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Research and Development on Noise, Vibration, and Harshness of Road Vehicles Using Driving Simulators—A Review

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Abstract

Noise, vibration, and harshness (NVH) is a key aspect in the vehicle development. Reducing noise and vibration to create a comfortable environment is one of the main objectives in vehicle design. In the literature, many theoretical and experimental methods have been presented for improving the NVH performances of vehicles. However, in the great majority of situations, physical prototypes are still required as NVH is highly dependent on subjective human perception and a pure computational approach often does not suffice. In this article, driving simulators are discussed as a tool to reduce the need of physical prototypes allowing a reduction in development time while providing a deep understanding of vehicle NVH characteristics. The present article provides a review of the current development of driving simulator focused on problems, challenges, and solutions for NVH applications. Starting from the definition of the human response to noise and vibration, this article describes the different driving simulator technologies to tackle all the involved perception aspects. The different available technologies are discussed and compared as to provide design engineers with a complete picture of the current possibilities and future trends.

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1. Introduction

Noise, vibration, and harshness (NVH) strongly affects car occupants' comfort and carmakers devote great efforts for its improvement. Ride comfort, defined as the overall comfort level of occupants during vehicle travel, is closely related to NVH. In fact, the main discomfort source is the vibration and noise of the vehicle transmitted to the cockpit. NVH research and development aims at reducing vibrations and noise in the vehicle and to provide a comfortable driving environment to the occupants [1]. From a NVH perspective, the full vehicle can be considered as a system with excitation sources, transfer paths, and a receiver. Excitations of the vehicle mainly come from the powertrain system, tire/road, and wind. Vibrations are transmitted from the excitation source to the steering wheel, seat, and pedals that are the so-called touch points between vehicle and occupants. Noise is transmitted to the occupants' ears through the vehicle structure and the surrounding air. In the first case it is referred to as structure-borne noise, while in the second case airborne noise.

Experimental and computer-aided engineering (CAE) technologies are currently widely used for NVH research and development. Modal analysis [2], Vold–Kalman order tracking [3, 4], acoustic beam forming [5], and transfer path analysis (TPA) [6] are the most relevant experimental techniques for analysis of vibration and noise signals, transmission paths analysis, and identification of noise sources. However, experimental methodologies are strongly dependent on physical prototypes resulting in costly and time-consuming activities. CAE technologies, such as multibody system dynamics (MSD) [7, 8, 9, 10, 11], finite element analysis (FEA) [12, 13, 14], boundary element method (BEM) [14, 15], computational fluid dynamics (CFD) [16, 17, 18, 19], and statistical energy analysis (SEA) [20, 21, 22, 23, 24], enable engineers to virtually simulate and optimize NVH performance.

Unlike other vehicle performance, NVH cannot be directly evaluated by objective data and is heavily dependent on human subjective perception [25]. In general, in the NVH development process, CAE models are used to conduct virtual experiments, while experimental tests are mainly used to validate the CAE model and to assess the actual vehicle performance. For example, the vibration response at the touch points or the acoustic response at the ears of occupants can be obtained by CAE models, but physical prototypes are still required to subjectively evaluate whether the obtained objective response is pleasant or not. However, conducting a subjective experiment on the physical prototype is very expensive and time consuming, especially at the early concept stage. Driving simulators have the potential to greatly reduce the need of physical prototypes for NVH development [25, 26], while allowing for subjective comfort evaluations from the very early stages of the design process. Driving simulators can provide engineers and even inexperienced decision-makers' and customers' opportunities to experience the vehicle NVH subjectively in a safe way, while reducing costs and time [27].

With the advancement of driving simulation technology, various driving simulators have been developed and are widely used in development and research activities. Reviewer papers [27, 28] can be found in the literature, comprehensively summarizing the existing driving simulators and describing their architectures and capabilities. However, these papers mainly focus on driving simulator capabilities in relation to vehicle handling. In this context, the papers mainly delve into developments and researches on autonomous systems, powertrain systems, vehicle dynamics, and driver behaviors. The mentioned papers do not fully address the problems, capabilities, and opportunities associated with the use of driving simulators. The present article aims to bridge this gap by providing readers with a comprehensive review of currently available simulators and techniques suitable for NVH research and testing.

This article is organized as follows. NVH and the human response to the vibration and noise are briefly introduced in Section 2. Section 3 describes the human perception in driving simulators and how the driving simulators achieve realism. Section 4 introduces the applications of driving simulators in vibration analysis. Section 5 shows noise analysis using driving simulators. In Section 6, the challenges and the future trends are discussed. Finally, Section 7 concludes the article.

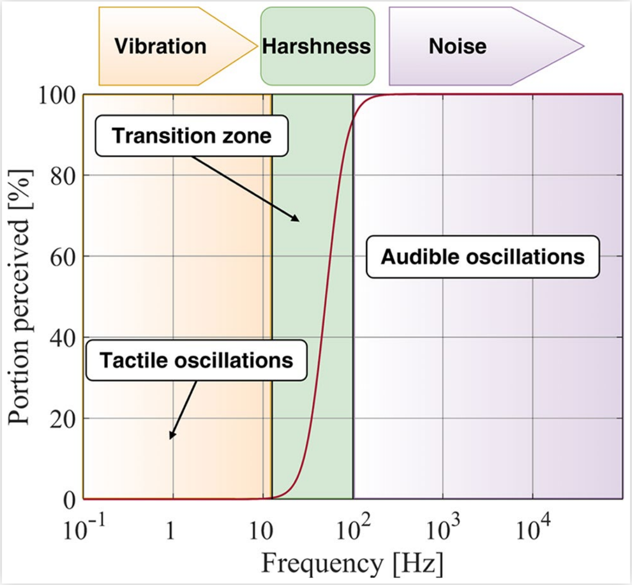
2. Vehicle NVH

Vehicle NVH, also known as noise and vibration (N&V), is the study of the noise and vibration characteristics of vehicles. Usually, mathematical models are employed to analyze car subsystems to find out the factors that have the greatest impact on ride comfort, to mitigate the sources of vibration (amplitude reduction or frequency shift), and to control the transmission of vibration and noise to the interior of the vehicle. Vehicle vibration can reach approximately 200 Hz, while the interest frequency range of vehicle noise can reach up to 8000 Hz [1]. In general, as shown in Figure 1, vibration dominates in the frequency range between 0 and 20 Hz, while noise dominates above 100 Hz. The term "harshness" is used to describe the phenomenon in the frequency range between 20 and 100 Hz, in which vibration and noise occur simultaneously [29]. N&V can be easily measured as objective physical quantities, namely acceleration and sound intensity, but harshness is a more subjective assessment based on human perception and usually needs to be evaluated subjectively by a jury [30].

