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# A Review of Driving Simulation Technology and Applications

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**ABSTRACT** Driving simulation has become a very useful tool for vehicle design and research in industry and educational institutes. This paper provides a review of driving simulator components, including the vehicle dynamics model, the motion system, and the virtual environment, and how they interact with the human perceptual system in order to create the illusion of the driving. In addition, a sample of current state-of-the-art vehicle simulators and algorithms are described. Finally, current applications are discussed, such as driver-centered studies, chassis and powertrain design, and autonomous systems development.

**INDEX TERMS** Driver-in-the-loop, driving simulation, motion cueing, vehicle dynamics, vehicle simulator, virtual simulation.

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## I. INTRODUCTION

The concept of simulation can be defined as the emulation of a specific behavior through a generic imitating system [1]. In the automotive field, simulation is used both in academia for research and in industry for design purposes. The reason is that by using virtual simulation, new systems can be developed and evaluated within lower time and with lower financial investment. In the automotive industry for instance, virtual simulation can be used throughout all phases of development of a new vehicle. During virtual design, model-in-the-loop analysis enables the comparison of different system architectures, e.g. comparison of powertrain topologies to evaluate the fuel consumption and emissions.

Virtual simulation also speeds the testing phase. Structural, fluid dynamics, and multibody simulation not only optimize the characteristics and geometry of the components, but also work as filters for component selection, e.g. definition of spring pre-load and shock absorber dynamic curve in suspension tuning. Without virtual simulation, not only would the development cost increase, but also the timeframe needed to accomplish each step of development would be longer. During calibration of on-board software parameters or performance components, virtual simulation reduces the number of prototypes that will eventually be manufactured for testing. In this way, the design process as we know it today, with rapid release of new products, is only possible due to simulation. Within the various types of vehicle simulation, the ability to imitate a ground vehicles response in real time given real driver inputs is called driving simulation and it relies on virtual cues to trick human perception and create the illusion of immersion and motion in a controlled environment.

In the early 1910 s the first motion simulators begin to appear in England and France as a means to safely provide flight training [2]. Motion simulation technology would not be restricted to flight training for long, however. It is not clear though which driving simulator was the first to appear, some researchers acknowledge the system designed in [3], published in 1934 but given the simple architecture of this traffic simulator some authors prefer to point out later works as the real beginning of relevant developments of driving simulators. During the 1970 s several 3 degree-of-freedom (DOF) driving simulators were developed by auto makers and research institutes as depicted in [1], such as the well-known device designed by Volkswagen and another at the Swedish Road and Traffic Research Institute. In addition, the pioneer work to develop the Computer Generated Display Simulator by General Motors together with the Virginia Polytechnic Institute and State University from 1973 to 1975 is acknowledged in [4].

All previous attempts made significant contributions, but it was in 1985 that Daimler-Benz came up with a 6-DOF hexapod motion system integrated to a vehicle dome [5] that would be later accepted as the most common configuration of high level driving simulators around the globe. Rapid development of new graphic sources happened between the late 1990 s and early 2000s [6]. Digital three-dimensional (3D) graphics, new display resolution, and real-time graphic processing opened a new world of possibilities for driving simulators. The combination of various electronics improvements over the years made the increasing fidelity of driving simulators possible.

Recent studies use driving simulation technology to assess energy management strategies (EMS), human machine interfaces (HMIs), active control systems (ACSs), advanced driver assistance systems (ADAS) and road planning. The purpose of the present work is to break down the mechanisms behind the driving simulation technology, describing the main components of a driving simulator, as a guide for resource centers that want to implement this technology. This work contributes to providing a comprehensive review of the past and current state-of-the-art technologies, driving simulator examples, and applications. Former reviews of this kind can be found in [6], where a thorough survey of relevant simulators at that time was conducted. In that review, the simulators are clustered by their level of cost, a very common form of classification. Additional reviews were presented in [7], with example applications in medicine and engineering, in [8], that details motion system design, and in [9], where the focus is on the classification.

The paper is organized as follows. Section II introduces the human perceptual system. Section III explains the architecture of driving simulators. It discusses each component separately, exposing current technologies and giving examples. Section IV brings examples of driving simulators in research and industry. Section V discusses various applications throughout automotive industry and research. Finally, Section VI concludes the work and state the prospects for driving simulation.

## II. HUMAN PERCEPTUAL SYSTEM

Since the role of a driving simulator is to imitate driving in the real world in order to deceive perception, it is important to understand how the human body perceives the driving experience. In driving simulators, multiple systems are combined to form the self-motion perception as further detailed. Because driving is primarily a visual task, one of the most important human sensors to be accounted for in driving simulation is the visual system. In fact, the visual system accounts for the majority of motion perception in a three-dimensional environment [10]. The optical flow together with visual direction and extra-retinal direction form the visual information to be interpreted by the brain in order to define heading [11]. Although less important than the visual system, the auditory system can also be classified as a self-motion perceptual system. It is proven in [12] that through audio means only, separate from other sensory systems, individuals are able to identify, with certain precision, the time-to-collision of sources of noise. Interesting research is conducted in [13] where the authors concluded that adding auditory cues to visual cues increases the illusion of motion.

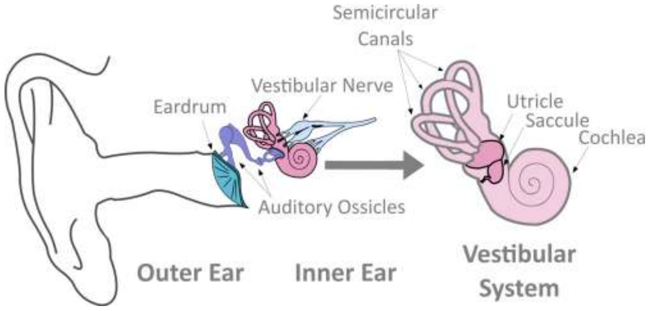

**FIGURE 1.** Human vestibular system [17].

While in static simulators the visual and auditory systems are responsible for all motion perception, in motion simulators other body sensors are also engaged to build the driving experience. The somatosensory system is responsible for all tactile perceptions and proprioceptive sensors [11], the former accounting for force changes due to motion and the last accounting for position perception and accelerations. As proposed by [14], it is possible to create an illusion of motion by vibrating postural muscles. Therefore, the better the cabin mimics the actual environment of a vehicle cockpit (e.g. by representing with fidelity the internal components, dashboard, seats, texture, commands, and pedals) as well as faithfully representing the vibration and the friction resistance for moving each component, the more realistic the driving experience.

