilting [53]	Aligning head movements with vehicle motion to minimise sensory mismatch.	Improves sensory alignment; helps anticipate motion, which can help prevent MS.
	Behavioural interventions [52]	Techniques such as focusing on the horizon and/or controlled breathing to relieve symptoms.	Easy to practice, natural symptom relief without side effects, but effectiveness can vary and can limit engagement in NDRTs.
Anticipation systems	Tactile, visual and auditory cues [47], [48] [49], [50]	Providing tactile, visual, and auditory cues about the vehicle's movements to inform passengers of upcoming motions.	Reduces sensory conflict and improves alignment, potentially lowering MS, but may only offer limited relief.
	Visual technologies [29]	Visual display adjustments, Virtual and Augmented Reality (VR/AR) Systems.	Reduces sensory mismatch by aligning vision with actual motion, which can help reduce MS, but if poorly designed, it can cause disorientation or worsen symptoms.
Seat technologies	Adaptive seating [55]	Seats that adjust position, orientation, and posture to help maintain comfort.	Can be designed to reduce MS symptoms, although effectiveness may vary and might be limited for severe cases.
	Seat suspensions (Section III)	Manage the motion of the seat.	Adjust seat motion to mitigate MS; can be costly to implement.
Chassis control systems (Section III)	Active suspension systems	Adjusts vehicle suspension to manage body movements and reduce the impact of road irregularities.	Addresses roll, pitch, and vertical motion to mitigate MS; can be costly to implement and maintain, and their effectiveness may vary depending on the quality of the actuators.
	Active anti-roll bars	Utilises active anti-roll bars to reduce body roll during cornering.	Enhances vehicle stability; reduces body roll, which may reduce MS.
	Torque vectoring	Distributes torque to improve handling, stability, and comfort.	For example, braking or acceleration torque distribution can reduce pitch motion, improving comfort & potentially reducing MS.
	Rear-wheel steering	Adjusts the rear wheels' angles to enhance stability, manoeuvrability and comfort.	Affects lateral motion, potentially reducing MS.
	Integrated chassis control	Coordinates multiple chassis control systems to optimise overall vehicle dynamics.	Can reduce MS by managing multidimensional motions through coordinated control of chassis systems.
Motion planning and control (Section IV)	Route planning	Planning routes based on selected criteria to reach the final destination.	Can be designed to avoid conditions that may cause MS, such as rough or winding roads. However, its effectiveness depends on route availability and traffic conditions.
	Trajectory planning	Controlling the driving style based on selected criteria.	Reduces motions that can cause MS, furthermore it can be adaptive and individualised.
	Trajectory tracking	Tracks the planned path and speed by optimising ride smoothness and minimising unexpected motions.	Enhances ride quality; reduces MS. Effectiveness may vary depending on tuning, robustness and precision.
	Integrated trajectory planning and chassis control	Combines trajectory planning with chassis control to achieve the desired dynamics, ensuring comprehensive motion control.	Enhances comfort and reduces MS through coordinated vehicle dynamics and control.

sickness over time. Therefore, other important properties of motion sickness prediction include the estimation of how MS develops at a slower rate over time and the estimation of its reduction dynamics when motion exposure stops. Kufver and Förstberg [90] proposed the net dose value method to represent these properties (e.g adaptation implemented as a leakage integrator) and advanced it beyond the existing ISO 2631 standard. In summary, ISO 2631-based methods are valued for their simplicity and ease of implementation, and overcoming their identified limitations is expected to lead to more advanced versions being adopted in the future.

B. SUBJECTIVE VERTICAL CONFLICT (SVC) THEORY BASED MODELS

Sensitivity to motion sickness in different directions could be due to the complex interactions between the vestibular (inner ear balance) system, visual input, and somatosensory signals (e.g. sensations from muscles, joints etc.) that the brain processes to maintain balance and spatial orientation. Evidence also suggests that susceptibility to MS is linked to components of the brain (cerebellar nodulus and uvula) and the vestibular organ [44]. Therefore, modelling the dynamics of the vestibular system and understanding how the interactions between vestibular, somatosensory, and visual

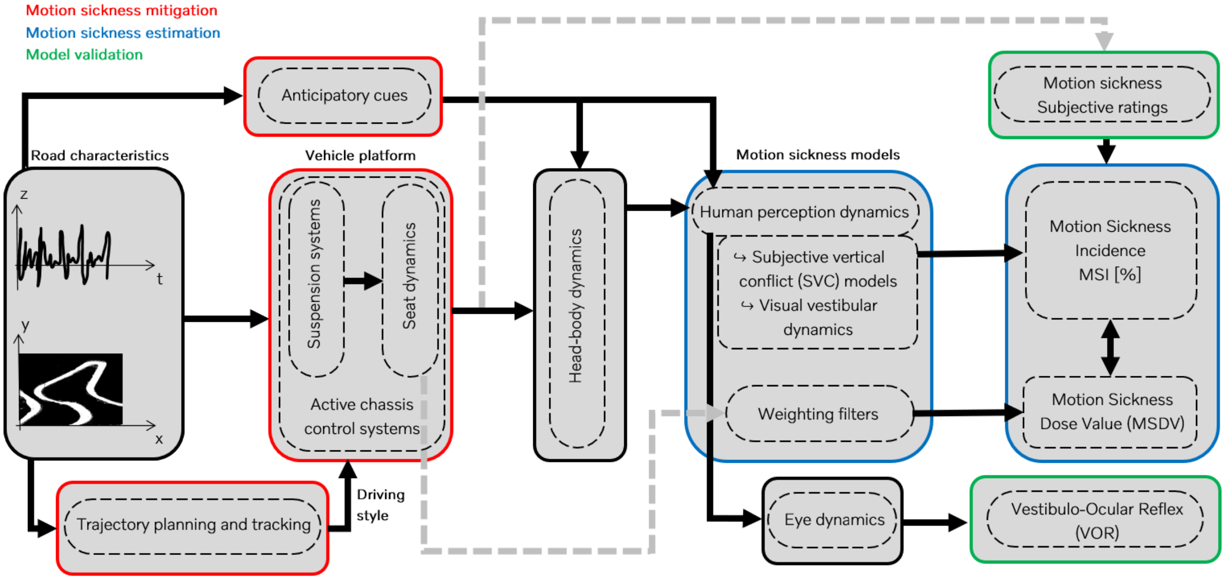

FIGURE 4. An overview of motion sickness prediction, assessment and mitigation strategies in autonomous vehicles.

inputs are processed in the brain are necessary. A promising mathematical approach considering the dynamics of the vestibular organ was developed by Oman [44] for the quantitative prediction of motion sickness. This model is formulated based on the sensory conflict theory proposed in [46]. In a study by Allred and Clark [91], this framework was implemented by integrating the sensory conflict-based observer model with Oman's motion sickness dynamics, demonstrating accurate predictions of MS at the population level using experimental data. Another similar theory, the Subjective Vertical Conflict (SVC) theory [40], hypothesises that motion sickness is specifically linked to a conflict between the subjective vertical, based on past experiences, and the vertical as perceived by the sense organs, e.g., the vestibular system, which consists of otolith organs (OTO) and semicircular canals (SCC). Mathematical models based on this theory are commonly applied and further developed to predict motion sickness. The general modelling structure of the SVC based models is illustrated in Figure 6, and can be expressed mathematically as:

$$\mathrm{MSI}(t) = \Psi\left(\int_0^t \Phi\left(\|\mathbf{v}_s(\tau) - \mathbf{v}_e(\tau)\|\right) d\tau\right) \tag{1}$$

where:

- $\mathbf{v}_s(t)$: Sensed vertical (from sensory input)
- $\mathbf{v}_e(t)$: Expected vertical (from internal model)
- $\|\cdot\|$: Vector norm (e.g., Euclidean)
- $\Phi(\cdot)$: Nonlinear conflict mapping function (e.g., Hill function)
- $\Psi(\cdot)$: Cumulation function mapping conflict over time into motion sickness incidence / severity (e.g., leaky integrator)
- t: Time (exposure duration)
- $\mathrm{MSI}(t)$: Motion sickness incidence / severity at time t

Based on the SVC theory, Bos and Bles [40] introduced an alternative to Oman's model, known as the 1D-SVC model. The model estimates the motion sickness incidence (MSI) value, which represents the vomiting rate due to motion for a specific duration, and the results were validated using laboratory test results obtained by O'Hanlon et al. [79] and McCauley et al. [78]. Experimental studies have found that MSI has a direct linear relationship with MSDV [84]. An advancement of the 1D-SVC model, by including the effects of horizontal accelerations, is referred to as the subjective-vertical–horizontal (SVH) conflict model and was proposed by Khalid et al. [92], [93]. This model was validated using vertical [77], [78] and horizontal [81] motion experiments with humans. In addition, Braccesi and Cianetti [94] extended the 1D-SVC model to include 3D (x, y, and z) translational accelerations. This extended model, known as the 3D-SVC UNIPG model, has also been experimentally validated using results in [78]. Furthermore, a 6 DOF (degrees of freedom) motion model considering both translational and rotational motions was developed by Kamiji et al. [38] and Wada et al. [39]. These SVC based models were also validated with experiments using vertical excitations [78]. Such modelling approaches are increasingly central to current research and is expected to advance further due to its multidimensional capability. It is important to note that current model development mainly relies on single-directional test data [78]. However, since the models are multidirectional, additional experimental studies, including subjective motion sickness ratings across different motion types, are essential for proper validation.

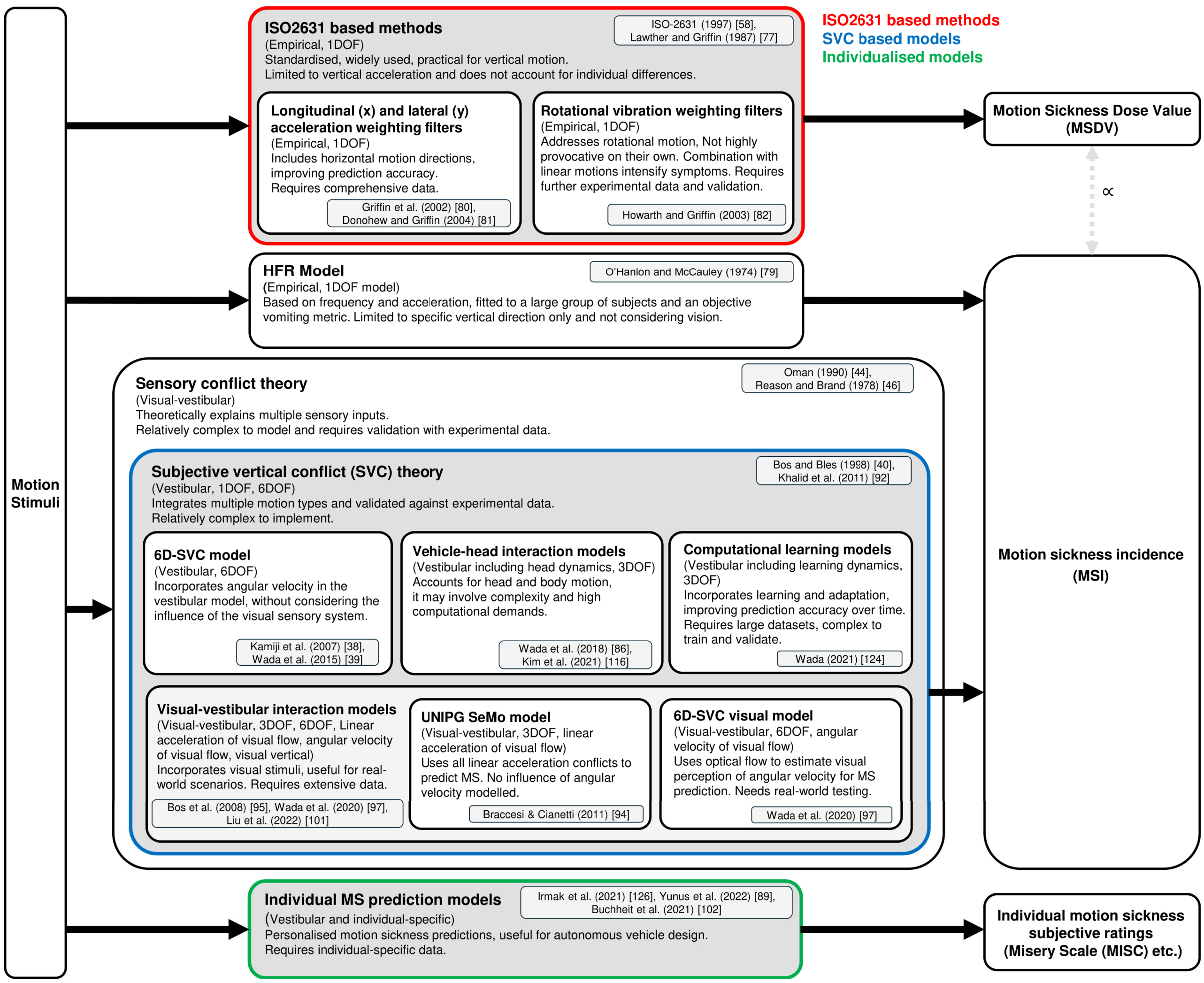

FIGURE 5. Example of motion based methods and models for motion sickness prediction, including representative literature and brief notes.

In the following, recent developments in SVC based models are presented and discussed, along with anticipated future research directions.