For both vibration and noise, the system can be described as a "source–transfer–receiver" model. Vibration and noise are generated at the source, such as road and powertrain and transferred through transmission path to be perceived by the receiver, namely vehicle driver or occupants. Figure 2 shows the main sources and the transfer paths of vehicle N&V.

Depending on frequency and vehicle speed, different transfer paths and N&Vs sources become predominant. In particular, frequency has a strong influence on transfer paths,

FIGURE 1 Frequency ranges associated with the terms noise, vibration, and harshness.



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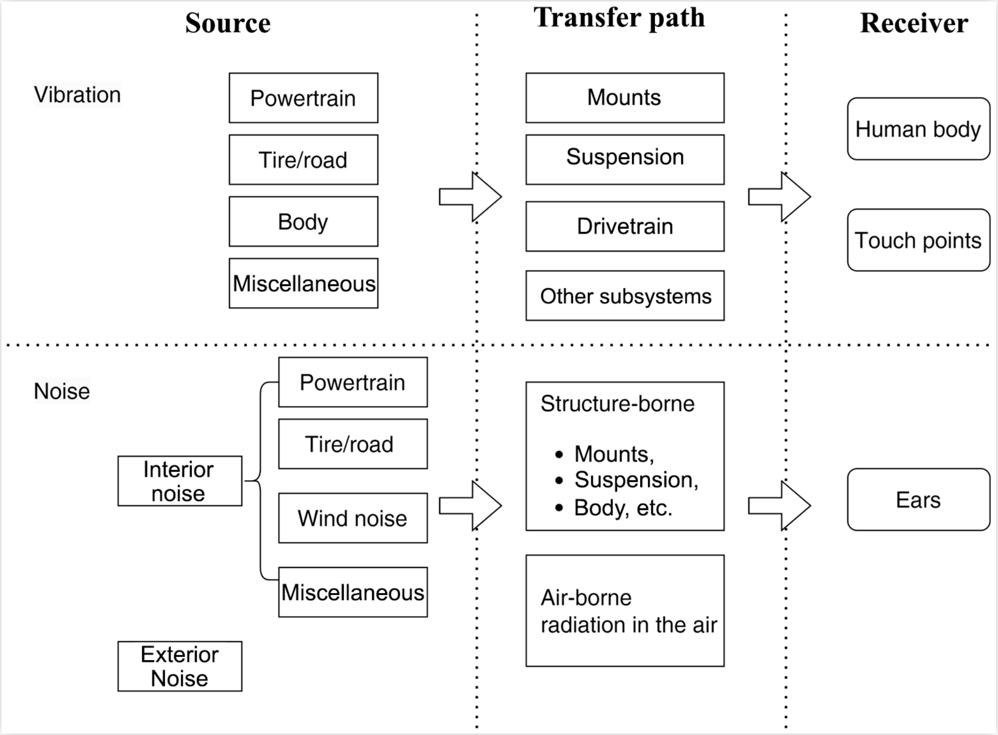
while vehicle speed on N&V sources. For excitation frequencies below 400 Hz, structure-borne noise dominates vehicle interior noise. In this case, vibrations coming from tire/road or from powertrain are transmitted by suspension mounts and excite the vehicle structure. For higher frequencies, airborne noise dominates [32]. Referring to vehicle speed, for low to medium velocities (30–120 km/h) powertrain noise and tire/road vibrations are dominant. In particular, powertrain noise is dominant during accelerations, while tire/road vibration is the major component of interior noise at constant speed. At higher velocities, greater than 130 km/h, wind noise becomes the dominant noise source [32, 33]. Noise is normally described by sound pressure level. The human ear does not respond equally to sounds of all frequencies. Typically, humans can hear sound from about 20 Hz to 20,000 Hz and are most sensitive to sound around 2000 Hz [30]. Therefore, to approximate human hearing sensitivity, the A-weighting characteristic is used to adjust the measured sound pressure level [34].

Vibration is normally measured in terms of acceleration levels. The human body response to vibration is closely related to not only the magnitude but also the direction and the frequency of the vibration [32]. The frequency range relevant to human health and comfort is approximately 0 to 100 Hz [35]. Below about 0.5 Hz, the vibration can cause occupants motion sickness, such as sweating, nausea, or vomiting [35]. In the higher-frequency range (above 100 Hz), vibration mainly has an impact on the health and comfort of the person holding a tool, i.e., hand–arm vibration, but for whole-body vibration, the high-frequency vibration can be attenuated significantly or even isolated by the human body [35]. In vehicles, vertical vibration is the dominant component of vibration below 20 Hz and is transmitted through the seat [32]. The resonance frequency, which causes significant amplification of vibration in the human body, typically varies for different parts of the body and posture [35]. It is generally accepted that 5 Hz is the

FIGURE 2 Vehicle noise and vibration.