The vestibular system is an inner ear complex comprising semi-circular canals and otolith organs, to recognize linear as well as angular motion [9]. As detailed in [15], the semicircular canals consist in three circular cavities filled with a fluid (endolymph) that deflect hair lining the canals when an angular acceleration is experienced, such as when the individual is nodding or tilting their head left to right, with an output proportional to angular velocity. The otolith organs, on the other hand are made by the combination of small sacs of sensitive hairs. The role of the sensitive hairs is to sense linear acceleration as well as gravitational forces and transmit it to the central nervous systems. The utricle detects the motion in the horizontal plane, while the saccule detects it in the vertical plane. A representation of the inner ear organs is depicted in Fig. 1. An example of modelling the visual-vestibular system was presented in [16], showing how drivers make use of the vestibular system to determine steering angle. Furthermore, this work provides evidence that drivers adapt depending on how those cues are given.

## III. ARCHITECTURE

As mentioned before, the goal of a driving simulator is to create an illusion of the driving experience. To accomplish that, different systems are combined. The diagram depicted in Fig. 2 shows not only the interdependence between each subsystem but also how driver and vehicle model are in the center of the process. Driver input is used to calculate the vehicle

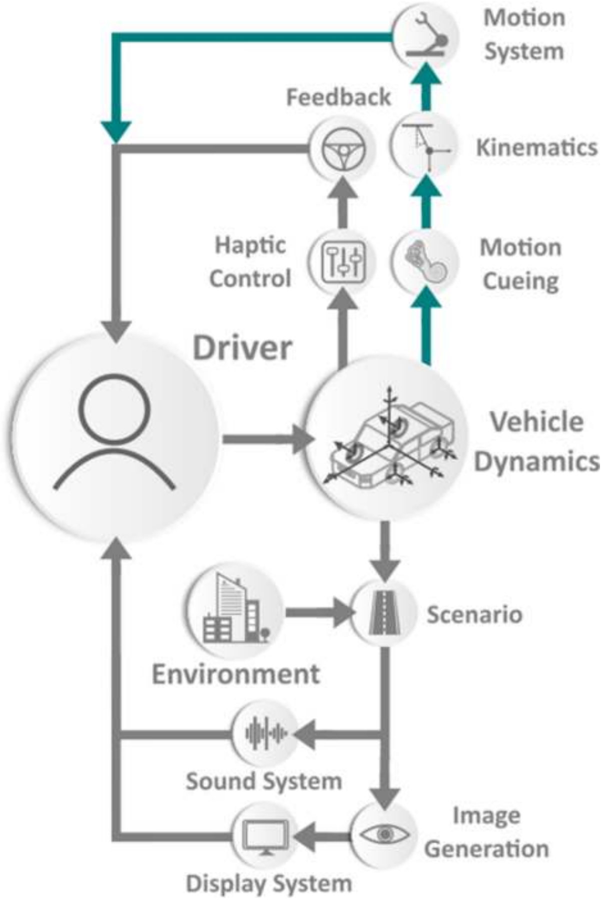

**FIGURE 2.** Diagram of a driving simulator.

dynamics by the vehicle model, which will be used by the feedback systems to give the driver the necessary cues. The scenario control uses the definitions of environment (terrain), and the vehicle dynamics to output visual and sound cues. In simulators where multiple projectors are used to create a seamless image typically projected onto curved screens, the warping and blending of the image must be done before projection. Haptic feedback such as steering torque, active seats and belts is also used to provide cues from the vehicle dynamics.

The green path in Fig. 2 shows optional systems in the sequence for providing motion in driving simulators. This can improve the immersion considerably, and better allow for experiments examining the dynamics of the vehicles such as for the development of active systems. In motion simulators, the motion cueing algorithm will take the vehicle response and determine how to move the motion system accounting for the kinematics of that system, be transformed into actuator commands by the kinematics of the machine, and then produced by the motion system providing cueing to the human driver.

### A. VEHICLE DYNAMICS MODEL

The definition of model is presented in [18] as a simplified system that reproduces the characteristics of a more complex structure or organism. In vehicle simulation, often third-party software is dedicated to the vehicle dynamics model. This model must contain a mathematical representation of the vehicle subsystems (i.e. body frame, suspension, tires, brakes, steering and powertrain) [19] and it must be able to compute the dynamic behavior relative to a fixed global orientation system, calculating component forces and non-linearities [20]. Furthermore, driver-in-the-loop simulation applications require the vehicle models to be calculated within the available time step, without losing accuracy [6].

A simple way to represent vehicle motion is through the quarter car model detailed in [21] that isolates the analysis by focusing on the motion and forces of a single wheel. Although this model is helpful to understand wheel dynamics, it does not represent all motion available in a vehicle. The single-track model and the linear roll model add lateral dynamics and roll dynamics respectively [20], still those models do not account for the minimum necessary motion to fully reproduce driving experience. The twin-track model (TTM) is the simplest model that can support the needs of a full motion driving simulator [20]. The TTM without the Kinematic Wheel Suspension (KWS) model has 14-DOF, i.e. it models the translational and rotational motion around the longitudinal, lateral and vertical axes (x, y, and z), the rotation of the wheels, and the vertical motion of each wheel individually. Considering the full motion of the wheel suspension and steering components the twin-track model can describe the vehicle motion accounting for 30-DOF. Since multibody system approach is based on the relationship between rigid bodies and joints as subsystems, it is considered ideal for mechanical systems simulation. Therefore, the most common vehicle dynamics software are multibody solutions. In addition, an important characteristic these days is co-simulation with a third-party software, which enables the assessment of several advanced control systems such as electric power steering, electronic stability control, and powertrain control systems [18]. Furthermore, by being able to interact with other vehicle systems modules the driving simulator becomes a platform for hardware-in-the-loop simulation and validation of those systems.

### B. SCENARIO DESIGN

Another key feature of driving simulator is the possibility of creating specific scenarios. In driving simulation, a scenario can be described as an event that happens in a virtual environment. The event can be a predefined situation, e.g. a pedestrian crossing in front of the ego vehicle, or a situation created by the driver, e.g. a sine with dwell maneuver. In these examples, the environment is the terrain, road, signs, buildings, and other objects surrounding the ego vehicle. The scenarios are created by varying the traffic, weather, and events in that environment. As described in [22], there are different methods to generate driving scenarios and pre-defined trajectory of virtual vehicles in order to simulate traffic. The trajectory of those vehicles can be developed simply based on road geometry, imported data from other simulations, or through an interface that interacts with the driving simulator engine. The work developed in [23] instead builds a platform to co-simulate multiple driving simulators, which increases the realism of the traffic scenario. The study in [24] uses a traffic scenario to evaluate how traffic density affects overtaking and lane change maneuvers.

In [25] the scenario construction was focused on signs and roadside information warnings, instead of other vehicles. The idea was to measure how the rivers journey decision is affected by the information available. Repeatability is very important in early phase of development because engineers can easily visualize the problems a certain system presents in specific condition. Although possible to forecast, weather is usually a limitation in vehicle testing, depending on which region the manufacturer testing center is located. In the case provided by [26] and [27], the low visibility in foggy situations and the risk brought by this condition is evaluated.