1) INTEGRATING VISUAL-VESTIBULAR DYNAMICS

Reading a book while travelling can lead to a conflict between the optic information perceived by the visual system and perceived motion by the vestibular system, increasing susceptibility to motion sickness. Therefore, integrating visual-vestibular interaction into motion sickness modelling is important for accurate MS severity prediction. Bos et al. [95] introduced a motion sickness modelling framework incorporating visual inputs like angular velocities and visual vertical (VV) information. Braccesi et al. developed a 3D model (considering linear motions without angular velocities) with visual-vestibular dynamics (UNIPGSeMo) [96]. Furthermore, Wada et al. extended their previous 6DOF-SVC motion sickness model by considering visual-vestibular interaction and implementing the visual perception of angular velocity (optic flow) [97]. As an example of its application, Tamura et al. [98] experimentally demonstrated that the model proposed by Wada et al. [97], which utilises both vestibular and visual inputs, can be used to create visual cues to reduce motion sickness. In a separate study, Jalgaonkar et al. [99] proposed a visual-vestibular model (VVM) for predicting motion sickness severity using the Telban approach [100] (based on visual perception of angular velocity). This is a human motion perception model that takes into account visually sensed motion, however the proposed model needs to be validated. Instead of using a visual flow approach, Liu et al. [101] expanded upon the 6DOF-SVC model introduced by Kamiji et al. [38] and Wada et al. [39] by integrating the perception of visual verticality (VV), and validated their 6-DOF SVC-VV model through experiments. While this study addresses motion sickness in personal mobility vehicles, it may not fully capture the field of view experienced by autonomous vehicle passengers. Additionally, since the low-speed experiments

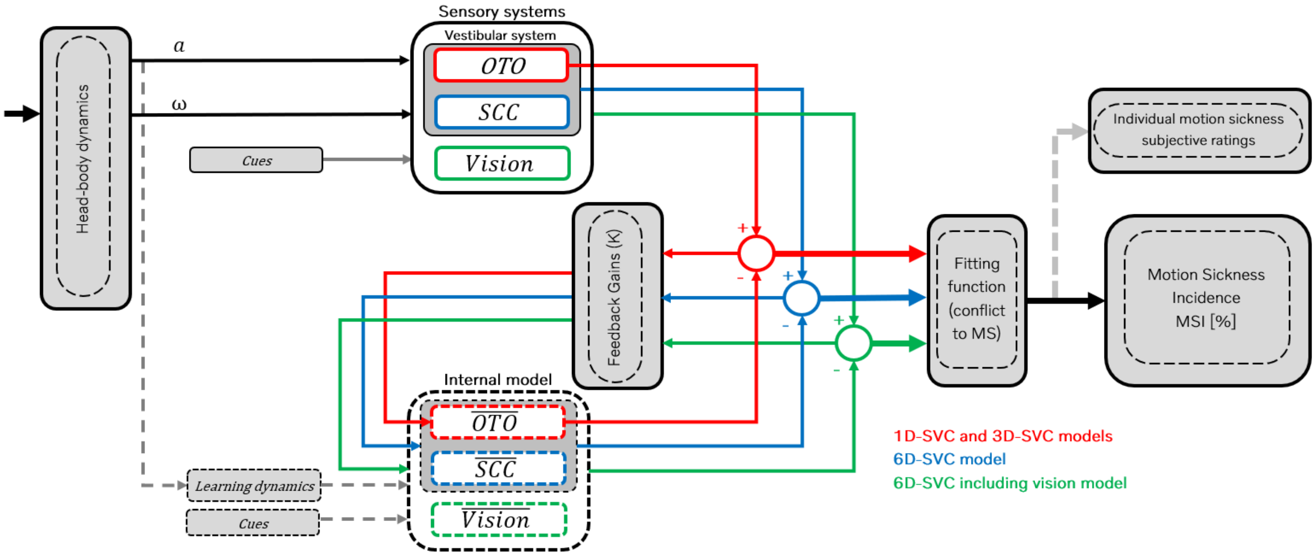

FIGURE 6. The general structure of the SVC based motion sickness models.

may not reflect real-world high speeds and dynamics, further testing is suggested to evaluate the model's applicability to autonomous vehicles under such conditions. These modelling efforts indicate that the integration of visual components into motion sickness models is a rapidly advancing research area. In this context, accurately modelling vestibular–visual interactions and validating the results to enhance MS prediction remains a promising direction for future work.

2) INTEGRATING HEAD-BODY DYNAMICS

Another important aspect involves integrating human-vehicle interaction models into motion sickness modelling to translate vehicle motions into body and head motions and predict motion sickness. The significance of this integration is supported by experimental studies [15], [86] that have demonstrated the impact of head motion on motion sickness. For instance, Wada et al. [86] investigated the effect of the head tilt strategy on motion sickness, measuring head movements of both drivers and passengers during slalom driving. The 6DOF-SVC model was applied to predict the MSI for these two groups, and the predictions fit well with experiments. Various approaches have been explored by researchers [87], [102], [103] to modeling vehicle-head interaction. Another example involves modelling upper body and head kinematics using the inverted spherical double pendulum, as proposed by Cyrén and Johansson [104]. The model was tuned using optimisation methods and validated based on experimental data, showing that the model is able to accurately replicate the body-head kinematics for pre-crash manoeuvre simulations. It demonstrated applicability for safety oriented analyses but also has potential for use in comfort studies. A similar approach using an inverted pendulum was applied by Messiou et al. [105], where the authors employed an predictive-based control algorithm, integrated in a 3D double inverted pendulum model, to predict head-neck dynamics. The model was tuned using experimental data and demonstrated significant accuracy in predicting head-neck dynamics by replicating the intrinsic behavior of the central nervous system (CNS). In a more detailed approach, Happee et al. [106] integrated a 3D multisegment neck model with postural controllers and motion perception models to estimate low-frequency head angles and velocities, demonstrating a good match with experimental data. However, to the best of the authors' knowledge, no existing models fully integrate CNS-driven postural control to accurately predict head motion under multi-directional disturbances. Fard et al. [107] investigated the dynamic response of the head-neck complex to horizontal trunk vibration, focusing on its dynamics during fore-and-aft motion. The study by Duz et al. [108] examined and modelled the head-tilting motion caused by braking and acceleration. Differentiating between driver and passenger head motions, the research proposes two dynamic models—Wiener and Neural Network models—capable of estimating test subjects' head pitch angles and capturing longitudinal acceleration movements, as demonstrated by experiments. Although their real-time implementation has not been tested, the study recommends the Wiener model due to its simplicity estimating passenger's head pitch angle, suggesting its use in comfort-focused studies for autonomous driving. To capture human and vehicle interaction, motion sickness models can be combined with multi-body dynamics models, such as neck-head multi-body models by Salter et al. [87]. In the same direction, Papaioannou et al. [109] coupled human body transfer functions, extracted from experimental data [110], [111], with motion sickness models to explore how different sitting conditions (back-on and back-off) could affect MSI. Extending this work, Papaioannou et al. [112] combined 3D human body transfer functions [110], [111], [113], advanced human body models [114] and efficient human body models [115] to explore how the complexity and the accuracy of these models could affect the prediction of motion sickness levels. Their simulation results showed an underestimation of MSI levels by neglecting the head-body-vehicle interaction, but no experimental validation was conducted. A practical example of application is demonstrated in the study by Kim et al. [116], which involves constructing a model of a vehicle, including the passenger, using bond graph techniques to calculate lateral and roll motion of both the vehicle platform and the passenger's head. Their proposed model aims to contribute to the development of a suspension control system for mitigating motion sickness. These studies highlight that vehicle-head motion interaction is important and needs to be carefully integrated for accurate MS prediction, contributing to the development of more effective mitigation strategies.

3) INTEGRATING HUMAN PERCEPTION MODELS

The importance of accurate human perception models in predicting motion sickness has been emphasised in previous research [117], [118], [119], [120]. Enhancing the accuracy of human perception models can be achieved by validating them through the vestibulo-ocular reflex (VOR), which stabilises vision by utilising vestibular afferent signals during head movement. The relationship between the VOR and MS has been explored in literature studies by [117], [118], [121], and [122]. Sato et al. [118] investigated the correlation between MS and VOR accuracy using the 6DOF-SVC model, which integrated VOR calculations from [117], and human experiments to explore their connection. Their simulations and experimental results confirmed that a decrease in VOR accuracy resulted in more severe MS, particularly with motions around a frequency of 0.2 Hz. Various 6DOF-SVC model structures, such as those with or without integrals in the conflict signal feedback loop, were investigated by Inoue et al. [120] to optimise the model parameters and increase the accuracy of the 6DOF-SVC model in capturing both motion perception and MS. These studies indicate the potential of enhancing human perception models to improve MS prediction accuracy. Hence, a promising direction for future work is the integration and refinement of both human perception and MS models to enable more effective evaluation of proposed mitigation strategies.

The role of anticipation in motion sickness, as another influential factor, has also been studied. Experiments have shown that repeated motion can induce less MS compared to unpredictable movements [123]. Addressing a limitation of MS models' capability to account for the impact of predictability of motion patterns, Wada [124] introduced a computational model, adding a Gaussian process regression model as a feedforward component into a 3DOF-SVC model to be able to describe the impact of learning dynamics on MS. The model shows the ability of predicting experimental results of Kuiper et al. [123] and could be used to design MS mitigation methods that use anticipatory cues. Reuten et al. [125] experimentally tested and discussed the role of cognitive cues for self-motion perception which could be potentially integrated in human perception and MS models. Based on these studies, the development of multisensory integration in motion sickness models is motivated and can be helpful in describing dynamics such as adaptation and learning. Considering and modelling these dynamic properties would be advantageous for accurately predicting MS in traffic conditions such as stop-and-go and repetitive routes. Therefore, their integration should be investigated further, as it offers the possibility of enabling the development of more effective MS mitigation strategies for real-world scenarios.

- *General summary:* Existing research indicates that the development of more comprehensive motion sickness models, which include various considerations such as the visual system, head-body dynamics, and vestibular mechanisms under different assumptions, aims to achieve more accurate predictions. As models become more detailed and remain to be a primary focus of research, experimental studies have lagged behind; limited data is available for validating these models, restricting their applicability in general use. Therefore, further research in the experimental field is essential. While some models benefit from easier implementation due to their reduced computational complexity, in contrast, the development and application of certain mitigation systems may require complex models and related experiments that account for multiple factors, such as 6DOF, the visual system, sensory cues, and learning dynamics.

C. PERSONALISED MOTION SICKNESS MODELS

As mentioned previously, motion sickness can be influenced by various factors, such as gender, age, and prior motion experience, leading to differences between individuals. While many studies have focused on predicting group average subjective ratings, studies such as [89], [102], and [126] have specifically focused on predicting individual MS severity. For instance, Irmak et al. [126] utilised a motion perception model, adapted to predict individual MS by generating lateral acceleration conflict during slalom tests. Yunus et al. [89] employed a 6DOF-SVC model, showing that tuning the model parameters can predict self-ratings during road tests and capture the MS adaptation of test subjects. The developed prediction models of these studies can assess the level of MS for individual passengers and enable the design and fine-tuning of personalised motion sickness mitigation systems, especially targeting autonomous vehicle control algorithms. Future work should focus on integrating these advancements with real-time autonomous vehicle control, potentially leading to adaptive, personalised solutions to mitigate MS in diverse passenger populations.

D. IMPLEMENTATION AND EXPERIMENTAL EVALUATION

The development of motion sickness prediction methods and models, along with their validation, is crucial for designing effective MS mitigation systems for AVs. The review in this study of existing motion based methods and models shows progressive advancements; however, achieving accurate real-time prediction remains critical for implementing effective solutions. The literature includes several examples of real-time MS prediction methods based on physiological signals [127], [128], combinations of motion and physiological data [129], and artificial intelligence techniques reviewed by Rahimzadeh et al. [130] that could be applied to real-time implementations. Salter et al. [129] further proposed integrating motion based and physiological data for real-time prediction and developed a dedicated device for this purpose. Similarly, patented systems, such as the motion detection system by Tartz [131], also leverage motion-based and physiological signals. Another example demonstrates the integration of acceleration data and physiological signals into seat systems to enhance MS prediction [132]. These examples indicate a potential for the growth of real-time models to predict MS in future applications. The performance of proposed MS prediction methods and models can be evaluated using subjective ratings in both laboratory environments (e.g., employing motion simulators) in diverse test scenarios and real-world testing scenarios. Figure 7 illustrates their development process, with experimental evaluations often conducted in both settings to validate model accuracy. Slalom tests, for example, were used by Irmak et al. [126] to evaluate and fine-tune their motion sickness prediction model. Similarly, Henry et al. [133] employed slalom driving tests to study the effects of lateral acceleration and path predictability on MS, focusing on physiological and subjective responses. Test track evaluations under more realistic scenarios were conducted by Yunus et al. [89] to further validate MS prediction methods and models. In other studies, real-world driving scenarios have been used to collect motion and physiological signals along with subjective ratings [22], [134]. These datasets have been valuable for validating and improving motion sickness prediction models. For example, Schulman et al. [135] validated their proposed MS prediction model using data from previous studies conducted by Jones et al. [22].

In conclusion, the development and validation of real-time MS prediction and detection systems through experimental testing and evaluation play a key role in advancing AVs. This area remains an open and important field of future research.

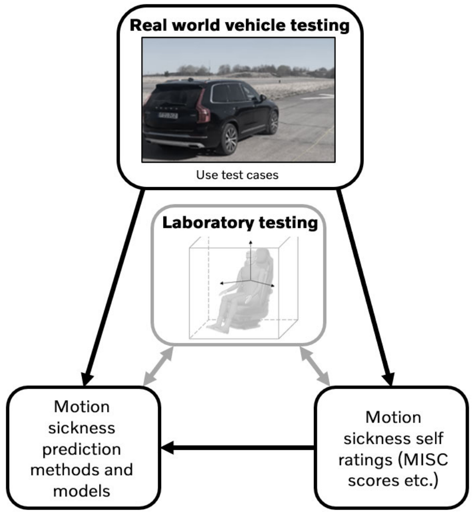

FIGURE 7. Development process of MS prediction methods and models.

III. CHASSIS SYSTEMS AND CONTROL

The motions transmitted to the vehicle occupants are determined by the chassis dynamics and can be further controlled by the use of active chassis systems. The chassis systems play a crucial role in characterising the motion of the vehicle platform and may mitigate motion sickness by compensating for various motions, such as roll, pitch (rotation around the longitudinal and lateral axis respectively) and heave (vertical translation) of the sprung mass, as well as longitudinal and lateral accelerations and yaw motion that occur during vehicle manoeuvres. Road and vehicle dynamics parameters influencing MS are outlined in Table 2, including vehicle dynamics based systems that can be designed to mitigate their effects. Active chassis control systems are expected to be integrated into autonomous vehicle platforms, providing several options to enhance comfort. Strategies such as active suspensions [70], active seats [136], active anti-roll bar systems [137], torque distribution [138] and rear-wheel steering [139], have been shown to contribute to improving motion comfort and potentially reducing MS in AVs, as discussed in [59]. Figure 8 illustrates a generalised control loop block diagram that utilise vehicle dynamics and control based MS mitigation strategies. Various control algorithms, including classical, modern, and data-driven approaches (e.g., Proportional Integral Derivative (PID), Linear Quadratic Regulator (LQR), Model Predictive Control (MPC), H-infinity, Sliding Mode Control (SMC), Fuzzy Logic, Adaptive Control, Neural Networks (NN), and Reinforcement Learning (RL)), are implemented to control these systems. Each has its own advantages and limitations as illustrated in Figure 9, which includes examples of vehicle dynamics control based mitigation studies applying these algorithms. Rather than reviewing all existing control algorithms for active chassis control systems, this section focuses specifically on chassis systems with the potential to mitigate MS and also discusses their effectiveness (summarised in Table 1). In addition, algorithms with significant potential for integration and practical application in mitigating MS are also discussed.

A. SUSPENSION SYSTEMS

The main purpose of the vehicle suspension system is to maintain a smooth ride and good road handling by managing the motions of the passenger cabin (sprung mass) in relation to the wheels (unsprung masses), including heave, roll and pitch of a vehicle [140], [141]. To reduce motion sickness, the setup of different suspension parameters (track width,

TABLE 2. Effect of road and vehicle dynamics factors on motion sickness.