Based on Ref. [31]. © Gianpiero Mastinu, Haoxiang Xue, Giorgio Previati, Massimiliano Gobbi first major resonance frequency of the human body and that vibration acceleration often causes discomfort. The second resonance is in the range 7 to 12 Hz [35]. Longitudinal, lateral, and rotational vibrations are also considered important for comfort in many studies [36, 37, 38, 39, 40]. In [37], all seat–head transfer functions have been experimentally identified, showing that two resonances occur for longitudinal head motion at 1.5 and about 8 Hz, respectively; while the resonance frequency for the lateral one is 2 Hz. Also, the seat back can change the seat–head transmission of vibration of a seated subject [32, 41]. Rotational vibration dominates discomfort at very low frequencies, typically less than 0.5 Hz [38, 39]. In addition, human body is more sensitive to random vibration than sinusoidal vibration [42]. Experiments show that humans are very sensitive to low-frequency random vibration both in vertical and longitudinal direction (below 1 Hz) [43]. Thus, according to the sensitivity of human body to different frequency vibration, the international standard ISO 2631-1 [44] applies frequency weighting to vibrations.

In addition to whole-body vibration, hand–arm vibration has also received attention. Finger or hand exposure to vibration or repeated shock can give rise to various symptoms, such as joint and bone disorders, muscle disorders, neurological disorders, and vascular disorders [32, 35]. In road vehicles, vibration transmitted to the hand through the steering wheel occurs at low magnitudes or for short durations and is more reasonably associated with discomfort than injury or disease. At low frequencies, energy cannot be absorbed locally into the hand and, if of excessive magnitude, can generate large displacements of the steering wheel making driving difficult or even impossible to drive the vehicle [32]. At high frequency (above about 1000 Hz), the vibration can be easily attenuated by the interior components of the steering wheel or gloves. Therefore, it is commonly considered that the frequency range of interest for hand–arm vibration is approximately between 8 and 1000 Hz [35]. The international standard ISO 5349-1 [45] specifies frequency weighting for the evaluation of hand–arm vibration.

Summarizing, human response to vehicle vibration and noise is very complex and closely related to the frequency of excitation, transmission path, and driving scenarios. In such situations, mathematical models alone are insufficient for a comprehensive evaluation of human perceptions in a vehicle. Experimental activities become necessary. Driving simulators can be a viable solution for these activities, provided that the simulator employed achieves a sufficient level of realism.

3. Driving Simulator Fidelity and Human Perception in Driving Simulators

As described in the previous section, humans are sensitive to various ranges of vibration and noise. As each human has a different perception of such quantities, an objective relationship between vibration and noise and some NVH performance index is rather difficult [30], its assessment strongly relays on subjective evaluation. Driving simulators are a powerful tool to allow engineers to confidently evaluate NVH when a physical prototype is not available.

When using a driving simulator for reproducing a feature of a vehicle, the most critical issue is the actual correlation between the driving simulator and real-world experiences. For this reason, one of the key issues of the driving simulation technology is achieving a fully immersive real-world driving experience for the driver. The level of realism that a simulator can provide is referred to as its “fidelity.” The fidelity of the driving simulator is mainly considered in terms of physical fidelity, functional fidelity, behavioral fidelity, motion fidelity, task fidelity, psychological fidelity, and the like [46]. Among them, the physical fidelity is the most frequently emphasized. According to the physical fidelity, the driving simulator can be classified as low-level, mid-level, and high-level based on the physical hardware configuration [47]. Low-level driving simulators typically consist of a PC and a monitor. Mid-level driving simulator equips with advanced imaging technology, a large screen, and a realistic cab. High-level driving simulators include a close to 360° screen, full-feedback motion base, and a vehicular cockpit with full controls [47]. In general, a driving simulator with a lower level of physical fidelity cannot match the realism of a higher-level driving simulator [48]. Furthermore, drivers’ behavior is closer to driving a real car if the vehicle responds more realistically, resulting in higher fidelity [49].

In the driving simulator, the human body perceives the driving experience through multiple sensory systems, including the auditory–visual, somatosensory, and vestibular systems, which are essential for providing a realistic driving experience [28]. Studies examining the effects of drugs [50] and sleepiness [51, 52] on driving performance using driving simulators have shown that the driving simulator can estimate the impact of these factors on driver response. However, because driving in a driving simulator is more monotonous than real-world driving, drivers are more susceptible to hypovigilance. Furthermore, differences in lighting conditions and traffic between on-road studies and driving simulators could account for the discrepancies observed in the results [52]. Additionally, while high-fidelity driving simulators are more valid than low-fidelity ones, the absolute validity of the driving variables related to sleepiness has not yet been achieved even with high-fidelity driving simulators. To address these limitations, it is crucial to create a driving environment for participants as close as possible to the real world. For NVH work highly dependent on subjective feelings, high-level simulators that can immerse the driver realistically have a more compelling potential. However, for the initial stages of vehicle concept design or single phenomena such as noise, low- to medium-level simulators are the more efficient and economical choice since no complex model is required.

In static driving simulators, the driver perceives motion primarily through visual and auditory [28]. In [53], time to contact (TTC) was evaluated on the static driving simulator in considering different conditions, namely vision-only, auditory-only, and vision–auditory scenarios. As a result, the relative weight of vision and auditory was obtained, suggesting that visual sensory accounts for the majority of motion perception. Auditory perceptions can enhance the driving experience. Therefore, particular care is taken in the graphical and sound environment of the driving simulator. Rounded screens and three-dimensional sound are introduced in the most advanced driving simulator. Also, rearview vision is added to most driving simulators for enhancing the realism [54]. Additionally, virtual reality (VR) head-mounted displays (HMDs) can be used as an alternative in driving simulators to visually immerse the driver in the simulated environment [55, 56, 57].