### C. VISUAL CUES

Over the years, visual cues evolved from analog video presentations and film to digital graphics. These digital graphics rapidly improved from a low number of polygons to high count textured and shaded polygons that provide a highly realistic environment for use in driving simulation. In addition, the improvement of projector technology with increasingly higher pixel resolution, brightness, and contrast ratio, made the accurate projection of such graphics possible [6]. On the contrary, these projectors have been used with similar front projection curved screens as presented in [28] since the 1970 s, which has only now begin to change in limited applications with the use of head mounted devices (HMD). Even with the advent of HMDs, projection screens are still preferable in most cases, as the limited field of view, image lag, and the obscuring of the vehicle interior limit the usefulness of this type of device. Nevertheless, a few authors explored the suitability of these systems in driving simulators in [29] and [30]. Although they foresee an increase in the use of head-mounted devices, they agree that screen-based projection systems still are preferable among tested subjects since they give a better perception of velocity and surroundings.

In an attempt to enhance the visual cues, several authors present different add-on solutions to the conventional rounded screens presented in the most advanced driving simulators. In [31] a visual scale factor is used in an attempt to enhance the speed perception by changing the geometric field of view. In [32], the authors replaced a monoscopic projection system with a 3D-stereoscopic system for improved depth perception, to investigate the use of 3D projector for enhancing velocity as well as distance judgement in a driving simulator. The passive stereoscopic 3D was achieved by using 10 projectors, one projector per eye for each one of the 5 channels for the forward view. The masking is done through a wavelength multiplex process which requires filtering of the projector signals and filtering glasses for the driver. The main drawbacks of such system are the cost associated with the added complexity, the packaging of the projectors in the display structure, and the potential for increased eyestrain and resulting simulator sickness. By exposing subjects with attested regular stereopsis to a simple car following scenario, the authors were not able to provide strong evidence of the improvements. Lastly in [33], a headlight glare system is created to help understanding how driver performance with different populations is affected by the glare of oncoming vehicles during night driving in rural highway scenarios.

Improvements in PC hardware for rendering virtual worlds has enabled the use of gaming engines in place of the previously used custom rendering hardware. One widely used software package for rendering virtual environments in simulators is OpenSceneGraph (OSG) [34]. Other products that have gained momentum recently given their realistic rendering are Unity [35] and Unreal Engine [36]. Realistic animation and vast object databases can highly improve immersion. The work in [37] assesses how different the driver behavior given different fidelity of visual systems. In that work, a low graphic fidelity simulator was compared to a high fidelity one built with the Unreal engine. The results show that visual attention and situation awareness are highly impacted depending on the fidelity of the visual system. Given its ability to reproduce realistically external objects, Unreal can also be used as a platform to train and test autonomous systems, as developed in [38].

### D. AUDITORY CUES

As defined in [39], the importance of the audio cues is justified by how it affects speed judgement, driver awareness, and fatigue. In fact, the audio impact on speed perception is depicted in [40]. In this work, an experiment is conducted with subjects of different age ranges (young and older adults) that are exposed to driving tasks where visual cues to self-motion are provided while the respective presence/absence of auditory cues is manipulated. The conducted experiment proves the assumption that auditory cues affect longitudinal motion perception (speed and acceleration), with older adults more susceptible. Therefore, it is also important to have a well-designed audio library in order to provide quality congruent cues to the driver and maintain the immersion created by the visual system.

Three-dimensional sound is the most suitable choice in driving simulation application [6] since the noise inside the cabin is a combination of noises from different sources, i.e. aerodynamics, tire interaction with the surface, and driveline [9]. As explained in detail in [41], the majority of simulators use the wave table method which consists of lookup tables that receives input values from the sources in the simulation engine (e.g. road, powertrain, and wind sounds) and outputs interpolated cues. In addition, the importance of low frequency speakers is also explained since interior cabin noises are in this frequency range.

### E. HAPTIC CUES

The control components (i.e. steering wheel and pedals) act as a bridge between human input and vehicle behavior, making them essential tools in vehicle dynamics feedback. For that

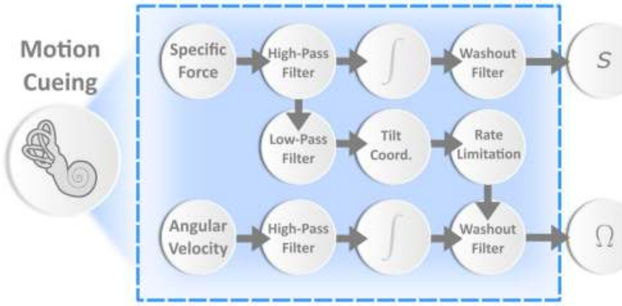

**FIGURE 3.** **Diagram of a classical filter motion cueing algorithm [45].**

reason, the human-vehicle interaction must be mimicked in order to provide a high-fidelity driving experience. Most driving simulators include components that provide force feedback through the steering wheel and braking system as exemplified in [1], [6], [42], [43], [39]. The vast majority use a torque motor for the steering wheel force feedback, commanded by the vehicle dynamics model. As stated in [9] the accurate vibration on the steering wheel, mimicking tire-road interaction, provides cues for speed and trajectory, enhancing driver perception.

### F. MOTION CUEING ALGORITHM

The presence of a motion system requires the inclusion of a motion cueing algorithm. This algorithm is responsible for creating the displacements of the motion system accounting for human perception and the available workspace [42], therefore its role is to govern the motion of the simulator to provide the driver realistic driving sensations [44]. There are several approaches for motion cueing algorithms as described in the following sections. The work in [45] details the development process of the classical, the optimal, and the adaptive motion cueing for flight simulators, being an essential read for motion cueing developers although it does not include newer approaches such as model predictive control.

*Classical Filter:* The classical filter (or washout filter) is the most simple and fast method for motion cueing design [46]. As depicted in Fig. 3 the washout algorithm relies on the interaction of high- and low-pass filters that are responsible for the platforms translational and rotational cues [9]. In the picture, S represents the displacement cues and Ω represents the angular. The tilt coordination is a tool used to replicate low frequency sustained accelerations, it performs a tilt of the cabin in order to create a component of the gravitational force in a desired direction [42]. Although the design and implementation of the classical filter is not very complex compared to other methods, its tuning might be time consuming given the fact that it relies extensively on trial and error.

*Adaptive Filter:* In the adaptive filter algorithm, the parameters that make up the washout algorithm can self-tune. The work in [47] presents a fuzzy logic-based motion cuing classical filter that accounts for both physical boundaries of the platform and error between reference motion and actual motion when outputting the filter gains. This work develops an algorithm that not only provides a better use of space but also reduces the human perception of motion error, having a performance similar to the algorithms that use model predictive control, later explained. As detailed in [43] the parameters of the motion algorithm can also be calculated through the minimization of a cost function, based on the error between vehicle model and platform acceleration and on the motion system limits. In this case, the sensitivity equations are solved through an extension of Laplaces method (Method of Steepest Descent) which makes the filter to be non-linear. In another work in [48], the authors develop an adaptive tilt-coordination that maximizes the use of the XY environment instead of relying solely on tilt to sustain the acceleration imposed by the driver. The authors accomplish their objective by labeling the acceleration state and regulating the error between the perceived and actual acceleration using linear quadratic regulation. One challenge faced by the authors in this case was the difficulty in finding representative range for the adaptable parameters. The most noticeable issue with using adaptive filters though, is that filter tuning is replaced by cost function tuning. If the parameters are allowed to be updated rapidly, motion distortion resulting in false cues occur.