Factors	Details and effect on MS	Example of possible solutions
Road irregularities	Roughness of the road: Amplifies vibrations, can increase MS	**Active suspension** – Reduces effects of road roughness by adjusting suspension. **Route planning** – Strategic selection of route that avoids rough surfaces to reduce MS.
3D road	Inclination and elevation changes: Roll and pitch variations may increase MS	**Trajectory planning** – Creates a comfortable driving style to reduce unwanted vehicle motions and minimise MS. **Active suspension** – Reduces effects of inclination and elevation by adjusting the suspension to help mitigate MS.
Turning frequencies	Number of turns on route: Specific lateral frequencies can trigger MS	**Route planning** – Strategic selection of route that avoids frequent turns to reduce MS. **Chassis control** – Uses active control systems (e.g., rear steering, active anti-roll bars) to reduce lateral motions that can cause MS.
Acceleration / Jerk	Sudden speed changes: May trigger MS due to rapid changes	**Anti-jerk controls** – Smooths out changes in acceleration (jerk) that may lead to MS. **Trajectory tracking** – Accurately follows planned paths to keep motion smooth and predictable, helping to mitigate MS.
Braking dynamics	Deceleration and pitch changes: Sudden stops may cause MS	**Torque vectoring / distribution** – Adjusts the distribution of driving or braking torque across wheels to reduce unwanted motions that may lead to MS.
Turning dynamics	Lateral acceleration, yaw and roll motions: Sharp turns cause head motions that may trigger MS	**Chassis control** – Uses active control systems (e.g., active suspension, rear steering, active anti-roll bars) to reduce lateral motions that can cause MS. **Motion planning** – Planning of future vehicle states to avoid motions that can cause MS.

auxiliary roll moment, spring stiffness, and damper characteristics) was explored in a sensitivity study [142]. Simulations conducted with different setups indicated possibilities to reduce vertical acceleration root mean square (RMS) values at 0.5 Hz, potentially decreasing MSI. However, further investigation is required for more complex manoeuvres. A design challenge for suspension systems is the trade-off between comfort and handling, which needs to be taken into consideration, as discussed in a sensitivity analysis of ride comfort and handling in relation to roll centre height [143]. Ananthakrishnan et al. [144] used a quarter car model to analyse the influence of the vehicle's suspension parameters, specifically the damper coefficient and spring rate, with regard to motion sickness levels in the context of MSDV. Their simulation results demonstrated that tuning spring rates was much more effective in reducing vehicle body accelerations in the vertical direction in the MS frequency area of interest (0-2 Hz [145]) than the dampers. Additionally, Papaioannou et al. [109] conducted an assessment of optimal passive front suspension spring and damper tuning for MS mitigation (in the context of MSI) on various road profiles and sitting conditions. Their simulation results suggest that MS correlates with changes in pitch vibration levels. However, experimental verification is necessary to validate these findings.

Passive suspension systems are constrained by their narrow range of settings, making it challenging to meet diverse requirements. In contrast, active suspension systems provide a much broader range of adjustable settings to effectively satisfy these requirements [141] and also offer greater potential in reducing motion sickness [144], [146]. A novel active air spring suspension system equipped with an adjustable rolling piston was developed in [147] to address the low frequency vertical oscillations that lead to MS. Their hardware-in-the-loop (HiL) tests demonstrated that the proposed system effectively reduces MS and significantly enhances comfort. Research by DiZio et al. [70] experimentally demonstrated that an active suspension system can reduce vibrations in the range 0.8 to 8 Hz, which improves visual performance and therefore helps to alleviate MS while passengers are engaged in reading activities. Although the system has not specifically targeted the low frequencies (0-2 Hz), it is still beneficial for reducing MS. Moreover, Ekchian et al. [69] have presented promising experimental results for MS mitigation algorithms implemented in an active suspension system, reducing reported average MS ratings by over 50% among test subjects. Wadi et al. [148] proposed a roll compensator that can be applied to an adaptive suspension system to minimise MS by adjusting the roll angle to reduce the sensed lateral acceleration. For chosen test scenarios, the method lowered the MSDV and improved passenger comfort. Wu et al. [149] developed active suspension control strategies using different algorithms (LQR, Fuzzy-PID, Change-Fuzzy, ANFIS (Adaptive Neuro-Fuzzy Inference System)) to reduce pitch motion and vertical vibrations. Driving conditions involving acceleration and deceleration cycles, as well as traversal over speed bumps, were simulated. The ANFIS strategy demonstrated the best performance among the tested methods, reducing the pitch motion RMS value by up to 55% and effectively mitigating MS in their simulated cases. However, unlike Wadi et al. [148], Wu et al.'s [149] study neither included frequency-domain analysis nor used motion sickness-specific measures, such as ISO 2631, to directly evaluate the impact of the proposed system on MS. Instead, their focus was on RMS values for pitch motion and vertical vibrations, offering only an indirect assessment of MS reduction. A further advancement by combining active suspension systems with information about the upcoming road profile and future trajectory in an optimisation based controller, so called vertical trajectory planning, has been shown to be successful in reducing low-frequency motions [150], [151]. Their findings demonstrated that their approach can lead to a reduction of up to 14.5% in MS as calculated using the ISO 2631 method. Another approach based on preview information involves using Nonlinear Model Predictive Control (NMPC) for curve

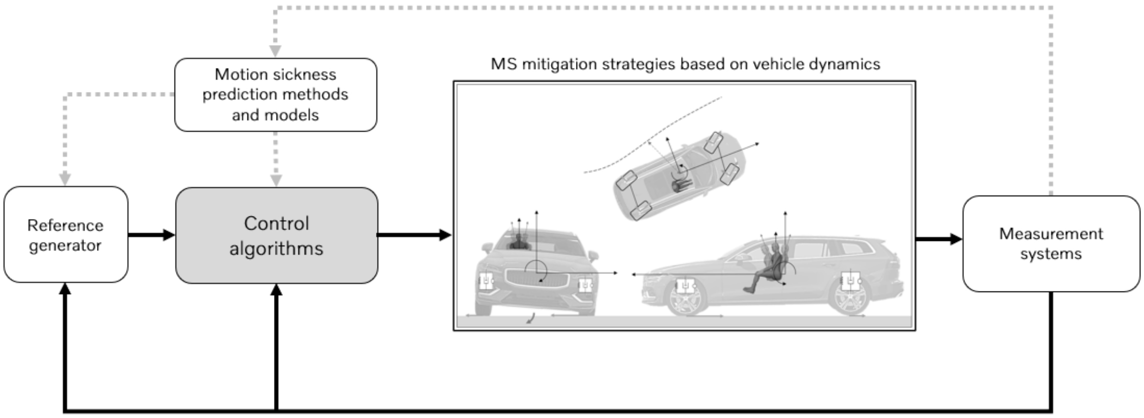

FIGURE 8. An illustration of a generalised control loop block diagram that utilise vehicle dynamics based motion sickness mitigation strategies.

tilting, which employs active suspension [152] to enable a reduction in sensed lateral acceleration and control of roll angle, thereby decreasing MS in selected cases tested through HiL simulations.

While traditional control methods struggle to adapt to varying driving conditions and require precise system modelling, data-driven approaches offer significant advantages. Mozaffari et al. [153] pointed out the potential of learning-based suspension control systems, which can learn and improve over time and adapt to changing conditions. These systems handle uncertainties in road roughness and provide accurate estimates for robust suspension control, enhancing performance and reliability. The adaptive nature of NN allows the system to learn and adjust, providing better performance in dynamic environments. Liu et al. [154] have presented a robust and adaptive control strategy for active suspension systems using NN, effectively addressing challenges posed by nonlinearities and system uncertainties, resulting in improved ride comfort and reduced vertical vibrations. However, real-time implementation may be challenging in automotive systems due to limited processing power, and training NN requires extensive datasets that accurately represent all possible operating conditions, which can be difficult and costly to obtain. Data-driven active suspension control has advanced significantly, particularly with deep reinforcement learning (DRL), a model-free machine learning method known for its strong online self-learning capabilities in intelligent decision-making. DRL can directly learn complex high-dimensional mappings from state to control action without relying on exact mathematical models. Ming et al. [155] and Lee et al. [156] proposed DRL based methods for semi-active suspension control. Ming et al. [155] used an improved Deep Deterministic Policy Gradient (DDPG) algorithm with empirical samples to enhance learning efficiency, while Lee et al. [156] employed Trust Region Policy Optimisation (TRPO) with a state normalisation filter for improved stability and robustness. Both approaches outperformed the classical Skyhook controller in terms of ride comfort in their quarter car simulations. Lin et al. [157] proposed a RL backstepping-based control design for a full vehicle active Macpherson suspension. Their simulations demonstrated improved ride comfort by reducing the RMS of vertical acceleration and pitch and roll angular accelerations compared to passive suspension (improved by around 35%) and conventional backstepping control, particularly in handling random road disturbances. This approach leverages the strengths of both backstepping control and RL to achieve better transient response and robustness. To further enhance data-driven approaches, efforts are focused on improving training methods. For instance, Tan et al. [158] proposed integrating pre-training with PID expert samples, increasing efficiency and accelerating the convergence of the DDPG algorithm for active vehicle suspension systems. Wang et al. [159], [160] enhanced DRL by integrating expert-guided constraints and reward functions, improving active suspension control systems. Their quarter car model simulations showed better performance than DDPG across all analysed frequencies (0-14 Hz) but underperformed compared to MPC in the low-frequency range (below 5 Hz), which is critical for addressing motion sickness. While these studies have not specifically focused on mitigating motion sickness, they offer promising approaches for future research if their limitations are addressed.

The reviewed studies show that various algorithms have been applied in active suspension systems to enhance comfort, each with its own advantages and disadvantages, as previously discussed. Active suspension systems, with their ability to provide multi-directional control (such as managing acceleration, roll and pitch compensation), are expected to play an important role in future advancements. They offer the potential to reduce acceleration magnitudes at targeted frequency ranges and address the complex, multi-directional nature of motion sickness. Future research in this field should focus on real-world experimental validation to ensure effective mitigation of MS across diverse driving conditions.

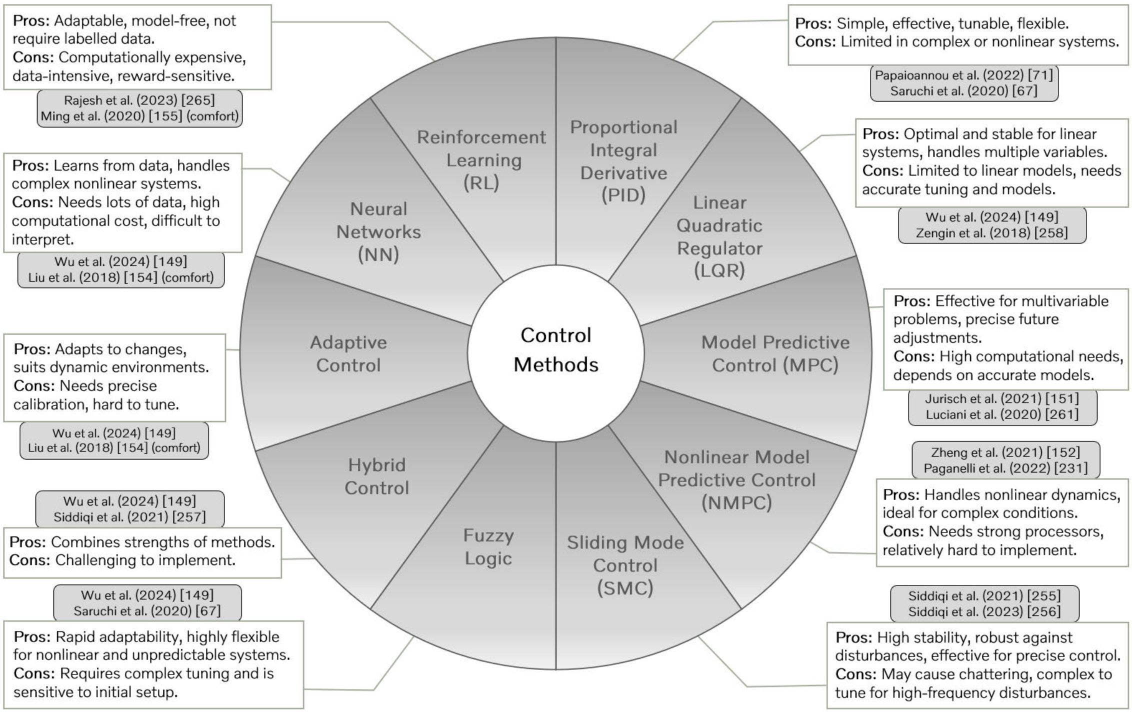

FIGURE 9. An overview of different control algorithms and example studies that utilise vehicle dynamics based motion sickness mitigation strategies.

B. SEAT SYSTEMS

If vehicles are driven on low-quality roads and/or lacks good suspensions, then the seats are exposed to high vibrations, leading to discomfort for the occupants. Therefore, seat suspensions can be used to complement the work of vehicle suspensions. Seat comfort depends on both "static comfort" (e.g. seat stiffness) and "dynamic comfort" (e.g. vibration magnitude) [161]. Recent advances in this field have promoted a new class of seat suspension systems, which are based on embedded negative stiffness elements. Such isolators are able to isolate low-frequency vibrations and have been studied in the literature [71], [162], [163]. At the same time, the advent of metamaterials as means of structural vibration attenuation has shown that isolators composed of periodic finite lattices deliver increased flexibility in terms of design and performance [164], [165]. However, these have not been tested on seat suspensions yet. Another aspect refers to seat designs that can offer multiple degrees of freedom isolation. Apart from the vertical isolation, additional degrees-of-freedom seat suspensions can be employed to further complement the concepts of curve tilting or flat braking, hence enhancing motion comfort and mitigating motion sickness. For instance, experiments have shown that a reclined posture in seating enables MS mitigation in autonomous driving [55]. Kia et al. [166] found that active suspension seats could reduce certain vibrations and discomfort in a simulated vehicle environment but did not significantly reduce MS. Sun et al. [167] proposed a horizontal vibration reduction of a seat suspension using negative changing stiffness magnetorheological elastomer isolators. Although experiments showed that the proposed system can reduce horizontal vibrations between 4-10 Hz, the system has not been tested for frequencies below 4 Hz, which are relevant for addressing MS. A similar model was introduced by Maciejewski et al. [168]. They suggested a horizontal seat suspension that employs pneumatic muscles for the purpose of active vibration control. The novel seat design demonstrated significant improvement in comfort by isolating vibrations in the 1-10 Hz frequency range. The researchers mostly focused on comfort and conducted limited investigations into MS mitigation. Albeit longitudinal vibration control is important and its investigation is crucial, limited work has been conducted on multi-DOF seat designs. Bai et al. [169] designed an integrated semi-active seat suspension for both longitudinal and vertical vibration isolation. Even though this design implies that MS could be mitigated by controlling the longitudinal vibrations, this has not been explicitly studied in the paper. The model in Bai et al. [169] was extended by Papaioannou et al. [136], investigating an integrated active seat suspension for enhancing motion comfort. In addition to the control design, they conducted extended comfort and motion sickness analysis, illustrating a potential improvement of around 10% in reducing MS for the simulated scenarios.