In dynamic driving simulators, not only visual and auditory perceptions account for the motion feedback, but other sensories are also involved, such as somatosensory and vestibular systems. Due to the limited workspace of the driving simulator, the motion of the real car cannot be fully reproduced, i.e., a "1 to 1" real-car response on the driving simulator cannot be replicated. Motion cueing algorithms [58] are introduced to convert the vehicle motion response in a feasible driving simulator motion, which complies with the available working space. Motion cueing algorithms can be categorized as washout filter algorithm [59], adaptive filter algorithm [60, 61, 62], optimal filter algorithm [63, 64, 65], and model predictive control (MPC)-based algorithms [66, 67, 68]. Among them, the MPC-based algorithm, despite the need for complex models and a great deal of computational effort, can provide a more effective utilization of the available space in relation to the driver experience and according to the characteristics of the human vestibular system [28]. Additionally, to provide a more refined acceleration feedback to the driver and increase the realism of the virtual environment, an active seat can be used. The active seat is controlled by a nonlinear model predictive control (NMPC) based on multi-sensory cueing algorithm (MSCA) [69].

In [70], a study on the comparison of motion sickness assessment in static and dynamic driving simulators is presented. The study highlights that subjects' head movements in dynamic driving simulators are similar to those in real cars, while head movements in static driving simulators tend to differ significantly or even conflict with respect to those in the real cars.

Haptic feedback also plays an essential role when driving both real cars and driving simulators [71]. Thus, haptic-feedback steering wheel systems are employed to simulate the disturbance from tire/road and the response from vehicle dynamic [62]. In [72], by comparing the presence or absence of haptic feedback on the steering wheel, a similar conclusion is drawn that haptic feedback can improve the driving experience on the driving simulator.

Achieving a fully immersive real-world driving experience is a challenge due to the complexity of the human perception system and the physical limits of driving simulators. Many methods, such as improving physical hardware, motion cueing algorithms, visual–auditory cueing, and haptic feedback, can enhance the fidelity, namely the realism, of driving simulators. Table 1 shows a summary of driving simulators for NVH and ride comfort applications.

4. Application of Driving Simulators in Vibration Analysis

Vibration analysis is an important part of NVH. Vibration is transmitted from the road and the powertrain system through the structure to the human touch points such as seats, pedals, and steering wheel. As described, driving simulators can be classified as low-level, mid-level, and high-level based on physical fidelity. However, according to the components that generate the vibration, the majority of driving simulators for vibration analysis can be classified as shaker-based and hexapod-based. In this section, the application of driving simulators in vibration analysis is presented, based on the two considered types of driving simulators. The main feature and applications of these two types of driving simulators are presented in Table 2.

4.1. Shaker-Based Driving Simulators

Shaker-based driving simulators are realized by fixing a rigid platform on a shaker to reproduce the vibration. This driving simulator can typically provide relatively high-frequency vibrations, up to 200 Hz [97]. In addition, due to its simple structure and ease of control, this type of driving simulator has been extensively used to study human perception of vibrations [73, 74, 75, 96, 97, 99, 100, 101, 102].

Ahn et al. [76] examined the effects of amplitude, frequency, and direction on discomfort of seated subjects using a driving simulator with a single-degree-of-freedom vertical shaker. They also explore the weighting method of the standard BS 6841 and note that for low frequencies, the weighting W_b underestimates the discomfort level for high amplitude, while gives reasonable estimation for low and moderate values.

Besides seated human response to vibrations, single-shaker driving simulators can also be employed to investigate the response to steering wheel vibration, namely hand–arm vibration (HAV) [103, 104]. Steering wheel driving simulators consisting of a rigid frame, a steering wheel, a steering shaft, and an electrodynamic shaker connected to the shaft are employed to reproduce steering wheel vibrations in several papers [77, 78, 79]. In Ajovalasit et al. [78], the human subjective response to amplitude-modulated steering wheel idle vibration is investigated. They found that humans cannot feel the difference in amplitude modulation when such modulation amplitude is below a critical value. When the modulation

TABLE 1 Driving simulators serving NVH and ride comfort.

Simulator type	Research institutes and companies	Features	Applications in NVH and ride comfort	References
Seat Vibrator Platform	Institute of Sound and Vibration Research, University of Southampton	Equipped with a hydraulic vibrator for vertical vibration	Human whole-body response to vibration, ride comfort	[73, 74, 75, 76]
Steering Wheel Simulator	The University of Sheffield, UK	Equipped with an electrodynamic shaker for rotational vibration and headphones for noise	Hand–arm vibration	[77, 78, 79]
Seat Vibration Simulator	Delft University of technology	Equipped with four excitation units composed of longitudinal and vertical shakers below the seat. 5-DOF vibration between 10 and 80 Hz, no yaw	Ride comfort	[80]
SI2M	Institut Image, Arts et Métier, France	Equipped with 4 D-BOX actuators for touch-point vibration, head-mounted display (HMD) for visual and sound	Simulator sickness	[81]
Multi-Axis Ride Simulator (MARS)	The United States Army Aeromedical Laboratory	Based on a hexapod platform with 6 DOFs. Capable of offline vibration tests	Military vehicle ride comfort	[82]
Universal Driving Simulator	University of Tokyo	Based on a hexapod platform, surround screen for visual. Capable of integrating with multibody dynamics simulations	Ride comfort	[83]
Simulateur Automobile Arts et Metiers (SAAM)	Arts et Metiers ParisTech	Based on hexapod platform system, equipped with 150° dome view and integrated multi-level real-time measuring techniques	Motion sickness	[70]
BMW Ride Simulator	BMW research center	Based on hexapod–tripod platform with projection screen	Ride comfort, chassis development	[84, 85]
VTI Simulator III	Swedish Road and Transport Research institute	Based on a 4-DOF platform. Equipped with three DLP projectors for 120° of vision, a vibration platform provides high-frequency vibrations	Ride comfort, road noise evaluation	[86]
Desktop NVH Simulator	Bruel & Kjaer North America Inc.	Consist of a screen, steering wheel, and pedals. Free-driving tests with CAE models. Exterior Sound Simulator (ESS) software can be installed for vehicle exterior noise simulation	Vehicle interior/exterior noise evaluation, powertrain sound quality	[87, 88, 89, 90]
Vehicle Sound Simulator (VSS)	RENAULT S.A	A Desktop NVH simulator consists of a screen, steering wheel, pedals, and headphones for vehicle sound. Model-based system testing is applicable for NVH assessment in free driving	Vehicle interior noise evaluation, active sound design	[91]
On-road NVH Simulator	Nissan Technical Centre Europe	Sensors mounted on a real car replace the instantaneous performance of the vehicle used in Desktop NVH simulator	Vehicle interior noise evaluation	[92]
Operator-in-the-loop Driving Simulator	DaimlerChrysler Corp. Michigan Technical Center	Equipped with 220° wrap-around spherical projection screen, electrodynamic actuators to generate touch-point vibration, binaural sound environment delivered through headphone and speaks	Touch-point vibration, vehicle interior noise evaluation	[93]
VI-grade Compact Driving Simulator	VI-grade	Based on the desktop simulator, extra shakers provide touch-point vibration	Vehicle interior noise evaluation	[94]
Full-vehicle NVH Simulator	Bruel & Kjaer North America Inc.	Based on a mid-size sedan vehicle body, projection screen for visuals, on-board shakers for touch-point vibration generation, headphones, and subwoofer for sound	Touch-point vibration, vehicle interior noise evaluation	[95]