*Optimal Filter:* Another approach is the optimal filter algorithm. This method either adds the human perception model (vestibular model) or uses a reference vehicle motion previously recorded to set a comparison between the real and the virtual experience calculated by this new model [49]. The comparison is built and optimized through a transfer function that links the simulator motion inputs to the actual vehicle motion. The objective is to minimize the error in human perception. The major difference between the classical and the optimal approach is the way the filters are calculated, in this case beforehand, through an optimization process that can be done as in [9] through the use of genetic algorithm (GA), or as in [50] using linear quadratic regulator method (LQR) together with GA, or simply the linear quadratic optimization as proposed in [51]. Neural network (NN) approach can also be used as in [52]. The performance of optimal filter methods is linked to the quality of the reference signal whether it comes from a model or empirical measurement. Therefore, model and test limitations can negatively impact the results. Also, the optimization might output different parameters for different set of maneuvers. The impacts of rapidly switching between parameters should be observed as previously mentioned for adaptive filters.

*Model Predictive Control Algorithm:* Derived from the optimization methods, the model predictive control strategy (MPC) consists of predicting the evolution of dependent variables caused by changes in the independent variables. In essence, the MPC selects an optimal control input at the current time based on prediction of the future behaviour over a given time window. With this future prediction feature the MPC strategy can optimize the motion input, making a better use of the available workspace and motion structure when compared to simple methods such as the classical washout

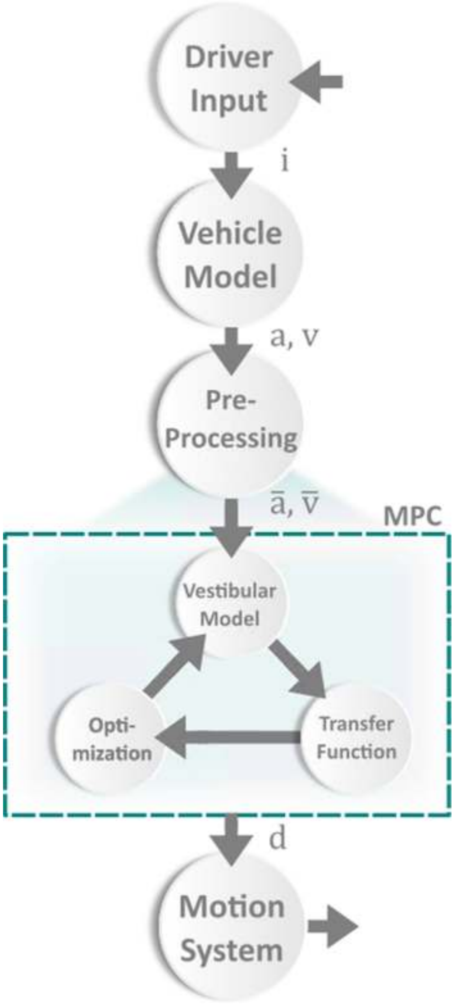

**FIGURE 4.** **Diagram of an MPC motion cueing algorithm [42].**

filter [53]. As shown in [54] and as depicted by the workflow in Fig. 4, the inputs (i) given by the real driver are received by the vehicle dynamics model which passes forward the vehicles acceleration and angular velocities (a,v). This information must then be pre-processed to build a predicted sequence of reference variables. Often, the next step is to assess the vestibular model to build the perceived values of acceleration and velocity. Other methods might simply use the angular velocity and specific force. As a final step, the system displacement (d) is calculated in order to track the perceived values before being handled to the motion control system. The importance of the reference over the MPC prediction horizon is highlighted in [55] where the future behavior of the driver is modelled as an optimal controller to have its behavior predicted and in [56] where the motion scale is treated as an optimization variable and a model of the kinematics of a 7-DOF motion system is used for motion prediction. In this work it is shown that the separation of the penalty on the motion gain from the overall target perception benefits the motion reproduction since excessive high-pass filtering and tilt-coordination becomes not required when reproducing long-period forces.

Although the process in the diagram is simple, the computational burden is complex given the presence of so many complex models. In [57], both the human vestibular system and dynamic platform are modelled. For the vestibular system, linear transfer functions for the otoliths (translational motion) and for the semicircular canals (angular motion) are considered. A multi-objective problem is solved using the sorting genetic algorithm-II (NSGA-II) method, where the outputs are the gains for the translational and angular displacements and velocities of the platform. The proposed nonlinear MPC in [58] uses a multi-sensory cueing algorithm (MSCA) that accounts for the coordinates of the 9-DOF motion platform together with the coordinates for the active seat and active seatbelt. In addition, a model of a seated driver is added to the vestibular model to predict the effects of the forces generated by the seat and seatbelts. It is shown that this approach has a great impact in compact simulator since the use of space is optimized.

Although the MPC method has the potential to optimize the use of space and the driver experience, its often-understated limitation resides in how far ahead it can foresee without compromising the real time requirement. It is important to highlight how imprecise prediction can undermine the fidelity of motion. Some works focused on different methods aiming to reduce the optimization time. In [59], a continuous-time recurrent neural network (RNN) is used. In this work the authors model the dynamic platform kinematics and use a RNN to compute and apply the optimal trajectory of the platform online.

It is possible to conclude that the MPC method allows better use of the available hardware and automated tuning of the cues when compared to the previous methods, although its implementation requires complex modelling of different systems and massive computation power. Nevertheless, the MPC approach is considered promising for enabling state-of-the-art simulators to deliver best possible motion cueing.