Recent studies show that motion sickness is increasingly being considered in seat suspension designs. Active seat suspensions offer the advantage of enabling multi-directional control and directly managing occupants' motions. Future designs are expected to integrate these systems with other chassis control systems to achieve further enhanced performance and mitigate MS; however, ensuring cost efficiency remains important.

C. TORQUE VECTORING/DISTRIBUTION

In recent decades, electric vehicles have become increasingly popular, largely due to their advantages, such as enhanced energy efficiency [170], [171], [172], [173]. Additionally, their electric motors offer significant design flexibility for integrating vehicle control systems. One of the systems that can be integrated into electric vehicles is torque vectoring, with its capacity to control each wheel's drive/brake torque, enabling customisable handling and comfort based on customer preferences [174], [175], [176]. Sforza et al. [177] conducted a review on how electric vehicles can employ various torque distribution strategies to enhance energy efficiency. In contrast, De Novellis et al. [176] focused more on safety and handling aspects in their review study. However, these reviews demonstrate that there is a limited number of studies currently focusing on comfort and MS. A human-centred torque vectoring control is suggested in [178] as a potential solution to improve ride comfort by reducing frequent acceleration and deceleration. Furthermore, Jaafari and Shirazi [179] conducted simulations showing that vehicles equipped with torque vectoring offer enhanced comfort compared to conventional vehicles. Longitudinal motions affect both comfort and MS; in this context, Tavernini et al. [138] addressed comfort through a MPC based torque distribution algorithm designed to minimise pitch angle by adjusting brake force during braking. Their simulation results demonstrated smooth stops for improved driver comfort without compromising braking distance. However, achieving a zero pitch angle might not always be feasible due to practical vehicle dynamics constraints (e.g suspension geometry, and braking force limitations). In such cases, seat systems could be useful in adding compensatory pitch motion control and aligning the body with the GIA direction to achieve minimum MS. Moreover, reduced acceleration peaks at the driver's head during braking suggest potential MS reduction. An additional method to enhance longitudinal dynamics involves employing anti-jerk controllers, which have been shown to improve comfort [180]. Fukudome [181] analysed longitudinal vehicle body and unsprung mass vibrations using in-wheel motors, demonstrating reductions in longitudinal vibration through calculations and tests, indicating potential comfort improvements. However, they have not analysed the impact on MS mitigation. These comfort oriented studies can be further expanded to explore the potential for mitigating MS, with an emphasis on real-world driving conditions and diverse scenarios.

D. REAR WHEEL STEERING AND ANTI-ROLL BAR SYSTEMS

The lateral dynamics of a vehicle could be improved by integrating a rear-wheel steering system, which, for instance, reduces the turning radius in narrow spaces at low speeds. At higher speeds, the rear wheels align with the front wheels, contributing to lateral movement with reduced yaw motion. In the literature, there are several studies about all/rear wheel steering, as discussed in [182], [183], and [184]. Utbult [139] developed control algorithms and found that rear-wheel steering improves comfort, reduces motion sickness, enhances manoeuvrability at low speeds, and boosts safety through improved yaw stability. The simulation results showed that rear wheel steering reduces MSDV by around 5% for passengers during specific manoeuvres.

Another system that can improve handling, ride comfort, and vehicle performance is the active anti-roll bar system, which achieves this by reducing body roll during cornering, adjusting load transfer between the wheels, and enhancing steering characteristics. The impact of active anti-roll bar systems on the compromise between handling and comfort have been discussed for example in [185], [186], [187], and [188]. The development of a combination of SMC, feedforward, and PI-based control strategies for active anti-roll bars to increase roll damping and reduce the effect of low-frequency road disturbances is presented in [137]. Their simulation results show that active anti-roll bar systems significantly improve both ride and handling performance compared to passive systems. This study shows promising results and could be further developed to mitigate MS. The study by Jurisch et al. [189] found that their simulator experiments on active roll stabilisation and rear-wheel steering systems did not demonstrate a significant effect on reducing MS, which could be due to controllers that were not appropriately tuned. Therefore, further investigation is needed to validate the findings.

While existing studies provide valuable insights, the research on the effects of rear-wheel steering and active anti-roll bar systems on motion sickness remains limited. Given the critical role of lateral motions in inducing MS, future research should place greater emphasis on this area. Experimental validations and more comprehensive testing are needed to confirm the potential of these systems in mitigating MS, while balancing between handling and motion comfort.

- *General* summary: Various chassis control systems can be designed to play a significant role in mitigating MS by influencing specific vehicle motions, as illustrated in Figure 10. Suspension systems can address longitudinal, lateral and vertical motions, with active suspensions demonstrating enhanced abilities over passive systems and showing significant reductions in low-frequency motions, which are critical for MS mitigation. Seat systems complement suspensions by isolating passengers from vibrations, particularly in vertical and horizontal directions. Advances in multi-degree-of-freedom seat suspensions offer enhanced comfort and potential for MS reduction. Although studies in the literature have demonstrated significant benefits in their simulations, further experimental validation is still required. Torque vectoring systems improve longitudinal and lateral dynamics by optimising torque distribution across wheels, reducing sudden accelerations and pitch motions,

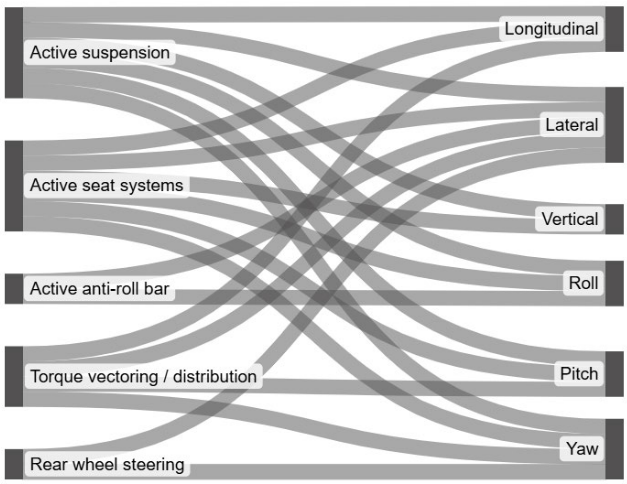

FIGURE 10. An overview of different chassis control systems and the motion directions they influence.

which are factors that may trigger MS. Active anti-roll bar and rear-wheel steering systems control lateral dynamics by reducing body roll and enhancing stability during cornering. While these systems improve comfort and handling with the tuning of control algorithms, their effects on MS are not well established, emphasising the need for further research. To enable the mitigation of MS, the chassis control systems (Figure 10) together with the control algorithms summarised in Figure 9 can be integrated into the general control loop shown in Figure 8. This highlights the importance of appropriately selecting both the implemented chassis systems and the control algorithms as part of the MS mitigation systems. Future research should focus on integrating these systems with predictive algorithms, leveraging road profile and trajectory data to enhance MS mitigation across diverse driving conditions.

E. INTEGRATED CHASSIS CONTROL

By combining various chassis control strategies, integrated chassis control [190] offers extensive possibilities for vehicle control across multiple dimensions, contributing to the enhancement of both safety and comfort. A brief review of integrated chassis control has been given by Vivas-Lopez et al. [191], which points out how researchers combine the different control systems to improve multi-conflicting objectives such as safety, comfort and performance. The progress and future direction of chassis control systems show a shift from standalone systems to multi-actuated integrated chassis control systems designed to handle multiple objectives [190], [191], [192], [193]. This transformation primarily aims to enhance vehicle active safety, a critical concern for both automotive manufacturers and consumers. Consequently, automakers and suppliers prioritise active safety in their design of integrated chassis control systems to meet the demands of consumers and regulatory bodies [192], [193]. The main goal of integrated chassis control systems is to improve safety; however, enhancements in energy efficiency and comfort are often achieved as secondary benefits. In the context of over-actuated integrated chassis control systems for AVs, future trends are expected to focus on enhancing vehicle comfort and addressing MS [194]. Autonomous vehicle platforms could be featured with chassis systems that may be in conflict. One example is the active rear steering system, which helps during turning by adjusting the rear steering angle. Another is the vehicle dynamic control system, which generates a yaw moment using differential braking/traction. Both systems influence how the vehicle turns. These two systems operate differently and affect e.g. acceleration differently, potentially influencing MS. Therefore, control allocation strategies between these systems plays an important role. By adjusting the coordination between these systems, algorithms can customise the vehicle behaviour using for example a multi-objective control allocation method as suggested in [195]. Optimising coordination between these systems enhances vehicle dynamics and could help reduce MS.

Although still relatively few, research and industrial applications show that integrated chassis control systems have substantial potential for effectively mitigating MS. Future research is expected to expand, with a stronger focus on integrating MS mitigation into the design process, ensuring optimal comfort and safety while maintaining an emphasis on energy and cost efficiency. This approach is encouraging, offering a comprehensive vehicle dynamics based solution for addressing MS.

F. IMPLEMENTATION AND EXPERIMENTAL EVALUATION

The implementation of chassis control systems in AVs not only enhances performance and safety, but also offers promising solutions to mitigate motion sickness. There are some industrial examples existing that offer possibilities to minimise MS using chassis control systems. A combined control mechatronics chassis concept has been suggested to help prevent MS [196]. Another example is a four-wheel driving system [197], which integrates electric motor control to minimise pitch and dive during acceleration and braking, potentially helping to mitigate MS. These examples reflect the growing interest in leveraging chassis control technologies to address MS.

Developing active chassis control strategies and algorithms and evaluating them for different test scenarios will contribute to the advancement of future autonomous vehicle platforms. While standardised tests for vehicle active safety evaluation, such as the J-turn and single and double lane changes (NHTSA and ISO 3888), are well-established, comprehensive tests for motion sickness are still lacking. Current ISO 2631 focuses solely on vertical motion and neglect multi-directional motion effects, which should also be considered. As discussed in Section II, enhancements on objective methods for multi-directions (e.g., 6DOF acceleration-based models) exist and can be used to calculate

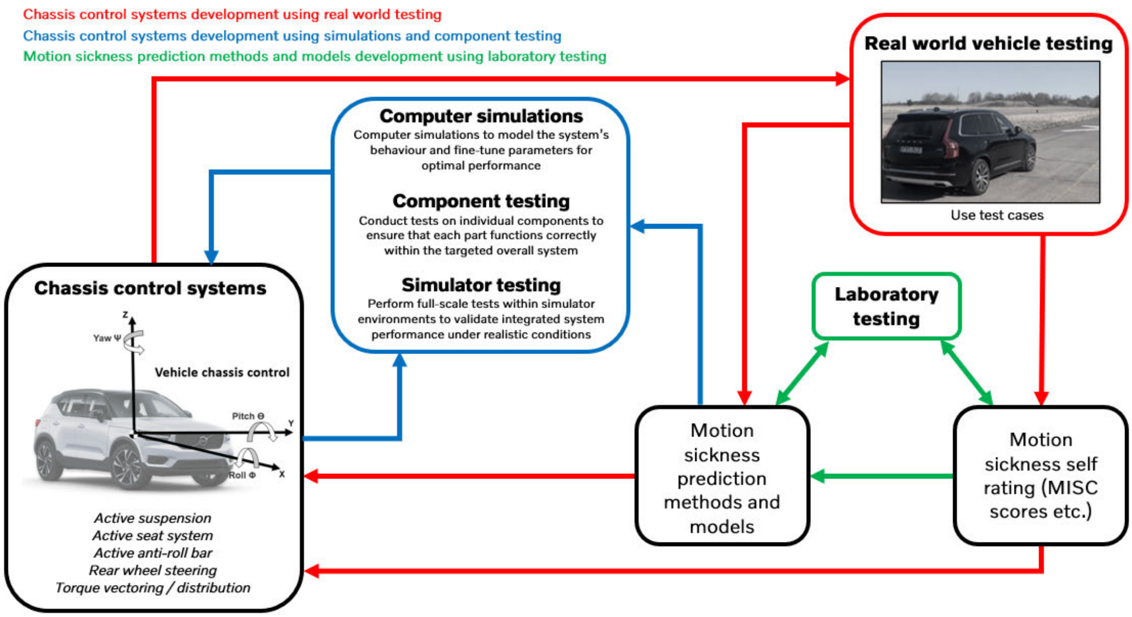

FIGURE 11. Illustration of a proposed integrated approach for how objective and subjective evaluations of motion sickness can be incorporated into the development and tuning processes of chassis control systems to mitigate MS.

MSDV and/or MSI values. The performance of proposed mitigation methods can be evaluated through simulations for their capability of reducing these values. In addition to simulations, researchers often use subjective ratings in both field and laboratory tests, dividing participants into groups with and without applied mitigation methods, and conducting statistical analyses of self-ratings to evaluate the effectiveness of the proposed mitigation methods. In this context, Figure 11 illustrates a proposed integrated approach for how objective and subjective motion sickness evaluations can be effectively incorporated into the development and tuning processes of chassis control systems to mitigate MS.

Most studies, such as [50] and [198], have focused on laboratory tests using single direction motion generation devices (e.g., shakers, linear sleds) to simplify vehicle motions and evaluate their proposed solutions on selected test subjects. This narrow and limited approach, focusing on a single direction of motion in laboratory settings, fails to reflect the multi-directional motions of real-world driving and may not be applicable to its complex and dynamic nature, therefore resulting in incomplete evaluations. To partly overcome this challenge, Saruchi et al. [199] used slalom tests to evaluate their proposed mitigation method for vehicle lateral control, while Hainich et al. [200] and Reuten et al. [201] employed repetitive lane changes. Based on this, slalom and repetitive lane change tests show potential to be standardised for evaluating MS mitigation methods. These specific simple manoeuvre tests are although limited for capturing the full spectrum of motion experiences that contribute to MS. Studies such as [22], [51], and [89] used specifically designed test tracks (closed-loop controlled environments), allowing for consistent conditions to perform repetitive tests involving more complex motions. However, the test tracks used may not fully reflect real-world driving scenarios and could remain limited in scope. In addition, more extensive field tests are needed to validate laboratory findings and ensure that the proposed mitigation methods are effective under real-world conditions.