TABLE 2 Primary features and applications of shaker-based and hexapod-based driving simulators.

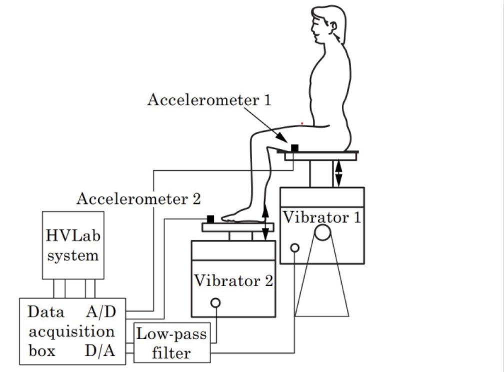
	Feature	Application
Shaker-based		
Single-shaker-based driving simulator	One DOF vibration	• Human response to vibration [73, 74, 75, 96, 97, 98, 99, 100, 101] • Active suspension [102] • Steering wheel vibration [77, 78, 79, 103, 104]
Multi-shaker-based driving simulator	Multiple DOFs vibration	• Human response to vibration [43, 80, 105, 106, 107, 108] • Vibration analysis at touch points [81, 93, 95, 109, 110]
Hexapod-based		
Stewart platform	6 DOFs vibration	• Human response to vibration [111]
Stewart platform + extra mechanisms	6 DOFs vibration, redundant DOFs to split high and low frequency of actuation	• Ride comfort evaluation [83, 84, 85, 112, 113, 114, 115]
Stewart platform + extra shakers	6 DOFs vibration motion, on-board shakers compensate for high-frequency vibration	• Suspension development [83, 84] • Seat suspension design [116]

amplitude is above this critical value, the stimulus–response relationship increases monotonically according to the Stevens power law [117], which describes the psychophysical relations above the modulation amplitude threshold.

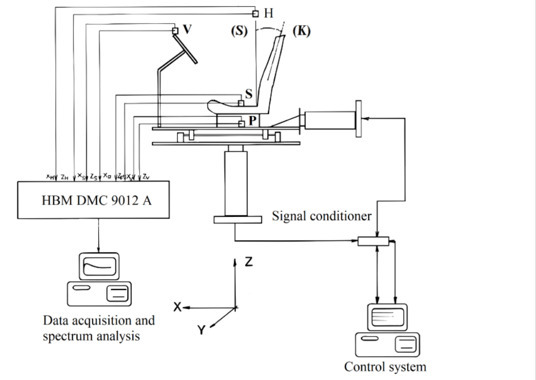
Shaker-based driving simulators equipped with just one shaker can only provide a single-degree-of-freedom vibration. Combining two or more shakers more DOEs of vibration can be reproduced [105, 106, 107]. Jang et al. [108] investigated the effect of phase differences between seat and floor on the seated human body with different postures (with and without thigh contact) by using a driving simulator, which consists of two vertical shakers [Figure 3(a)]. They found that humans are more sensitive to phase difference at low magnitude vibration with thigh contact than without thigh contact. Demić et al. [43] placed two shakers horizontally and vertically [Figure 3(b)] to simulate the vehicle body response under longitudinal and vertical vibrations, finding that the human head response for multidirection vibration (longitudinal and vertical) cannot simply be approximated by superimposition on the human head response for a single-direction input. In addition, equivalent comfort curves were developed based on the results of the subjective experiment, which indicate that the human body is more sensitive to multidirectional vibration. In Zhao [80], the vertical and longitudinal vibration of a seat is studied by mounting a specially designed excitation unit [shown in Figure 4(a)] at each mounting point of the seat base. The excitation unit is composed by two shakers connected to a bracket and acting one in the vertical and one in the longitudinal direction. Seats of different dimensions can be accommodated in the driving simulator [Figure 4(b)]. A time waveform replication (TWR) process is employed to provide the vibration time histories to the different actuators. According to the results of the study, the TWR method can provide a good accuracy to tracking the target vibration stimuli within 6 to 80 Hz.

In a realistic driving environment, vehicle vibrations are transmitted to the driver through the touch points, namely steering wheel, pedals, seat base, and seat back. However, the previously mentioned driving simulators only reproduce the vibration response at one touch point such as seat or steering wheel. In order to provide a more realistic situations, driving simulators with shakers at multiple touch points have been introduced [93], such as SI2M driving simulator [81, 109] [shown in Figure 5(a)] and Vi-grade compact driving simulator [94] [shown in Figure 5(b)]. In [95], a full-vehicle driving simulator (shown in Figure 6) with shakers at different touch points in the cockpit allowing for better simulation of the cabin environment is presented. In this article, the full-vehicle driving simulator has been employed to compare the sound and vibration characteristics of two very similar vehicles that received different subjective comfort evaluations. It turned out that by employing a realistic driving simulator environment, the reasons for different subjective evaluations became clear. Genuit et al. [110] conducted a subjective evaluation of the vibration response of a car in a static full-vehicle driving simulator and compared the results with similar tests performed on the actual vehicle. The result shows that rating scores of seat and steering wheel vibration are significantly different between driving simulator and actual car. Such differences may be caused by the mismatch between the expected lack of vibrations in a stationary vehicle and the actual perceived vibrations in the static driving simulator. This mismatch led to perceiving the vibrations more uncomfortable than they were in the actual car. Interestingly, tests on the vibrations perceived in a situation of starting engine showed a very good agreements between the ratings given on the static driving simulator and on the real car. This showed that if the expected situation does not differ between the real car and the static driving simulator, similar comfort evaluations can be obtained.