### *G. KINEMATICS*

The kinematics algorithm plays an important role connecting the motion cueing commands with the motion systems structure and hardware. The output of the motion cueing algorithm is trajectory of the cabin in Cartesian space, and this trajectory must be achieved by varying the length of the actuators. Therefore, actuators action is a function of desired cabin motion. As explained in [60] and [61], the concept of kinematics in driving simulation can be classified either as forward kinematics or inverse kinematics. The authors agree that forward kinematics is the process of determining the position of the motion platform once the actuators lengths are known (or predefined). Inverse kinematics is the process of acquiring the actuators length given the desired position of the motion platform. Likewise, in [62], inverse kinematics is defined in a more generic way as the process of calculating the joint coordinates from the end-effector coordinates. In

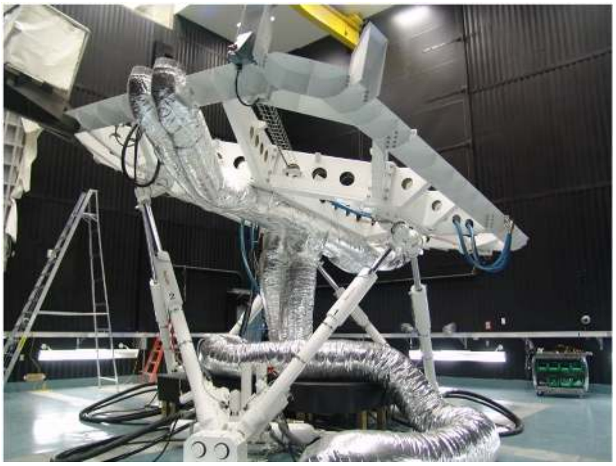

**FIGURE 5.** Hexapod motion system.

driving simulation, the end-effector is the mock-up cabin, and the joints are the couplings of each actuator to the motion platform. Since actuator length is a function of the desired motion of the cabin as previously mentioned, authors often specify the kinematics process in driving simulators as inverse kinematics.

The Stewart platform mechanism powered by electric/hydraulic actuators is very common among the state-of-the-art driving simulators. In [63], the authors describe a virtual modeling process of defining the kinematics of a Stewart platform and its boundaries, accounting for the type of the actuators, joints, and hinges. Stability is key to achieve real driving experience. Therefore, other studies focus on control methods to assure stability of those platforms. In [64], the requested position of the motion platform is performed using high order sliding mode control. In [65], a virtual PD+ controller on the basis of the passivity properties of the system was design to assure that the mechanism is asymptotically stable.

### *H. MOTION SYSTEM*

The better the motion system is matched with the vehicle dynamics model, likely the higher the fidelity of the motion will be. There are several mechanisms to reproduce vehicle motion, from low fidelity systems with 2-DOF [66] and 3-DOF [67], to high fidelity systems with up to 13-DOF [68]. These mechanisms can be comprised of serial and/or parallel actuators. The parallel manipulators mechanism is a synergistic machine, where multiple actuators work together to support a single platform. The most common arrangement of parallel actuators applied in driving and flight simulators is the hexapod configuration, also called a Stewart platform, which is a compact design allowing for 6-DOF. The hexapod provides translational movement along, and rotational movement about, the three axes, x, y, and z [6]. As depicted in Fig. 5, the hexapod consists of a lower platform and an upper platform coupled together with six identical linear actuators. Another example of parallel actuators is the tripod, with one actuator at each corner of the moving platform it allows 3-DOF; roll, pitch and heave [67]. One advantage of these type of systems over robotic manipulators is that an entire vehicle or a vehicle cabin can be mounted on them as seen in several cases. That represents a level of immersion difficult to achieve with a robotic arm manipulator for example.

In a serial mechanism, actuators are stacked and work independently, the most common example in industrial automation being a series of links connected by actuated joints from the base to one end-effector. An example of using this arrangement for simulator motion is depicted in [69] where a jointed robot arm moves around a motion envelope in order to create the motion cues. In the cited work, the motion trajectory was optimized for the 8-DOF motion system, combining the six-axis serial manipulator with a linear track and translational-actuated cabin. Although this has some advantages over the hexapod system, such as a larger motion envelope typically, it has some drawbacks. These include the limitations of speed and acceleration imposed by the joints, the lack of immersion given its form, a high degree of motion noise created by the high friction system, and the most notorious, the need for a very specific inverse kinematics algorithm.

Although many state-of-the-art simulators use a hexapod as the primary source of translational and rotational motion, the most advanced motion systems employ additional mechanisms creating redundant degrees of freedom for increased range of motion in a hybrid combination of parallel and serial actuation. Adding a turntable below the vehicle cabin or on top of the upper platform may help reduce simulator sickness as well as minimizing frame drops in the visual system by removing the need for the visuals to render a high yaw velocity, such investigation is conducted in [70]. Another hybrid system employed is coupling a linear XY motion structure to the lower platform, for a much larger longitudinal and lateral displacement. The large motion area set-up will provide most of the midrange frequency longitudinal and lateral motion, filling the large transfer function dip between the high-passed filtered specific forces and the low-pass filtered tilt coordination inherent with a hexapod alone. A sizing method for this type of configuration is presented in [71].

Some advanced driving simulators have this XY motion in the form of a rail system like in the University of Leeds Driving Simulator [72], the Stuttgart Driving Simulator located in Stuttgart University [73], others in the form of a steel belt drive on oil and bearings like the National Advanced Driving Simulator (NADS-1) [67] located in Iowa, United States. As explained in [68] the motion system of the NADS-1 presents 13-DOF achieved by the combination of a turntable (able to turn 330 degrees) mounted on top of a hexapod (6-DOF) that is attached to an XY platform with a large displacement area (close to 400 m). A dome is assembled on the upper part of the turntable to house the vehicle cabin that is mounted above high-frequency electric actuators. the XY rail track featured in the VTI IV simulator of the Swedish National Road Transport Research Institute [74]. In this work, the competence of this set-up (hexapod + rail track) in providing a motion that delivers realistic cues is proven. Experienced drivers were capable of noticing detailed handling differences caused by variations of the vehicle parameters.

Although the system presented in [68] is considered to be one of the most capable of providing an accurate reproduction of real-world motion in a driving simulator, building systems such as this is not feasible for most testing centers, research institutes, or even vehicle manufactures due to the very high cost and physical space required. Using the concept of a hexapod and linear motion mechanisms, the Driver in Motion (DiM) 9-DOF platform was designed. As detailed in [75], this type of motion system (DiM 150 and DiM 250) relies on the hexapod to provide rotational motion as well as small linear displacements. In addition, the hexapod is coupled to a planar tripod frame that slides on a flat surface through air pads, which allows lateral, longitudinal and yaw motion. This redundant DOF design provides larger workspace use and system bandwidth when compared to the classical hexapods [54], but at a lower cost than larger linear motion systems. Other configuration of the DiM simulator is presented in [59], DiM 700 uses a central pulley (called discframe) driven by four cables. With this configuration, the DiM motion system achieves an even larger motion envelope, which makes it a more suitable choice for applications that require the reproduction of longer sustained accelerations.

The DiM solution is objective of study of several papers regarding MPC motion cueing algorithms such as [76], and figures as one product of higher motion fidelity. When building a simulator, the definition of the motion system is key, and should be done based on the intended application. The work in [77] develops an objective approach to be used when selecting between a 2-DOF, 3-DOF, or 6-DOF motion systems. The work also proposes a method to optimize the motion system geometry based on the future application of the driving simulator. Likewise, the work in [71] proposes an approach to lower the cost of the set-up by optimizing the size of the motion system accounting for the available workspace and a high-fidelity motion response. Both works can be used together as relevant guides for institutes looking for designing their own driving simulators. When designing a motion system, the actuators are equally as important as the architecture. Most recent simulator hexapods use electric actuators in place of hydraulics due to their lower cost and maintenance. They also allow for a higher motion bandwidth, but at a cost of higher friction and motion noise.