The evaluation tests need to be of sufficient duration to induce motion sickness, allowing for the analysis of the effects of applied mitigation methods. Additionally, the selected test group must include a sufficient number of test subjects and be carefully chosen (considering test subjects MS susceptibility) to allow for statistical analyses. Otherwise, the effectiveness of the mitigation system may be challenging to analyse, as some participants might drop out early or not develop any MS at all. Furthermore, the subjective nature of self-reported MS symptoms can introduce variability and potential bias into the results. Subjective ratings are influenced by individual differences in perception, which makes it difficult to standardise and compare results across studies. Therefore, researchers should design the evaluation tests to effectively analyse their approach, ensuring that the methodology allows for a clear evaluation of the proposed solutions. Tests to evaluate MS mitigation methods represent an open research area that requires further investigation for standardisation.

IV. MOTION PLANNING AND CONTROL

When vehicles transition from being driven by humans to being autonomous, it becomes essential to further explore motion sickness from the perspective of motion planning and control, considering that the risk of experiencing MS is higher for passengers than for drivers [15]. Furthermore, there is a potential risk that when controlling the motion of autonomous vehicles, it can result in subjectively aggressive driving (rapid high acceleration changes) that may increase the MS severity.

Commonly, motion planning for autonomous driving is divided into several aspects: route planning, finding a path (path planning), searching for the safest manoeuvre (manoeuvre planning), and determining the most feasible trajectory with velocity profile (trajectory planning) [202]. Figure 12 illustrates some of the functional levels for motion planning that can be designed with consideration for motion sickness, showing their interconnected roles in controlling an autonomous vehicle. Autonomous vehicle control follows this flow in a hierarchical manner, and this section is structured accordingly to reflect this logic, from route planning to trajectory planning and tracking. To highlight their importance in achieving optimal results, cost functions are emphasised as the core of each planning and control layer. Redesigning these systems by taking motion sickness into account, while maintaining a balance with performance (travel time), safety, and energy efficiency, is framed as an important direction for future development.

Route planning involves determining a path from point A to point B on a global scale, taking into account multiple factors such as travel distance, time, cost, personal preferences of travelers, etc. [203]. Route planning algorithms aim to select the best route from the available options. The findings by Asua et al. [204] indicate that the route type is the primary cause of passenger discomfort. Their spectrogram analysis showed consistent driving patterns independent of the driver. Driving style influences power magnitude, making it a secondary effecting factor. They concluded that smoother roads lead to more comfortable driving, and a reliable route planning system for autonomous vehicles is crucial to mitigate motion sickness. Additionally, Buchheit et al. [205] proposed a data processing method using spectrograms for route profiling in motion sickness studies that provide an understanding of the provoked acceleration and frequencies which are important MS triggers. The use of this method may benefit real-world implementation of MS mitigation strategies. Furthermore, a patent has been introduced for a system that prevents MS using route planning, which calculates an MS index for different routes and selects the route with the lowest index to minimise the risk of MS [206]. These studies indicate that innovations and new applications in route planning with consideration of MS are expected to grow in the future.

After selecting the route based on preferences, the next step would be trajectory planning and tracking. SAE level 3 and higher-level autonomous vehicle architectures were surveyed by Badue et al. [207] that pointed out that trajectory planning is one of the challenging and critical functional layers for AVs. Autonomous vehicle trajectory planning aims to find a feasible and safe sequence of states of a dynamic system moving from a starting point to a destination point. Meanwhile trajectory tracking focuses on the low-level control of the vehicle to ensure that it accurately follows the planned trajectory by adjusting the vehicle's control inputs (such as steering, throttle and brake) to minimise the error between the planned and the actual trajectory. Therefore, the trajectory planning and control of the vehicle is important to provide a pleasant autonomous driving experience. An overview of trajectory planning and tracking is provided in Table 1, including their descriptions and potential benefits in reducing MS. In this section, trajectory planning and tracking algorithms are reviewed and discussed with regard to their potential use in mitigating MS and the design process that can be applied.

A. TRAJECTORY PLANNING

The importance of developing trajectory planning and tracking algorithms for comfortable driving of autonomous vehicles has been emphasised in previous studies such as Claussmann et al. [208] and Gonzalez et al. [209]. Furthermore, the study by Elbanhawi et al. [63] indicated a research gap in autonomous vehicle path planning for passenger comfort and motion sickness. A comprehensive review of motion planning and control algorithms, including a comparison of the strengths and weaknesses of the methods, is provided by Paden et al. [210]. This section focuses on a review of model-based trajectory planning methods that have the potential to mitigate MS. Figure 14 presents the focus areas of trajectory planning algorithm structures explored and discussed in this section. Table 3 summarises the research on trajectory planning aimed at reducing MS.

Trajectory planning can be formulated as an optimisation problem, aiming to optimise specified criteria through an objective function, with the goal to satisfy user expectations while fulfilling constraints set by chosen road and vehicle limits. For example, Elsner [211] discussed how cost functions can be implemented in trajectory planning algorithms to quantify the comfort level for passengers, whereas other researchers have focused on factors such as energy efficiency [212], [213] and motion sickness [66], [214], [215], [216]. Multi-criteria motion planner alternatives using a sorting algorithm was explored in [217], investigating the optimal control problem (OCP) with performance metrics such as driving style, energy efficiency, vehicle stability, and journey time. Figure 13 illustrates an example how planned trajectories for different cost functions may deviate from the centre of the road. Designing the minimisation of the cost function could be approached as follows:

$$J = \int_{t_0}^{t_f} \Big(w_1 \cdot E(t) + w_2 \cdot M(t) + w_3 \cdot P(t) + \sum_{i=4}^{k} w_i \cdot X_i(t) \Big) \, dt \tag{2}$$

subject to:

vehicle model, actuators and road constraints,

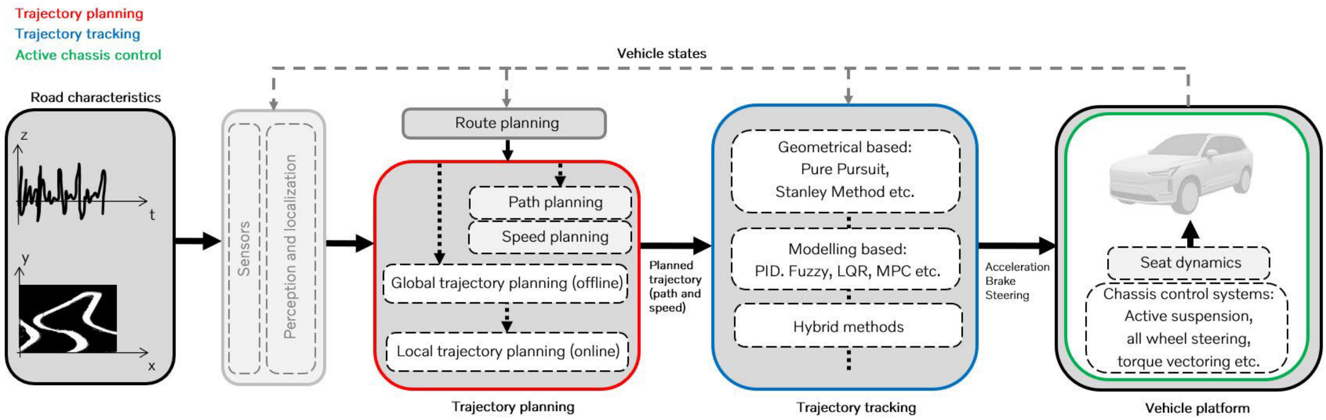

FIGURE 12. An example of a motion planning block diagram featuring functional levels that could be designed to account for motion sickness.

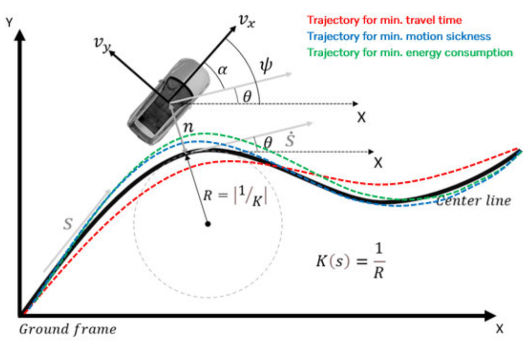

FIGURE 13. Sketches of planned trajectories for different cost functions when using curvilinear coordinates.

where:

$E(t)$: energy,
$M(t)$: motion sickness,
$P(t)$: vehicle performance,
$X_i(t)$: additional criteria considered (e.g., safety),
w_1, w_2, w_3, and w_i: weighting factors for each criterion,
k represents the number of selected criteria,
t_0 and t_f represent the initial & final times of the trajectory.

The optimal control framework is commonly employed for trajectory planning, such as addressing the minimum lap time problem (driving the vehicle to its handling limits) which is a useful tool for racing car design, a concept extensively studied in the literature. A comprehensive review on minimum-lap-time optimisation and simulation was provided by Massaro and Limebeer [218], which presented the fundamentals of OCP design, discussing different solution methods, and referring to existing applications. This framework enables the formulation of an OCP for trajectory planning of autonomous vehicles, achieved through global optimisation along a predefined route. Moreover, it can be adapted to address motion sickness concerns, optimising the trajectory to ensure both safe and comfortable travel within a specified time frame, thereby enhancing the overall autonomous driving experience. In the following, recent developments in OCP-based trajectory planning for MS mitigation are presented and discussed, with emphasis on design-influencing factors.

1) DRIVING STYLES AND MS, AN OCP APPROACH

A series of studies conducted by Htike et al. [66], [214], [219], [220], [221] investigated how to reduce motion sickness by employing trajectory planning as an optimal control problem. Several different objective functions were implemented, taking into account both motion sickness (based on ISO-2631) and journey time in the OCP formulation and their performance was investigated under various driving scenarios in a simulation environment. The designed global optimisation problem was solved using GPOPS-II [222] together with a nonlinear programming (NLP) solver. In Htike et al. [66] and [214] cost functions considering minimum motion sickness (represented by illness rating (IR) value based on ISO-2631) and minimum journey time were applied, demonstrating the advantages of road width flexibility over fixed paths. Another study by Htike et al. [219] explored velocity profiles and investigated various curvature scenarios along a predetermined path, considering the trade-off between motion sickness and travel time. Additionally, Htike et al. [220] employed a frequency weighting filter [81] for longitudinal and lateral acceleration to calculate IR based on ISO-2631, and different driving styles (sport, natural, comfort and anti-nausea obtained from different pairs of weightings on the trade-off between motion sickness and journey time in the cost function of the OCP) were analysed. According to the case studies, findings indicate that driving styles significantly influence the level of motion sickness and the duration of travel, more so than vehicle speed or road width. The research also draws attention to a trade-off between motion sickness severity and

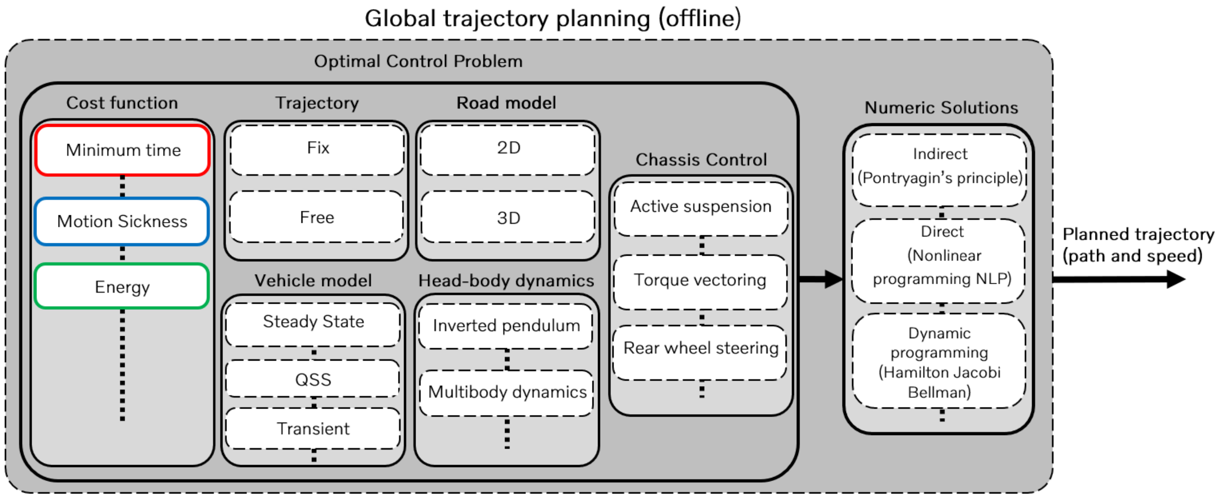

FIGURE 14. An example of a trajectory planning block diagram.

travel time, utilising Pareto front methods to explore optimal solutions that balance MS minimisation and journey time optimisation, enabling users to choose their preferred driving style [66], [221]. Another enhancement could involve further developing and customising trajectory planning algorithms to accommodate individuals with varying levels of MS susceptibility. For example, Tang et al. [223] studied the importance of personalised trajectory planning in enhancing the comfort and acceptance of AVs by addressing MS on an individual basis. Their simulation results demonstrated reductions in MS for passengers with varying levels of susceptibility. Such findings indicate the need for further research and validation to confirm the effectiveness of personalised trajectory planning in mitigating MS.

2) DIFFERENT COST FUNCTION DESIGNS

Researchers have integrated various designs of cost functions into OCPs to mitigate motion sickness. Wada [65] included the 6DOF-SVC model and minimised the MSI to determine the velocity profile for a single turn. To minimise the subjective vertical conflict, Ukita et al. [229] used the 6DOF-SVC model for trajectory planning optimisation, to evaluate the effect of the algorithm in a lane-change manoeuvre. Vroom [228] proposed using RMS accelerations and jerk as cost functions in the optimisation problem design, claiming that the results were sufficient to mitigate motion sickness. A comparison of using a 1D-SVC model and ISO 2631 as cost functions was performed by Htike [221], concluding that both approaches yield similar results. The 3D-SVC UNIPG motion sickness model was implemented by Certosini [233] into the cost function of a trajectory planning algorithm using MPC and a point-mass vehicle model. Three different cost function performance were evaluated: minimum time, minimum acceleration and minimum MSI. The simulation results showed that the MSI model-based approach is the most effective choice for minimising motion sickness. However, the vehicle acceleration cost function also effectively limits motion sickness, thereby enhancing simplicity. Comfort-aware trajectory planning was investigated by Paganelli et al. [231] and [234] using NMPC, and the implemented cost function included IR and travelling time. A single-track vehicle model was used for multi-objective analyses and the algorithm performance was evaluated in a closed-loop track, illustrating the influence of different weighting parameters in the cost function. An Adaptive Model Predictive Control (AMPC) algorithm was proposed by Moazen and Burgio [235] that uses MSDV in the cost function. The algorithm was implemented on an embedded platform and were evaluated for straight and cornering conditions (using same cornering manoeuvre as in Htike et al. [214]) with accelerations constrained to +/- $1\ m/s^2$. The results show that IR based on ISO 2631 is reduced compared with the values found by Htike et al. [214]; however, travelling time is increased by around 7% for a given cornering manoeuvre. A trajectory planning formulation as an OCP with a cost function determined using a frequency-shaping approach was proposed by Li and Hu [224]. The results show that using this approach the calculated MSDV can be reduced by up to 37% compared to the polynomial-based planning algorithm that optimises acceleration and jerk magnitudes, according to a simulation scenario of "pulling-out" from a bus stop (similar to lane change) and real vehicle experiments. However, these limited case analyses should be extended to cover more complex and general driving scenarios, so that broader applicability can be achieved in the future. Yunus et al. [225] investigated the approximation of frequency weighting filters in three directions (x, y and z) for the calculation of total MSDV and integrated it into the cost function, showing better performance than using RMS acceleration and RMS jerk to minimise motion sickness. Another investigation could involve the linearisation of the 6DOF-SVC motion sickness model, enabling the integration of MSI into the

TABLE 3. Summary of trajectory planning research for motion sickness mitigation.