FIGURE 3 Driving simulators with two shakers.



(a) Simulator with two vertical shakers



(b) Simulator with a vertical and a longitudinal shakers

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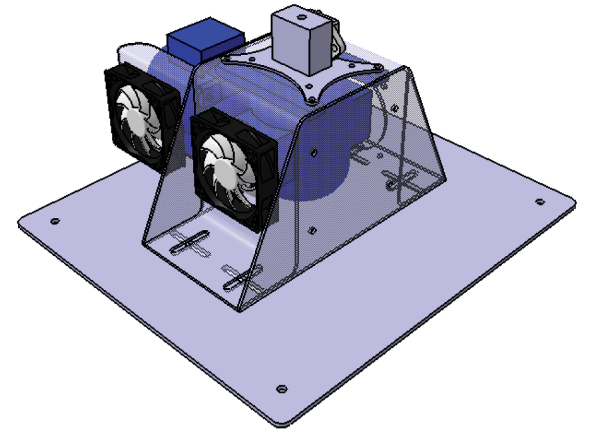
FIGURE 4 Ride comfort driving simulator with four bracket assembly units. Adapted from [80].



(a) Bracket assembly

(b) Overview of the driving simulator

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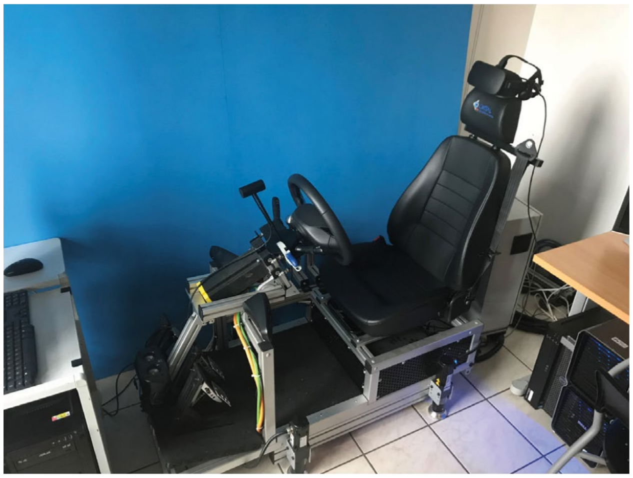
4.2. Hexapod-Based Driving Simulators

The hexapod platform is a system, usually, but not necessarily, based on Stewart mechanism, that can provide 6 DOFs of movement. It consists of a stationary platform, a moving platform, and six struts with changing lengths connecting these two platforms [118]. Modified Stewart mechanisms are also employed where instead of varying strut lengths, the spherical joints connecting the struts to the ground are moved, which reduces the total height of the dynamic driving simulator [119, 120]. The schematic of a standard hexapod platform is shown in Figure 7. The moving platform is used to support the load and the stationary platform is generally fixed to the ground. The full-motion platform like the hexapod platform is generally known as a dynamic driving simulator. Hexapod-based driving simulators can offer a large range of motion at low frequency, which means that they can provide a more realistic simulation of low-frequency driving conditions such as acceleration, braking, and steering.

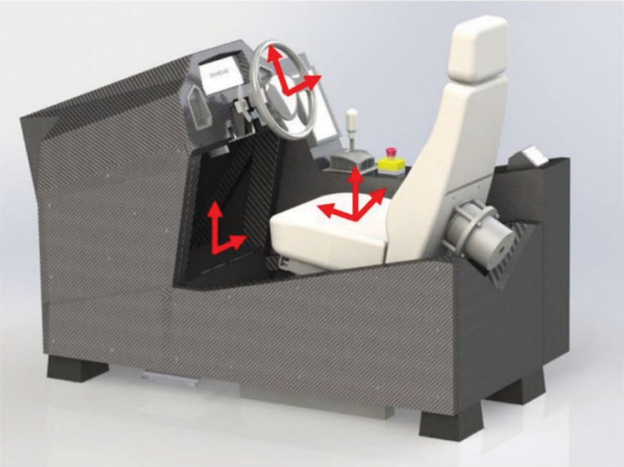
The hexapod platform has been widely used to reproduce vibration [121, 122, 123, 124, 125] and vibration isolation [126, 127, 128, 129, 130]. A hexapod platform, named MARS driving simulator, is used to reproduce the ride motion of army vehicles based on an offline control strategy to investigate the human response to the vibration [82]. In [111], in order to figure out how the human body reacts to absorb the vibration, a comparison of vibration response between a human body and a dummy is performed by sitting both human and dummy on a hexapod platform. As the human body is a biomechanical system, comprising both spring and damping effects of muscles and internal organs, a rigid dummy could not accurately reproduce human body vibrations. Thus, in [40], a non-rigid dummy has been developed for ride comfort objective evaluation.

Marjanen et al. [112] applied a hexapod platform to evaluate the discomfort on the basis of ISO-2631-1 standard and analyze the effects of combination of axes and location, frequency weighting, averaging method, and multiplying factors on the correlation. Frequency weighting and r.m.s methods can improve the correlation between vibration and the subjective rates, but the multiplying factors in the ISO-2631-1 standard could degrade the correlation. Shiiba et al. [83] employed a full-vehicle multibody model to provide a hexapod-based driving simulator with the vibration time histories of a considered vehicle in order to conduct ride

FIGURE 5 Representative driving simulators with shakers at touch points.