## IV. STATE-OF-THE-ART DRIVING SIMULATORS

This session describes recent state-of-the-art driving simulators. The purpose is to give the reader examples of the application of previously mentioned systems. Older examples can be found in literature [9]. Although the following examples vary in number of degrees of freedom and fidelity, they all show a highly immersive environment provided by real vehicle mock-ups and large field of view. It is important to note the widespread use of desktop simulators in education and research centers, which are capable of meeting many research needs, but are not within the scope of the present survey.

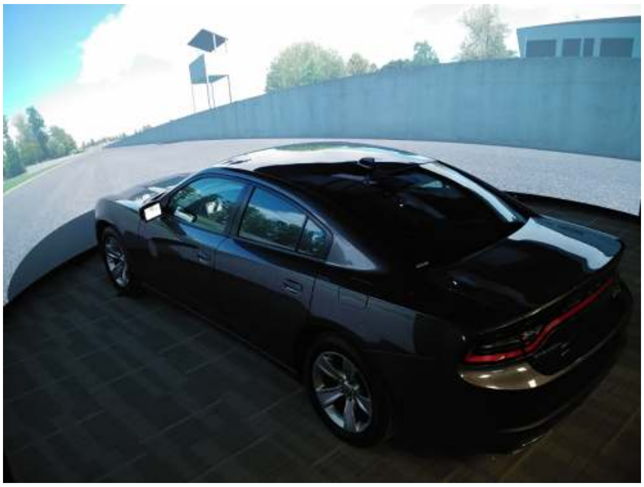

**FIGURE 6.** MARCdrive.

### A. *MARCdrive*

Static simulators are the most common structure applied in research center, both for the lower cost and simple implementation. Among this type of simulators is the MARCdrive lab installed in 2019 at the McMaster Automotive Resource Centre (MARC) in Hamilton, Canada, shown in Fig. 6. Although the MARCdrive is a static simulator, its high immersion is achieved by the real full vehicle facing a curved screen with 210 degrees of field of view (FoV) powered by three projectors. Low fidelity motion cues are given by the active seat and seatbelts. The first, built from air bladders inside the drivers seat, provides soft handling lateral cues (less than 10 Hz). The second pulls the drivers belt to provide longitudinal cues. Active steering and brakes also add realistic haptic cues. Different vehicle dynamics models such as CarSim [78] and VI-CarRealTime [79] can be used in the modular structure. The design of urban traffic scenarios is performed using Vires Virtual Test Drive VTD [80]. The main purpose of this driving simulator is for studies involving driver impairment, autonomous features, the analysis of hybrid powertrain, and energy management systems.

### B. *DriverLab*

DriverLab, shown in Fig. 7 is Canadas most advanced driving simulator and part of the Challenging Environment Assessment Lab located at KITE, the research arm of the Toronto Rehabilitation Institute. DriverLab contains a full Audi A3 mounted on 7-DOF motion system consisting of a 360-degree turntable and a hydraulic hexapod. A curved 360-degree visual projection screen with 12 projectors rendered at 120 Hz and a surround sound system fully immerse the driver in the virtual world. To maximize the level of realism, DriverLab offers two novel features, a rain simulator that produces real water droplets on the windshield and a robotic glare simulator that recreates the harsh glare of oncoming headlights at night [33]. SCANeRStudio [81] defines the scenario and

**FIGURE 7.** DriverLab.

renders the environment, while CarSim is used for the vehicle dynamics model. DriverLab is used to investigate driving safety in challenging conditions with various populations, including the effects of medications, brain injuries, sensory impairments, chronic pain, and neurodegenerative cognitive impairments.

### *C. UNIVERSITY OF LEEDS DRIVING SIMULATOR*

The driving simulator of the University of Leeds is a worldwide reference in driving simulation ever since its launch in 2006. Its 4 m diameter dome houses a complete 2005 Jaguar S-type. The FoV is 250 degrees using 9 projectors and the virtual environment is rendered at a frequency of 60 Hz [82]. Its 8-DOF motion is achieved by the integration of a hexapod and an XY structure 5 m long [83]. The UoLDS also includes features such as haptic feedback through the pedals and steering wheel, and an eye tracking system to monitor driver behavior. Current research using the UoLDS includes driver monitoring, testing of automated driving systems, and road design.

### *D. FIAT CHRYSLER AUTOMOBILES VEHICLE DYNAMICS SIMULATOR*

Inaugurated in 2019, at the Fiat Chryslers Automotive Research and Development Centre (ARDC), Windsor (Canada), the Vehicle Dynamics Simulator (VDC) showcases the next level of DiM technology. It features a DiM 250 driving simulator with a real vehicle cabin on top of a hexapod. The hexapod is coupled to a sliding table, with a tripod providing motion in the XY and yaw directions, which results in a 9-DOF structure. Actuators are electric to provide high frequency responses. The visual system consists of three projectors with a 230 degree FoV screen. Vehicle dynamics is calculated by the VI-CarRealTime software, and graphics are provided by the VI-Graphics engine.

### *E. NATIONAL ADVANCED DRIVING SIMULATOR (NADS-1)*

Although not new (1999), the NADS-1 simulator in Iowa is recognized to be one of the simulators with the highest level of fidelity in motion and immersion. With a combination of electric and hydraulic actuators and a 20 m × 20 m XY motion envelope, its 13-DOF motion system consists in the coupling of the hexapod and XY platform to a turntable where the dome sits on. The remaining 4-DOF are provided by high-frequency vibration actuators mounted replacing the front and rear suspension system at each wheel [68]. The dome receives projected image from 16 projectors resulting in 360 degrees of FoV. Research conducted at NADS-1 comprehends the field of driver-centered analysis as wheel as vehicle system-centered analysis.

## V. APPLICATIONS

Driving simulation is broadly applied in research and industry. As discussed in [84], the use of driving simulators expands with the increasing necessity of developing fast, cost-effective, and safe means of testing interactivity between vehicle, passengers, and environment. The following section showcases some applications for different types of driving simulators.

### *A. DRIVER STUDIES*

For all driver-in-the-loop simulators in the context of this review, the driver is an integral component of the total system being tested. However, one key branch of research is driver assessment, examining specifically the drivers behavior or performance rather than the vehicle systems. The most common use of driving simulation focused on the driver specifically are studies about driver training. Driving simulators can help drivers to enhance their ability and mitigate occurrence of accidents in the real world by presenting risky scenarios as in [85] and [86], typical common situations as in [87] and [88], or using both as shown in [89].