Category	Reference	Notes
Optimal driving style	Htike et al. (2020) [214]	Investigates optimal control trajectory planning with IR cost functions to minimise MS in simulations.
	Htike et al. (2020) [219]	Explores MS reduction through trajectory planning using cost functions involving IR and journey times, highlighting benefits of flexible paths.
	Htike et al. (2021) [220]	Analyses how different driving styles (sporty, comfort, etc.) influence MS and travel time using frequency-weighted acceleration profiles in planning.
	Li and Hu (2021) [224]	Introduces frequency-shaping for trajectory planning, focusing on lane changes and stop-start scenarios.
	Papaioannou et al. (2022) [217]	Evaluates trajectory planning based on comfort, energy, and travel time, proposing sorting algorithms for optimal solutions.
Considering 3D road & approx. frequency weightings	Yunus et al. (2023) [225]	Investigates approximated frequency weightings for multi-directional accelerations on 3D roads in trajectory planning, highlighting their effectiveness over RMS methods for MS reduction.
Including head dynamics	Steinke et al. (2022) [226]	Integrates head motion dynamics into trajectory planning to enhance comfort. Simplifies MS modeling by approximating vertical conflicts with jerk metrics.
Considering acceleration & jerk	Bae et al. (2019) [227]	Proposes algorithms that maintain comfort limits for acceleration and jerk along predefined paths to improve passenger comfort in public transport.
	Vroom (2021) [228]	Suggests jerk and RMS acceleration as cost functions in optimisation, showing effective MS reduction in simulations.
Using 6DOF-SVC model	Wada (2016) [64]	Uses 6DOF-SVC models to optimise velocity profiles to reduce MS in single-turn scenarios.
	Ukita et al. (2020) [229]	Simulates lane-change maneuvers using optimisation based approaches to minimise SVC and reduce MS.
	Yunus et al. (2022) [216]	Explores trajectory planning under different manoeuvres, emphasising trade-offs between comfort and travel time using different vehicle models.
MPC based approaches	Certosini et al. (2019) [215]	Introduces an NMPC approach integrating MS models to optimise speed profiles, balancing MS and journey efficiency in motorway simulations.
	Certosini et al. (2020) [230]	Proposes NMPC based speed optimisation, demonstrating reductions in MSI during motorway simulations while balancing comfort and travel time.
	Paganelli et al. (2022) [231]	Combines comfort metrics and travel time into NMPC based trajectory planning, evaluating performance through simulations.
Personalised trajectory planning	Tang et al. (2023) [223]	Introduces trajectory planning that addresses individual MS susceptibilities.
Integrated with active suspension	Zheng et al. (2021) [251]	Employs motion planning with active suspension for curve tilting to reduce sensed lateral acceleration during cornering.
	Zheng et al. (2022) [232]	Integrates roll motion planning with trajectory optimisation using active suspension, achieving both comfort and travel time improvements.

cost function for optimal problem formulation. This would extend the strategy to include complex motion effects in trajectory planning. Although various cost functions have been tested, the algorithm's effectiveness largely relies on the relevance and quality of the metrics chosen. Future research should focus on enhancing cost function designs and evaluating their performance under real-world conditions to mitigate MS.

As discussed previously, the head movements of passengers respond to vehicle motion and have a significant impact on comfort. An accurate estimation of head motion dynamics is therefore required for autonomous vehicle motion planning. Trajectory planning algorithms considering motion sickness and head movements in the design of the cost function were investigated by Steinke and Konigorski [226]. Their study proposed a simplification that could be achieved by using jerk to approximate vertical conflicts and the head dynamics was modelled using transfer functions. Similar results were obtained when the vertical conflict or jerk was integrated into the planning problem.

Trajectory planning is sometimes referred to as a speed planning problem along a fixed path. The study of Bae et al. [227] proposed an optimal velocity planning method for public transport vehicles that maintains the acceleration and jerk limits within the acceleration comfort envelope along a given reference path while solving the nonlinear optimisation problem. Certosini et al. [215], [233] suggested an NMPC based speed profile planning algorithm by integrating the 3D extension of the 1D-SVC model to decrease MSI while reducing the travel time. The proposed method was simulated for motorway driving and was compared to the base model (only time-dependent) to assess motion sickness reduction, showing that the proposed approach had significant benefits in reducing MS. Another study by Certosini et al. [230] proposed speed profile optimisation also using NMPC, analysing the effects of different cost functions, and demonstrated a reduction in MSI. They made a systematic investigation of various potential cost functions to minimise MS while considering journey time and found that an adaptive approach was most effective. Their adaptive approach found that on long journeys, slowing down the vehicle was advantageous, while on short journeys, maintaining a low MSI enabled the vehicle to follow the planned speed profile for the minimum-time solution. The findings also indicate that it is possible to reduce MSI without modelling its dynamics directly. Nevertheless, while other cost functions also reduced motion sickness, by for instance minimising acceleration and jerk, they were not as effective as the adaptive approach. Such studies also motivate the design of improved cost functions in future trajectory planning algorithms.

3) VEHICLE MODELING

Another factor that may affect the OCP is vehicle modelling. Different modelling approaches for minimum time, including steady-state, quasi-steady-state (QSS), and transient approaches for different assumptions of vehicle modelling, are compared in Siegler et al. [236] and Tucker et al. [237]. Their simulation results indicate minor differences between these methods. Generally, due to their computationally efficient and robust behaviour, the QSS approach is commonly preferred [218]. Htike et al. [66], [214], [219], [220] and Certosini et al. [215], [230] have utilised a point-mass vehicle model in their studies for trajectory planning algorithms that aim to reduce motion sickness. The effect of multibody vehicle model complexity for minimum lap time simulations is further investigated in Lot and Dal Bianco [238]. The simulation results show that a 10 DOF model gives almost the same results as a 14 DOF model (explicitly considering the dynamics of each wheel and suspension component) and significantly reduces the computation time. Due to the overly simplistic nature of the 7 DOF model (longitudinal, lateral, and yaw motions, as well as the rotations of all four wheels, without considering suspension dynamics), notable differences in minimum lap time simulations in the analysis were noted. Yunus et al. [216] investigated an OCP using point-mass and single-track vehicle models that consider different driving styles to find the best trajectories that minimise manoeuvre time and motion sickness, in a similar approach to that of Htike et al. [66], [214], [219], [220]. The simulation results show that the driving style has a large influence on MS, emphasising the importance of adjusting it according to personal preferences. Their results also showed that the vehicle model should be correctly selected to get realistic trajectory planning for high-speed (minimum time) driving conditions, while for low-speed conditions (minimum MS) a low-order vehicle dynamics model is sufficient. Such studies highlighted that selecting the correct vehicle model is critical for considering multiple objectives (e.g., comfort, performance and safety) in trajectory planning across various driving conditions.

4) ROAD MODELING AND NUMERICAL SOLVERS

Introducing a 3D curvilinear coordinate method to road modelling, Lot and Biral [239] transformed the equations of motion into the space (s) domain. This choice simplifies the numerical solution of the OCP. The study also included a comparison between 2D (flat - 2D curvilinear coordinates illustrated in Figure 13) and 3D (longitudinal, banking and elevation) road models for minimal time manoeuvres. Moreover, simulations for minimising lap time on 3D roads were conducted by Lovato and Massaro [240], [241]. They employed fixed-trajectory [240] and free-trajectory quasi-steady-state optimal control [241] approaches. The results indicated a significant impact of road three-dimensionality on lap time calculations. In another study, Lovato et al. [242] introduced a 3D curved ribbon model for highly banked roads, showing that camber variations affect lap times depending on the road design. Research shows that features important for minimum lap time simulation are not necessarily equally important for analyses related to mitigating motion sickness. For instance, in the study by Yunus et al. [225], it was found that the effects of road three dimensionality proved negligible for the selected track, based on the computed total MSDV. Other factors related to road characteristics, such as road roughness, also need to be investigated for their effect on optimal trajectory planning, considering motion sickness minimisation.

The choice of numerical solver plays an important role in the design of optimal control problems by influencing their implementation and results. Several studies [218], [243], [244] investigated various numerical solution approaches (e.g., PINS (indirect) and GPOPS (direct), free and fixed paths) for OCPs in minimum lap time simulations. These studies indicate that the selection of OCP solvers and vehicle models should be made with careful consideration, depending on the primary focus and objectives of the investigation. Since numerical approaches influence planned trajectories and acceleration levels, they can potentially impact motion sickness mitigation.

5) TRAJECTORY PLANNING COMBINED WITH CHASSIS CONTROL

To control complex vehicle motions, trajectory planning could be combined with active chassis control systems, such as active suspension control, torque vectoring, and rear-wheel steering systems. These integrated active chassis systems can be designed and tuned to effectively control passenger passive motions, aiming to increase comfort and minimise MS. As widely recognised, head motions can influence MS, and head tilting during cornering has been shown to help reduce MS [53]. Actively leaning the vehicle body toward the inside of the curve to counteract lateral forces is generally referred to as curve tilting. Zheng et al. [152] proposed an NMPC approach for the curve tilting control using active suspensions relying on a velocity-dependent curvature preview strategy. Their simulation results demonstrate that the discomfort level, as measured by the lateral acceleration RMS value, significantly reduced with the suggested system. However, their system is limited when a human driver is in control of the vehicle due to the unpredictable disturbances caused by the driver. As the authors suggested, this can be solved by coordinating the roll motion with the trajectory planning algorithms. Another study by Zheng et al. [232] suggested an enhancement by integrating roll motion planning for comfort-oriented motion planning in AVs. Their proposed approach enables the simultaneous planning of the vehicle's trajectory and roll, utilising active suspension technology. This also allows for a more accurate estimation of the disturbances from the planar motion and the optimal generation of reference roll motion for improved vehicle stability and passenger comfort. The findings indicate that adding active suspension to AVs can significantly improve comfort by around 30% for the same travelling time, or reduce travel time by about 15% while keeping the comfort level the same in the simulated scenario. Experiments in [245] demonstrate that incorrect timing or misaligned roll tilting considerably worsens MS. Therefore, careful design of such systems is essential. Another active chassis control system that can be integrated into trajectory planning is torque vectoring. The effects of passively and actively modifying the target understeer gradient of a vehicle equipped with a torque vectoring system for minimum time manoeuvring were investigated by Smith et al. [246], aiming to optimise the handling characteristics. It was concluded that the passive handling characteristics of the vehicle have a minor effect on minimum time performance. Furthermore, the research by Sedlacek et al. [247] investigated the influence of rear-axle steering, longitudinal torque distribution, and vehicle parameters on achieving minimum lap times, highlighting the significance of these systems in improving vehicle performance. Their results showed that for the selected vehicle and dataset, longitudinal torque allocation offered a higher possibility of improving lap times than rear-axle steering. These performance-oriented optimal control approach studies can be further developed with the aim of mitigating MS and integrated into trajectory planning for AVs.

These examples demonstrates the effectiveness of integrating trajectory planning and chassis control in achieving specific performance criteria. Most of the previous studies have investigated methods that have either operated independently or used basic feedforward/feedback mechanisms or other traditional control approaches [194], [248]. Integrating multi-chassis control systems into trajectory planning is more critical than simply advancing control methods, as it offers the additional directional control flexibility to mitigate MS. However, the integration and complexity of these systems also require sophisticated multi-capability control algorithms. Therefore, using optimal control approaches offers a multi-objective strategy that effectively regulates multiple actuators, significantly enhancing the ability to address the multi-dimensional aspects of MS.

B. TRAJECTORY TRACKING

Trajectory tracking algorithms aim to ensure that the vehicle can accurately follow a specified reference trajectory calculated by a trajectory or path planning module while maintaining stability and minimising tracking error [249]. These algorithms control both longitudinal (velocity tracking) as well as lateral dynamics of a vehicle using various control techniques, including geometric methods (such as Pure-Pursuit or Stanley) and model-based methods (ranging from PID to more advanced techniques such as LQR, SMC and MPC). Various control approaches have been proposed for the path tracking of AVs, with a focus on safety and stability while ensuring robustness to parameter uncertainties and external disturbances [250], [251], [252], [253]. For more details, methods used for trajectory tracking in AVs are reviewed in [210] and [254], presenting their strengths and weaknesses. A general summary of trajectory planning and tracking studies for mitigating motion sickness is provided in Table 4.

While path tracking controllers are primarily responsible for maintaining the vehicle on its intended path, they can also be enhanced to take motion sickness into account. In the literature, several studies [255], [257], [258], [259], [261] have focused on optimising path-tracking algorithms to minimise motion sickness. An ergonomic path planning of transition curves by investigating B-spline, Bezier and Hermite curves and trajectory tracking algorithms for autonomous driving is proposed by Siddiqi et al. [255]. The performance of two different control techniques, SMC and MPC, for path tracking were investigated. A proportional derivative (PD) controller is used for longitudinal control. According to the study, B-splines are promising curves for reducing motion sickness when tracked accurately by SMC or MPC-based methods. A hybrid solution is proposed in [257] using ergonomic path planning with NURBS to reduce factors contributing to motion sickness. In the study, hybrid control strategy with various controllers (PID, Fuzzy Logic and MPC) was investigated for reducing motion sickness (based on ISO 2631) during cornering manoeuvres by maximising handling comfort and minimising motion sickness and postural instability. Another study by Siddiqi et al. [256] proposed a motion sickness mitigating control technique that operates in parallel with the main path tracking controller. This control strategy employs two controllers—MPC and PID—targeting objective functions based on ISO 2631. The strategy was simulated under single- and double-lane change, and cornering manoeuvres, and compared with methods from the literature. The results demonstrate that the suggested control technique effectively reduces motion sickness without an impractical decrease in vehicle speed, thereby ensuring a limited impact on passenger journey time. However, these studies are limited to short manoeuvres and do not analyse the long-term effects of motion sickness. In addition, Zengin et al. [258] proposed an augmented road-vehicle model with a vestibular system model to investigate the effect of look-ahead distance for path-tracking algorithms. The simulation results indicate that the look-ahead distance and the MSDV are inversely related in the investigated cases, identifying the importance of selecting the correct look-ahead distance. Sever et al. [259] proposed to tune a gain-scheduled LQR-based path following controller to reduce the MSDV defined in ISO 2631, also integrating the dynamics of the human vestibular system similar to Zengin et al. [258]. One of the drawbacks of these approaches is the need for precise vestibular system dynamics modelling. A Stanley controller, corrected by an inner loop fuzzy

TABLE 4. Summary of trajectory tracking research for motion sickness mitigation.