(a) SI2M driving simulator



(b) Vi-grade compact driving simulator

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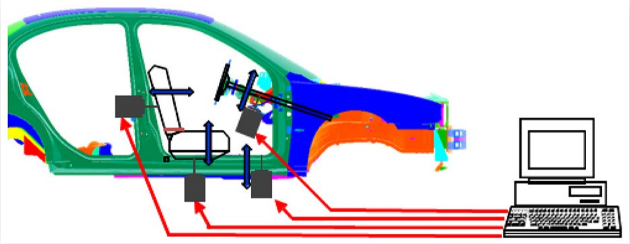
comfort tests. During the tests, spring and damping characteristics of the suspensions have been tuned accordingly to subjective comfort evaluations. In addition, the hexapod platform is also used for seat suspension design. Blood et al. [116] used a hexapod platform for seat suspension design, comparing the performance of three different types of seat suspensions, namely air-ride bus seat, air-ride truck seat, and electromagnetically active seat (EM-active seat). Through the subjective evaluation experiment, it is concluded that the EM-active seat ride comfort performance, passing over three different road, is better than other two seat suspensions.

Lower motion frequencies are limited by the travel of the actuators of the Steward platform. In order to expand the range of motion, most of state-of-the-art driving simulators mount the base of the hexapod platform over a platform able to move in the plane and to provide additional travel, typically in longitudinal and lateral directions and, in some cases, yaw rotation [27, 28]. Examples of arrangements with the platform can move only along the longitudinal and the lateral directions are the Renault driving simulator-ULTIMATE [131, 132] UoLDS of University of Leeds [133, 134], and the SHERPA2 driving simulator [135, 136]. A more sophisticated implementation is presented in [67, 68, 69, 119] where the hexapod is mounted on a platform able to move in the plane x and y direction and can also rotate around the vertical axis.

FIGURE 6 Schematic of full-vehicle driving simulator—shakers mounted close to the touch points inside the cockpit.



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Spickenreuther et al. [84] proposed an iterative design approach for improving ride comfort (Figure 8). In each iteration, after validating the MBS model, experts are allowed to experience it on a full-motion driving simulator and then suggest improvements to substitute back to the MBS model for further computation. In [114], skilled drivers are asked to perform the subjective evaluation of a vehicle on a driving simulator. The results show that the driver can accurately

FIGURE 7 Schematic of hexapod platform.

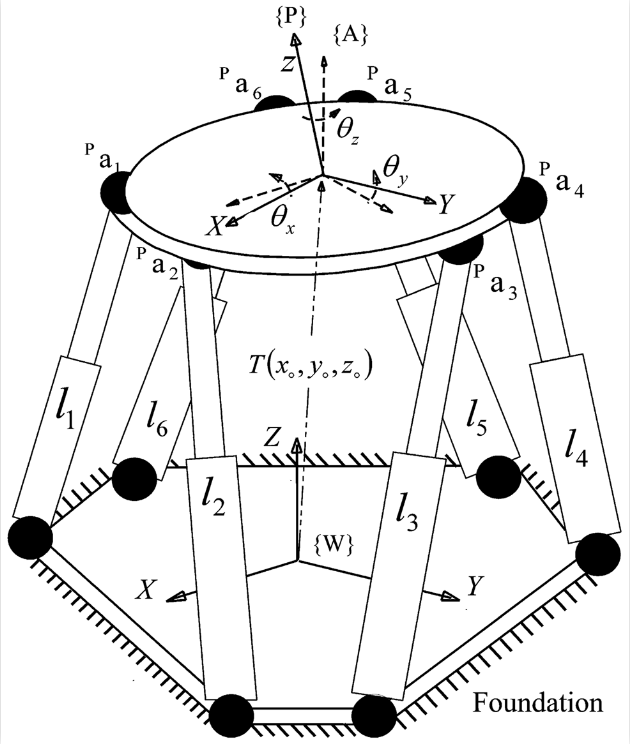

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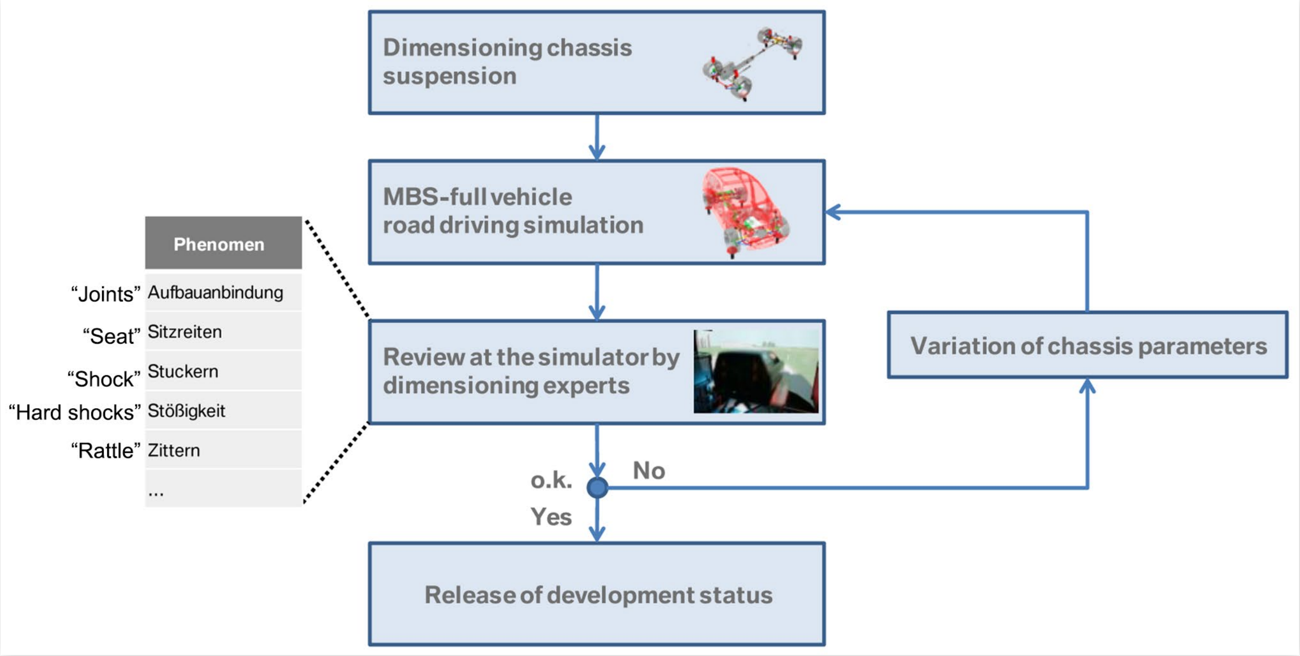
FIGURE 8 Application of the driving simulator during the dimensioning process of the chassis.