An example of testing driver performance is examining how substances such as alcohol and cannabis impair the ability to drive. To perform these experiments on real roads with real vehicles would be not only unethical but also irresponsible, while this kind of experiment can be safely performed in virtual environments. Examples using driving simulation with alcohol consumption is presented in [90] and [91]. In those studies, subjects were evaluated in low and high quantities of alcohol while others were provided with placebo. The authors agree that the ingestion of alcohol raises the risk-taking behavior of the drivers. They also agreed that lowering the legal limits of blood alcohol concentration (BAC) would lower the likelihood of accidents. Newest studies were similarly performed for cannabis in [92] and [93].

Simulation can also be used to assess sources of distractions. In [94] the influence surrounding vegetation has on drivers attention is evaluated through the use of an eye tracker. The results show that the vegetation plays a minor influence in longitudinal speed and lateral deviation although the roadside clear zone width can impact driving safety. Another use of an eye tracker system is presented in [95], where the system monitors drivers gaze to understand the effects of fatigue on eye tracking measures. It is shown that there is a significant change in the pupil when the driver is alert compared to a fatigued driver, demonstrating the effectiveness of the device on assessing fatigue. A similar device is introduced and tested in [96], using not only eye tracking but also heart rate and skin conductance measurements. Fatigue is also analyzed in [97], and how it leads to driver sleepiness during automated drives. In this paper a dedicated camera monitored head movement in addition to drivers gaze and the results showed that common features used for detecting drowsiness during manual driving might not be sufficient for performing the same detection during automated driving. Other driver assessments that would represent potential harm if performed in real environment but are easily done using simulators include testing mobile distractions [98], performance decay in older drivers [99], and the effects of daylight on sleepiness [100].

Driving simulators can also be used to test human machine interfaces (HMI). Some studies focus on how to design an interface that will be better for the driver to interact with, where simulators can be of great help. That is the case in [101], where the authors evaluate how drivers interact with a secondary device. The participants interacted with a touchscreen, rotary-controller, steering-wheel-controls, and a touchpad. This type of analysis can rate the ease of use of a device during the driving task and show what to employ depending on the purpose of the device. Again, performing these tests in real life could compromise the safety of the people involved. In addition, the ease of integration and testing of such systems in a driving simulator can be beneficial compared to implementing them in a real vehicle.

Most recently, the interaction between automated driving systems and drivers is being a subject of intense debate. In [102], the authors develop an approach to design and verify an HMI system to facilitate the transition from automated driving to manual driving. Other studies even propose interfaces that aim to build trust between passengers and machine in fully automated scenarios, such as in [103]. In this work the authors use VR system to provide the passenger a collection of cues that shares information from the sensors and the route planning.

### B. AUTONOMOUS SYSTEMS DEVELOPMENT

Driving simulation can also be used to test autonomous and advanced driver assistance systems (ADAS). A very common driving assistant system is the adaptive cruise control (ACC). This feature allows the driver to specify its maximum speed and minimum distance to the preceding vehicle. Examples of this work can be seen in [104] where driving simulation is used to explore the use of an ACC system in traffic situations, and in [105] where system failure is explored in different traffic scenarios.

One of the most important scenarios involving human interaction with ADAS is explored in [106], where the take-over maneuver is evaluated in different conditions. The volunteers had to face a forward collision situation with three different systems: autonomous vehicle with and without collision avoidance assistant, and manual drive mode. The results showed a lack of reaction by subjects when driving in the autonomous modes. In fact, the take-over maneuver is object of study of several papers regarding ADAS. In [107] take-over request is studied and an investigation of the orientation of the tactical alert given to the driver (whether towards to the hazard or away from it) is conducted. The transition is assessed in a lane change maneuver where the current lane presents a hazard four seconds ahead. In [108], tactile, visual, and auditory requests are given to the driver in order to understand the differences those modalities have in gaining drivers attention. The work in [109] highlights the importance of instruction and driver training on using ADAS.

Other works assessing take-over maneuvers can be found in [110] where different drivers are evaluated during a failure of the autonomous system, and in [111] where truck drivers face time critical take-over situations while performing a non-driving tasks. In [112], the authors evaluate how scheduled manual driving affects drowsiness and contribute to better take-over maneuvers when needed. In [113], an autonomous emergency braking system (AEB) that adapts to road friction is evaluated in comparison to a non-adaptable system. This scenario illustrates the highest level of assistance a driving simulator can provide during vehicle design because it allies the validation of a new safety feature in a driving condition very difficult to reproduce consistently (i.e. low-friction snowy road). It also highlights the importance of the ability to adapt to a changing situation or condition. Another example of AEB assessment is presented in [114], where several vehicle-bicycle imminent collision events are proposed with the objective of redesigning validation tests in order to cover a larger number of scenarios. A very well-known system is the lane keeping assistant. As described in [115], the lane keeping system helps the driver to keep the vehicle on a lane by applying torque (also called haptic feedback) to the steering wheel. In this work, the impact this system has on drivers fatigue during monotonous driving is investigated by monitoring the standard deviation of lateral position. The benefit of haptic feedback is also evaluated in [116], where the authors found that whole-body feedback during curves can be effective in avoiding hazardous situations when take-over is needed. Furthermore, in [117], a real-time adaptable haptic feedback is proposed based on the level of distraction of the driver.

Finally, driving simulation can be used to test the interaction between fully autonomous vehicles and passengers. In [118], the authors investigate the preference of passengers regarding the level of information the autonomous system exchanges, such as sensor information, directions, and status. This study points out that different users will require different levels of information, which should be accounted for when designing autonomous systems. Smoothness of the autonomous driving is assessed in [72], where a non-linear model predictive control (NMPC) is developed to govern the vehicle trajectory, accounting for safety and comfort, intended to develop a system with a human-like behavior. Another assessment of an autonomous driving system from the perspective of the passengers is depicted in [119]. Here, passengers eye movement is tracked using eye tracking systems to rate the trust in the system. In this work, the results show that driving styles appeared to affect the trust. This shows a relevant paradigm in the use of driving simulators for autonomous systems testing. Not only should safety and efficiency be pursued, but also interaction and compliance with passengers expectations of motion, to achieve mainstream acceptability and a comfortable driving experience.

### C. CHASSIS SYSTEMS DEVELOPMENT

In industry, one of the mainstream uses of driving simulators is for subjective dynamic evaluation and pre-design of chassis components. Although this is one of the larger use cases, due to the confidential nature of industry work, publications are not common. The work performed in [74] proves that experienced drivers are able to identify handling differences given parameter modifications using a driving simulator. The authors used different vehicle parameters such as roll stiffness and tire compliance to reproduced well-known maneuvers, e.g. single lane change. The driver subjective feeling was compared, as well as a comparison between the actual measurements and virtual values of yaw rate, roll, and steering torque. The results motivate works tuning lateral dynamics through suspension, steering, and active control systems. A similar test is conducted in [120], where acceleration of the drivers head was measured during a braking maneuver in a real vehicle and in a 6-DOF simulator. The study was to investigate if the whiplash motion of the neck could be reproduced in the simulator, validating its use for longitudinal dynamics assessments. In [121], different configurations of the steering system are tested by several subjects in three different scenarios, to evaluate how the environment and the system influence the drivers perception of controllability, ease of use and fun while driving. The work developed in [122] goes even deeper into an active steering system and proposed a new model that incorporates drivers gaze, justified by the fact that the steering behavior of drivers change with sightline distances. The results show that this concept can be further used in autonomous systems, since it was shown to achieve more precision than current proportional-integral-derivative (PID) controllers.