Category	Reference	Description
Ergonomic path planning and tracking	Siddiqi et al. (2021) [255]	Investigates the effect of transition curves (B-splines, Bezier, Hermite) on MS and evaluates SMC and MPC for accurate trajectory tracking.
	Siddiqi et al. (2023) [256]	Proposes an algorithm integrating path planning and using MPC and PID controllers to mitigate MS during cornering manoeuvres.
Hybrid approaches	Siddiqi et al. (2021) [257]	Proposes a hybrid approach combining ergonomic path planning with NURBS and various controllers (PID, Fuzzy Logic, MPC) to minimise MS.
	Saruchi et al. (2020) [67]	Proposes a Fuzzy-PID controller tuned by heuristic and PSO for reducing MS during slalom manoeuvres using 6DOF-SVC.
LQR based	Zengin et al. (2018) [258]	Analyses the impact of look-ahead distance on MS using augmented road-vehicle and vestibular system models.
	Sever et al. (2021) [259]	Designs a gain-scheduled LQR controller to reduce MSDV, integrating vestibular dynamics.
MPC based	Luciani et al. (2020) [260]	Designs a preview-based MPC for optimising passenger comfort, addressing lateral deviation, tracking velocity, and yaw angle.
	Luciani et al. (2020) [261]	Proposes using MPC with weighting parameters optimised by genetic algorithms to enhance passenger comfort and minimise MS levels.
	Arslan et al. (2024) [262]	Develops an NMPC considering lateral, roll, and yaw dynamics, evaluated using RMS and jerk metrics during lane change simulations, to potentially reduce MS.

logic controller [199], and a Fuzzy-PID controller tuned by heuristic and particle swarm optimisation (PSO) path tracking algorithm, was proposed by Saruchi et al. [67]. This controller was designed to control the wheel angle during slalom manoeuvres in order to reduce lateral acceleration and the roll angle of the driver and passengers' heads, aiming to reduce motion sickness. The results showed that the proposed control strategy effectively reduced MSI, which was calculated using the 6DOF-SVC model. The reduction in MSI analysed in this study could potentially be improved further by using GIA orientation as a reference instead of the driver's head roll angle. Luciani et al. [260] adopted a more advanced control approach by proposing a preview-based MPC controller that provided front wheel steering angle and acceleration/deceleration commands to optimise autonomous vehicle passenger comfort. Their study evaluated the comfort using ISO 2631 based on an equivalent acceleration and an MSDV index. The MPC weighting parameters were designed to achieve maximum vehicle performance in terms of lateral deviation, tracking velocity, and relative yaw angle while also maximising passenger comfort. Their approach was compared with an alternative control strategy based on the combination of a PID and a Stanley controller for the longitudinal and lateral dynamics. In another similar study by Luciani et al. [261], the weighting parameters of the MPC were tuned offline using a genetic algorithm. Their results demonstrate the success of the proposed techniques, resulting in a low MSDV value [260], [261]. In a recent study, Arslan et al. [262] proposed an NMPC approach where lateral and roll motions were evaluated using RMS and jerk based metrics during lane change simulations, demonstrating a reduction in these metrics. The study could be extended by incorporating frequency domain analysis to further assess MS. These proposed control strategies show promising potential but have only been tested in simulations in these studies, and their real-time applicability have yet to be demonstrated.

In the future, the number of approaches that integrate both trajectory planning and tracking is expected to increase, due to their potential to enhance computational efficiency and real-time applicability. For instance, Vázquez et al. [269] proposed a two level hierarchical controller strategy that significantly reduced the online computation load and enabled their method to be applied in real-time, which was validated through experimental studies. This approach could be further extended to mitigate motion sickness.

C. IMPLEMENTATION AND EXPERIMENTAL EVALUATION

The development of motion planning algorithms and their evaluation in various test scenarios play a key role in enhancing the autonomous driving experience. A similar approach to the development of chassis systems (as illustrated in Figure 11) can be applied by integrating objective and subjective evaluation methods into the design of trajectory planning and tracking systems to mitigate motion sickness. An overview of real-time trajectory planning methods, together with the highlighting of several challenges that need to be addressed before autonomous vehicles can operate on public roads, is presented in the survey by Katrakazas et al. [202]. These challenges, especially those arising from real traffic scenarios such as interactions with other vehicles, indicate that the solution lies in the real-time implementation of local optimisation for trajectory planning. Therefore, testing newly implemented technologies in a controlled environment is crucial for ensuring safety before moving to real-world testing. For instance, a recent study [270] proposed an MPC-based planner to design optimal path and speed references that recreate on-road motion sickness on a test track where mitigation strategies can be assessed. Some examples in the literature of implementation and experimental evaluation studies on MS mitigation strategies are presented in Table 5.

Jiang [271] investigated the development of autonomous racing cars and their positive influence on the development of future commercial autonomous vehicles. Autonomous racing competitions such as Roborace, the Indy Autonomous Challenge, and Formula Student provide a valuable platform for researchers to explore and test new technologies, enhance

TABLE 5. Examples of implementation and experimental evaluation studies on motion sickness mitigation strategies.

Category	Reference	Description
Simulator based studies	Jain et al. (2023) [263]	Investigates optimal trajectory planning in a simulated environment, demonstrating significant reductions in MS levels through human-in-the-loop experiments.
Human driver vs planner	Zheng et al. (2023) [264]	Compares comfort levels between human drivers and motion planners, emphasising advantages of motion planning in minimising MS in roundabout scenarios.
	Rajesh et al. (2023) [265]	Develops a DRL framework for vehicle trajectory planning, reducing MS and online computation time.
ADAS applications / MPC based ACC	Hong et al. (2022) [266]	Utilises a MPC-based ACC to improve collision avoidance and reduce MS through minimisation of MSDV.
Personalised ACC	Wang et al. (2022) [267]	Proposes a Gaussian process-based ACC for personalised MS mitigation, needs validation.
Integrated strategies	Diels et al. (2023) [268]	Mitigate MS by combining ACC, tuned suspensions, and visual cues.

system robustness, and drive at physical limits within a controlled, safe environment. Betz et al. [272] reviewed automated race trajectory planning algorithms, categorising them into global and local planning approaches. In global planning, a common approach to optimising lap time as an objective function is formulating an OCP. Meanwhile, local planning needs to be executed in real-time, posing challenges for the implementation of trajectory planning algorithms. MPC-based methods are often utilised in the literature for local trajectory planning [272], [273], [274] due to their ability to perform iterative calculations and real-time capabilities. In recent years, the MPC approach has become increasingly popular for both global and local planning, as demonstrated for example by Lima [275] through vehicle experiments. Anderson and Ayalew [276] proposed a cascaded optimisation structure for receding horizon MPC, exploring its application to the minimum-time manoeuvring. Additionally, optimisation-based hierarchical motion planning for autonomous racing is discussed by Vázquez et al. [269]. They employed IPOPT to solve the lap time optimisation problem offline and then applied an online NMPC motion planner. The approach was tested on a prototype racing car, demonstrating significant performance improvements in reducing lap times compared to the method previously proposed by Kabzan et al. [277]. These implementations of autonomous racing car trajectory planning may also incorporate additional customer expectations, such as motion sickness reduction, to enhance autonomous driving. While MPC-based solutions are suboptimal due to their limited preview horizon, their ability to handle constraints and optimise multiple objectives makes them one of the preferred implementation methods for mitigating motion sickness.

Several experimental studies have been conducted to evaluate the performance and impact of methods for mitigating motion sickness. For instance, the optimal trajectory planning algorithm proposed in [263] was evaluated through human-in-the-loop experiments on a moving-base driving simulator. The results highlighted its effectiveness in reducing MS, indicating its potential for future applications. In another experimental study, Zheng et al. [264] conducted realistic tests with roundabouts to compare human drivers and trajectory planning algorithms in terms of balancing comfort and time while driving. Human drivers might induce MS for passengers, due to their insensitivity to the motion which causes nausea. Their study suggests that autonomous vehicles can significantly enhance motion comfort compared to average human drivers, potentially addressing MS challenges without compromising time efficiency. Additionally, Rajesh et al. [265] proposed a DRL method to plan vehicle trajectories, focusing on minimising low-frequency accelerations. Their results demonstrate that the proposed method reduces online computation time. However, complex environments increase training time due to higher state and action space dimensions, posing optimisation challenges given limited computational power. They studied a realistic test scenario (real-world road with two roundabouts) and used driver data in their analysis, showing promising results. To achieve more complete evaluations, future studies should include a wider range of real-world driving scenarios with passenger subjective ratings. Another notable instance involves the use of advanced driving assistance systems (ADAS) for mitigating MS. In the study by Hong et al. [266], a method was developed that utilises Adaptive Cruise Control (ACC) for this purpose. They evaluated an MPC based ACC approach by calculating MSDV, which led to improved collision avoidance and a significant reduction in MS. In a separate study on personalised and learning ACC, Wang et al. [267] proposed a data-driven control approach. Although the research has not explored MS and lacks road tests, the methodology shows considerable promise. With further development, this approach could effectively address the individual variability in MS mitigation. Various strategies were tested to reduce MS in [268]. Combining ACC, tuned suspensions and visual cues resulted in a notable 28% reduction in MS for selected cases, indicating the need for an integrated solution.

V. FUTURE HORIZONS AND VISION ROAD MAP

This section aims to provide horizons for future research, addressing the problem from multiple perspectives and presenting a vision road map to navigate the complexities of mitigating motion sickness. Several review studies [72], [73], [74], [75], [278] have explored future research directions. For example, Emond et al. [278] focused on visual cues to reduce MS. Similarly, Pereira et al. [72] pointed out the importance of visual cues but also noted that vehicle-centric approaches are often overlooked and suggested they could start gaining

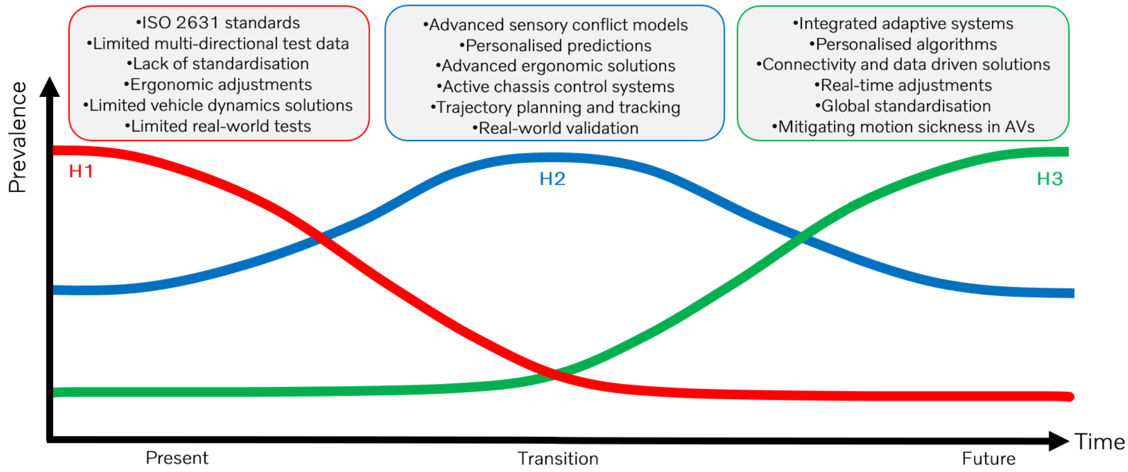

FIGURE 15. Three horizon approach to achieving the minimum motion sickness in autonomous vehicles.

attention as a focus for future research. Other reviews [73], [74], [75] provide valuable insights into various mitigation methods and proposed future frameworks. However, the reviews and discussions on vehicle dynamics based solutions remain limited and not detailed. Specifically, there is a lack of research into how these solutions can be further developed, how MS models can be effectively utilised and integrated into these advancements, and how these elements can be effectively combined to control vehicle motion. Although various solutions have been discussed, the challenges of their integration still need to be addressed, and further recommendations should be provided on how to overcome these obstacles. While the potential utilisation of connectivity features in AVs has been presented, addressing the challenges associated with the transmission of personalised data remains an essential area requiring attention, with studies exploring key aspects and future directions [279], [280], [281].

Beginning with an exploration of current limitations, this study identifies critical gaps, including the lack of comprehensive MS prediction methods and models, limited real-world testing, and challenges in integrating cost-effective solutions. These limitations underline the need for new research areas, such as developing integrated solutions for mitigating triggered MS motions, enhancing vehicle dynamics based technologies, and exploring personalised and connected solutions for AVs. Building on these insights, this section outlines possible future strategic directions and innovative approaches, presenting a vision road map for focus areas in addressing these challenges. This study proposes future oriented approaches to mitigate MS by placing the development of vehicle dynamics based technologies as a central focus. It also highlights challenges such as high implementation costs, data privacy concerns, and real-world testing complexities, which remain critical to address.

The three horizons approach is a tool for exploring future possibilities and understanding how change can happen [282]. It helps identify which current practices may need to be phased out and how innovative solutions can be developed to shape the future. Figure 15 illustrates the customised three-horizon approach, applied in this study to achieve minimum MS in AVs.

Horizon 1 - Current state: The current practices in MS prediction primarily rely on existing methods such as motion based approaches like ISO 2631, which focus mostly on vertical motion and are limited to laboratory tests. The notable lack of test data for validating multi-directional MS prediction models hinders their broader applicability. Standalone mitigation strategies are being investigated, focusing on addressing MS independently through singular strategies, such as adjusting chassis dynamics or improving interior design. Various ergonomics based and vehicle dynamics based solutions are being developed and tested to evaluate the effectiveness of individual systems. However, comprehensive and comparative analyses across these proposed solutions remain limited. Furthermore, there is limited focus on individual differences in MS susceptibility, which remains a considerable gap in current MS prediction and mitigation. The key limitations in this area include insufficient attention to multi-directional motion, a lack of comprehensive validation in real-world scenarios, and the absence of standardisation across methods, models, and testing protocols for both prediction and mitigation strategies.

Horizon 2 - Short-term innovations: Short-term innovations focus on emerging methods and technological improvements. Advanced models and methods are being further developed, such as multi-DOF sensory conflict models. Further enhancements, including the extension of human sensory integration, will be implemented, and MS dynamics (e.g., adaptation) would be considered to improve MS prediction. Additionally, comprehensive multidimensional validation are expected to be conducted to ensure the applicability of these models in real-world scenarios. While standalone MS mitigation approaches provide some relief, their overall effectiveness can be improved by shifting from a focus on singular aspects to a more integrated approach that combines multiple mitigation methods. Technological progress includes integrating active chassis systems, like rear-wheel steering and torque vectoring, into AVs and combining trajectory planning and tracking with active chassis control to address MS. Additionally, data-driven methods are increasingly employed to create personalised MS prediction and mitigation tailored to individual needs. Research efforts are further expanding into common scenarios such as slalom and lane-change tests for more realistic evaluations for these solutions. While some of these practices already exist, the increasing use of real-world test data and subjective passenger feedback for both MS model validation and testing the effectiveness of mitigation strategies represents a significant step forward.

Horizon 3 - Future vision: Future vision refers to the ultimate goal of creating fully integrated systems for AVs. Advanced systems would combine active chassis control, trajectory planning and tracking, with predictive capabilities to enable real-time adjustments adapted to mitigate passengers' MS severity. Personalisation and connectivity will play a important role, with algorithms tailored to individual MS susceptibility. These integrated, personalised, optimised and connected approaches represent a notable step towards providing a more comfortable travel experience. The development of globally standardised testing methods for MS, covering multi-directional effects and real-world conditions, is also a critical long-term objective. In line with this, highway scenarios such as lane changing, ramp merging, and platoon coordination, which involve sudden accelerations and directional changes that may trigger MS, have been used as evaluation scenarios in recent autonomous vehicle control research [283]. Complimenting these efforts, evaluations from actual driving scenarios such as stop-and-go traffic [284] and urban driving conditions [285] would provide a clearer view of the practical impact and real-world applicability of the proposed methods. Moreover, factors such as user adaptation over time, variability in driving environments, and sustained system reliability can influence the actual impact and long-term effectiveness of MS mitigation strategies. Integrating findings from recent user-experience-focused research (e.g., Arquilla et al. [286]) can also enhance the applicability and acceptance of the proposed solutions. Ultimately, these efforts aim to create an MS-free travel experience, enhancing passenger comfort and enabling the widespread adoption of AVs.

In this study, the triangle vision road map is introduced as a planning tool that highlights the strategies and focus areas required to achieve a selected goal, emphasising an overview perspective rather than focusing on timelines, which were already discussed using the three horizons approach. Accordingly, this road map directs efforts by outlining key topics and guiding research from a generalised to a specialised approach to minimise MS. The core objective is placed at the centre of the triangle, supported by three focus areas represented as interconnected domains, as illustrated in Figure 16. Surrounding these domains, the outer layers of the triangle show important considerations such as safety and energy efficiency, ensuring that the developed solutions are effective in addressing MS while remaining sustainable. The aim of the proposed vision road map is to bring actors together to address defined limitations and challenges, and achieve the future vision of mitigating MS, while also considering factors such as energy efficiency and safety boundaries. It also illustrates the interconnectedness of the focused domains, demonstrating that a holistic and specialised approach is essential to achieving the vision of minimising MS.

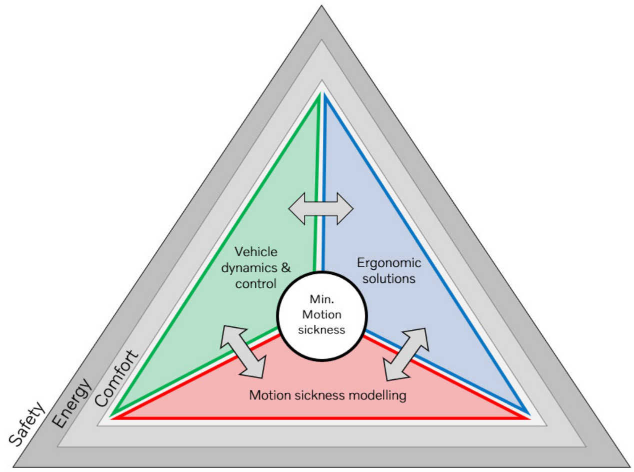

FIGURE 16. Triangle vision road map: Generalised to specialised approach to minimise motion sickness.

VI. DISCUSSIONS AND CONCLUSION

In this study, the emphasis is placed on the risk of motion sickness associated with the emergence of autonomous vehicles. The discussion covered potential risks that could lead to MS, such as being a passenger, backwards sitting, or engaging in non-driving tasks. The complexity of the MS problem within AVs was highlighted, providing a broad perspective on assessing, predicting, and preventing this issue. This review addresses a specific gap in the literature by integrating motion sickness prediction models with vehicle dynamics-based mitigation approaches — two areas that have often been studied separately. As illustrated in Figure 17, this integration represents a novel contribution, offering new insights into how data-driven, real-time, and personalised prediction can be linked with adaptive and optimised control strategies in AVs. In particular, the discussion includes specific future strategies such as the use of personalised MS prediction and advanced control systems to enhance the effectiveness of mitigation. Within this framework, specific research directions are proposed, with Figure 17 serving as a guide for formulating key research questions. Examples include: *"How can motion-based MS models be further developed to integrate psychological data and enable real-time, personalised prediction of motion sickness?"* and

"Can integrated chassis control systems be optimised and adapt in real time based on predicted MS severity to improve motion comfort?". A further possible question could be *"How should autonomous vehicles be driven and controlled, in coordination with chassis control systems, to minimise motion sickness?"*. Suggested methodologies include multi-directional motion testing, subjective passenger feedback, and integration of physiological monitoring. Potential outcomes involve more accurate MS prediction and effective mitigation during real-world AV operation. Specific technologies and approaches to be explored include active suspension, rear-wheel steering, adaptive seat systems, and control algorithms linked to personalised MS models, as well as trajectory planning and tracking combined with integrated chassis control. The review aims to offer a comprehensive overview of the motion sickness problem in AVs, showcasing the challenges in predicting and mitigating MS with a special focus on vehicle dynamics and control based methods. The following part of this section is structured to present the main findings and future research directions, with each point discussed in detail.

- *MS prediction methods and models:* Methods and models in the literature for predicting MS were explored and it was noted that motion-based approaches could be relatively cost-effective, rather than using e.g. physiological sensors, and could provide acceptable levels of prediction. These approaches have been frequently utilised for estimating statistical values of MS severity for groups and have been developed further by researchers due to their practical applicability and promising results. Recent literature developments suggest a shift towards models of MS that can be specifically tuned to individuals, with expectations for accelerated research in this personalised approach.

The study mainly discussed ISO-based methods and sensory conflict-based models and their advancements, as identified through experimental studies. Despite their simplicity, ISO-based methods continue to be widely utilised in applications because of their validity. For complex motion scenarios, research has increasingly concentrated on models grounded in sensory conflict theory, including multi-DOF models. These models and their potential for further development were discussed, emphasising their benefits and the need for detailed modelling of vestibular-visual interactions, head-body dynamics, and human perceptual mechanisms for accurate MS prediction. Further development of these models might also consider motion sickness dynamics, such as adaptation and learning, stressing the necessity for more experimental data including MS subjective ratings to validate advanced models. These models hold the potential for integration into vehicle system designs and/or control algorithms for MS mitigation. The prediction capabilities of these models can be further enhanced through the incorporation of psychologically based approaches, which are identified as a promising direction for future research.

- *MS mitigation utilising chassis systems and control:* A more efficient strategy for mitigating MS, compared to approaches such as vehicle interior design and ergonomics based methods, could involve directly addressing the motions that trigger MS, particularly focusing on vehicle dynamics and control based methods. Active chassis control systems are expected to be integrated into AV platforms, and chassis systems with the potential to mitigate MS were reviewed and their effectiveness were discussed. For instance, active suspension systems provide a wide range of control options, enabling the reduction of sensed lateral acceleration and control of roll and pitch motions, thereby improving comfort and potentially decreasing MS. Furthermore, these systems can be expanded by additionally integrating active seat systems. The importance of lateral motion was emphasised, and systems such as rear-wheel steering and torque vectoring were suggested for use. Within chassis control systems, the advantages and limitations of control algorithms have been discussed as important aspects influencing both design choices and the effectiveness of MS mitigation systems. The existing literature, which is mainly focused on performance and comfort, can be further expanded to explore the potential for mitigating MS. Lastly, the potential of integrating these systems together is discussed and proposed as a promising future direction. An integrated approach is also proposed, illustrating how both subjective and objective evaluations of MS can be incorporated into the development and tuning of chassis control systems, aiming to reduce MS and support human-centred AV design.

- *Trajectory planning and tracking for MS mitigation:* In this study, trajectory planning and tracking control algorithms, which are critical functions of AVs, were reviewed. These algorithms, by adjusting vehicle control inputs such as steering, throttle and brake, could potentially be used to reduce motion sickness. The integration of these systems, along with optimal control methods and the implementation of relevant MS-based metrics directly in the cost functions, was suggested to improve MS mitigation. The importance of developing and personalising trajectory planning of AVs for individuals with varying levels of MS susceptibility was highlighted. Moreover, it was suggested that these systems can be further improved by combining trajectory planning with active chassis systems. Performance-focused research in the current literature could be further explored and adapted for use in minimising MS and integrated into trajectory planning algorithms for AVs. Methods used in trajectory tracking and how they can be developed considering MS were presented, and common implementation studies of AVs encountered in practice were discussed. The main challenges in algorithm development and implementation for reducing MS were identified and discussed, along with potential considerations for future work. Additionally, data-driven approaches that have been the focus of extensive research recently are expected to be applied in future research to further enhance the prediction of MS as well as improve mitigation methods. Studies indicate that AVs could significantly enhance motion comfort compared to average human drivers and potentially address MS. The importance

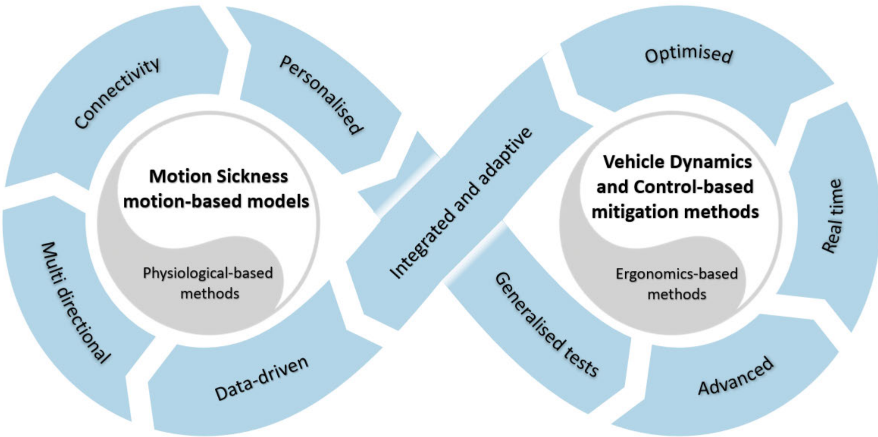

FIGURE 17. A conceptual dual-framework linking motion sickness prediction models with vehicle dynamics and control-based mitigation methods.

of trajectory planning and tracking for MS mitigation in AVs is emphasised in this study, and their integration with chassis control and ergonomics-based methods has been proposed as a potential research direction.

• *Evaluation and testing of MS prediction and mitigation:* The development process of MS prediction methods and models, including mitigation strategies that account for MS, was presented and discussed in this study. While advancements in vehicle dynamics based strategies for AVs can advance future vehicle platforms, comprehensive tests for evaluating motion sickness are still lacking compared to well-established active safety tests. The current standard, ISO 2631, primarily address vertical motion and neglect multi-directional effects. Objective methods using multi-directional models (e.g., 6DOF) can help assess MS values, but existing evaluations often rely on limited laboratory tests with single-direction devices, which do not capture the complexity of real-world driving. Slalom and lane change tests have been employed as part of MS testing in the literature. These are considered to hold potential for broader application and standardisation in MS evaluation. Although these scenarios provide valuable insights, their scope remains limited, underscoring the importance of real-world testing and field validation. Consequently, future research should focus on establishing standardised and comprehensive evaluation frameworks for both MS prediction models and mitigation strategies.

• *Concluding remarks:* In summary, this study underscores the significant challenges of evaluating and mitigating MS in AVs, emphasising the need for accurate MS prediction models, individualised approaches, and real-time capable, optimised, connected, and integrated vehicle dynamics and control-based mitigation methods. Expanding on the three-horizons approach and vision road map described in the previous section, future-focused strategies are outlined that are essential to address current limitations and achieve long-term goals. In conclusion, the advances in technology and research presented and discussed in this study demonstrate the potential for significant improvements in the prediction and mitigation of MS, providing a strong foundation for enhancing passenger comfort and satisfaction and facilitating the broader adoption of AVs.

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ILHAN YUNUS received the M.Sc. degree in automotive and motorsport engineering from Brunel University London, U.K., in 2013. He is pursuing the Industrial Ph.D. degree with the KTH Royal Institute of Technology, Sweden. He is currently employed as a Research Engineer at Volvo Cars. Before starting his Ph.D. studies, he worked in the industry for several years at companies including AVL and Daimler Trucks. His main research interests are in vehicle dynamics and control, with a focus on motion sickness and autonomous driving.

GEORGIOS PAPAIOANNOU received the Ph.D. degree from the National Technical University of Athens (NTUA), Greece, in 2019. He is currently an Assistant Professor of motion comfort in AVs with TU Delft, after conducting a Postdoctoral Research with the KTH Royal Institute of Technology, Sweden, and Cranfield University, U.K. His research interests include motion comfort, seat comfort, postural stability, human body modeling, automated vehicles, motion planning, and optimization and control. During the Ph.D. degree, he received the award regarding its innovation and impact.

JENNY JERRELIND received the M.Sc. degree in engineering physics from Luleå University of Technology, Sweden, in 1998, and the Ph.D. degree in vehicle dynamics from the KTH Royal Institute of Technology, Sweden, in 2004. She is currently an Associate Professor of vehicle dynamics with the Department of Engineering Mechanics, KTH Royal Institute of Technology. Her areas of research interests include tyre characteristics and modeling, motion sickness, over-actuated vehicles, vehicle energy efficiency, and motion cueing in driving simulators.

LARS DRUGGE received the M.Sc. degree in mechanical engineering and the Ph.D. degree in computer aided design from Luleå University of Technology, Sweden, in 1994 and 2000, respectively. He is currently a Professor of vehicle dynamics with the Department of Engineering Mechanics, KTH Royal Institute of Technology, Stockholm, Sweden. He is also the Head of the Vehicle Dynamics Group, KTH Royal Institute of Technology. His areas of research interests include vehicle dynamics of over-actuated vehicles, tyre modeling, human-vehicle interaction, and driving simulators.