As mentioned before, suspension systems are also an object of study in driving simulation, due to the ease of changing components, configurations, geometry, and dynamics without prototyping parts. For active systems, different tunings can be assessed without the need for software compilation. Active control systems such as electronic stability control (ESC) can also be tuned through driving simulation. The work detailed in [123] uses the driving simulator to prove the loss of control reduction provided by the ESC system. In that work, 120 subjects drove into typical crash situations with and without the assistance system. The results show the benefit of having ESC in all scenarios. Another work featuring an ESC system is depicted in [124], where vehicle behavior during anti-rollover interventions is investigated. This kind of test is important as it shows how safety systems behave in standard validation maneuvers compared to how well they perform in real world experiments.

More recent work described in [83] assesses the validity of a driving simulator in mimicking the dynamics of a low-friction test track, showing that although driving simulation can be used for dynamic assessment, there are still limitations in reproducing certain maneuvers and environments.

### D. POWERTRAIN SYSTEMS DEVELOPMENT

Certain aspects of powertrain design can also be studied in driving simulation environment. Given the increase of pollution and imminent shortage of fuel resources, the electrification of powertrain systems is gaining momentum, with research in this field indicating that this technology will be key to solving the energy issue [125]. Several energy management strategies (EMS) have been developed in the past few years [126] for many different powertrain configurations [127] in consideration of the electrification trend, with the objective of reducing energy consumption and raising vehicle efficiency.

In addition, the importance of the journey mapping and driving conditions (e.g. pavement, weather, and traffic) is highlighted by several researchers [83] and [128]. Once more, driving simulation can be a powerful tool, reducing design timing and cost, providing controlled environments, and allowing integration of technologies beforehand. In powertrain design, the HMI analysis is also important. An investigation on how augmented reality (AR) displays can guide the driver during the driving task is proposed in [129], where a hybrid electric vehicle (HEV) is emulated using a co-simulation between a hardware in the loop (HIL) test rig and a driving simulator. This study showed that fuel efficiency can be increased using simple display systems that guide the driver during the journey. The same concept is explored in [130] and [131], where the ability to foresee events using a V2X (vehicle to road/vehicle/database communication) is used in order to display instructions to the driver.

Using the same concept of driver guidance, several eco-driving studies were performed in [132] and [133] to evaluate fuel consumption improvement by instructing drivers on eco-friendly driving behavior. The work in [134] investigates the role gas pedal feedback can play in making drivers achieve a higher fuel efficiency. In this work two different pedal systems were tested by twenty drivers. The results show that the most fuel-efficient behavior is achieved when drivers are provided guiding force feedback (such as a step change in the pedal force) compared to a system that provided increased firmness.

In another study examining fuel consumption, [135] integrates a static simulator with a dynamometer. This integration makes it possible to evaluate the performance of electric vehicle (EV) systems in tests performed by real human in several driving conditions. In [136], ten different drivers were placed in a car following scenario that replicates a realistic driver model for fuel economy assessment of a HEV. The different driver behaviors were analyzed and categorized. This data is used to develop a car following driver model for evaluating fuel consumption, and to create a reference virtual driver that can provide real time feedback to human drivers.

Subjective longitudinal acceleration can also be validated using driving simulation. The authors in [137] used a 6-DOF driving simulator to present different engine configurations to drivers in a tip-in maneuver defined by a sudden step on the accelerator pedal from a constant engine speed (1500 rpm in second gear) without gearshift. The results showed that drivers have the sensibility to perceive changes in the acceleration profile for different engine configurations. That indicates that driving simulators can be used for subjective drivability assessment of powertrains prior to prototyping. In addition, the authors in [138] have shown that it is possible to categorize acceleration levels. That is an important insight to HEV developers since drivability and drivers perception has very tight requirements.

### *E. ROAD DESIGN*

In addition to the aforementioned vehicle design, road design can also be studied and improved through driving simulation. In [139], driving performance is evaluated for different configurations of road signs. A similar work is presented in [140], where audio warnings through differing pavement surfaces (rumble strips) in addition to visual warnings were examined, something that would be costly to create in a physical environment.

## VI. CONCLUSION

This review has explained the mechanisms of driving simulation technology by describing each system in the architecture. The human perceptual system was also briefly explained since the purpose of a driving simulator is to evoke a desired response from that system while imitating the driving experience.

Current state-of-the-art simulators are also presented, together with their most important characteristics and typical uses. These state-of-the-art systems aim for the highest level of fidelity by providing highly immersive set-ups with full vehicle mock-ups, a large field of view, and accurate vehicle dynamics models. The ability to create and control driving conditions and scenarios such as weather and traffic are also key. When using motion, these simulators also include well-developed motion cueing algorithms that account not only for the limitations of the human perceptual system but also for the boundaries of the motion system. Static simulators can often be used in studies where the focus is not primarily closed loop control of the vehicle by a human driver, while motion simulators offer an increased scope of use, including analysis of chassis control and autonomous features.

The final section has shown several examples of driving simulation use. It is important to highlight that the three of the most important benefits of driving simulation are the safety for subject drivers and other road users, the reduction of time in design phase, and the ability to reproduce a variety of controlled scenarios and conditions. In addition, it is possible to foresee positive prospects for expanded driving simulation use. The increasing momentum of autonomous and active control systems means that more virtual validation of these systems will be required in the future. Further, despite some claims that autonomous driving would mean less driver-in-the-loop simulation (due to less human driving), the need for a platform to test system acceptability and to train users will require increased use of simulation, similar to patterns that can be observed in the history of aerospace development. The need for environments that show no harm for the occupants and that can produce precise and reproducible emergency situations will also increase. The same increased use of simulation also holds for the electrification process.

Although some studies were already performed assessing powertrain systems, these analyses will become more common and precise as the need to virtually validate those systems increases. Moreover, driving simulation allows the validation of the interaction between different systems, both at the component and system level. It enables engineers to test the integration between autonomous systems with active safety systems for example, as well as analyzing it from the drivers perspective. This integrated interactive approach is key to develop systems that work as one.

Finally, the next generation of driving simulators will show high connectivity with other testing apparatuses, such as human condition tracking devices, mobile phones, and dynamometers. Although few works were found in this area, the necessity of integrating testing systems is clear given the necessity of integrating vehicle systems. The use of driving simulation is destined to increase, saving time as well as raising the safety of tests.

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