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determine the changes in vehicle response corresponding to the relevant parameters.

Driving simulator can be used for subjective evaluation to screen the design solutions, when the RMS level of acceleration of different designs are the same or similar, but with different frequency contents. Figure 9 depicts multibody dynamics simulation results for three different solutions, showing very similar frequency response. By using such results, it is very difficult to objectively define the optimal design, but the subjective evaluation of the three designs using the driving simulator allows for the selection of the design with the best ride comfort potential [84].

As level 3 autonomous vehicles are not permitted to be operated on public roads, Enders [85] conducted an investigation at the BMW research center using a hexapod–tripod dynamic driving simulator. The study aimed to assess the impact of current state-of-the-art suspension systems on driving comfort for automated driving, considering both subjective and objective perspectives. In this article, vehicle body vibration is weighted according to the ISO 2631 [44] and used for comparison. The driving simulator has demonstrated acceptable performance in reproducing vertical dynamics. Although there are distinguishable differences in objective values between the simulator and the real vehicle, the driving simulator effectively maintained the relative relation among suspension variants. Additionally, the subjective rating aligns with the overall trend observed in the objective values.

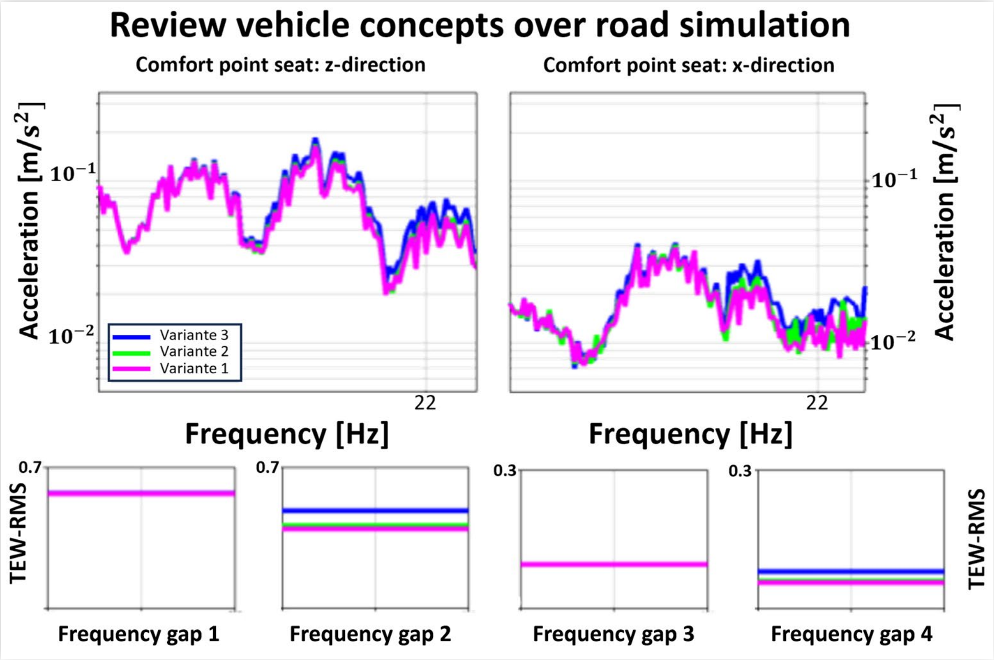
Normally, the hexapod-based driving simulator can only accurately reproduce low-frequency vibrations but can simulate the motions of the whole cockpit. Conversely, shaker-based simulators demonstrate an enhanced capability to replicate high-frequency vibrations as well as localized and nuanced vibration responses, but do not reproduce the low-frequency cockpit motions. In order to obtain a higher-frequency response on hexapod-based simulators, the benefits of shaker-based simulators can be exploited by installing additional shakers and add higher frequencies of vibrations [137, 138]. Additional shakers can produce vibrations up to 200 Hz, but shakers control and coordination with the hexapod platform are still open problems and have not yet been addressed. Table 3 summarizes the benefit of the driving simulator in the evaluation of all aspects of vibration with quantification. As we can see, the hexapod-based driving simulator with additional shaker has great potential in evaluating vibration, although there still are control challenges.

5. Noise Evaluation Using Driving Simulators

Occupants receive noise mainly through ears rather than through multiple contact points like vibrations. Therefore, for NVH simulators that simulate noise typically suffice a computer and a headphone or loudspeakers. Motion mechanisms, especially high-frequency actuators, can be present to increase the realism of the experience. There are mainly two types of NVH simulators: non-interactive and interactive.

Non-interactive NVH driving simulators are mainly used to reproduce a specific condition through headphones or loudspeakers based on test or simulation data. In [99, 139, 140], the previously recorded sound is reproduced by headphones or loudspeakers while the driver is seated in a shaker-based

FIGURE 9 Application of the driving simulator for the design selection—from the MBS simulation, three different alternatives show similar vibration response and RMS values in different frequency range.



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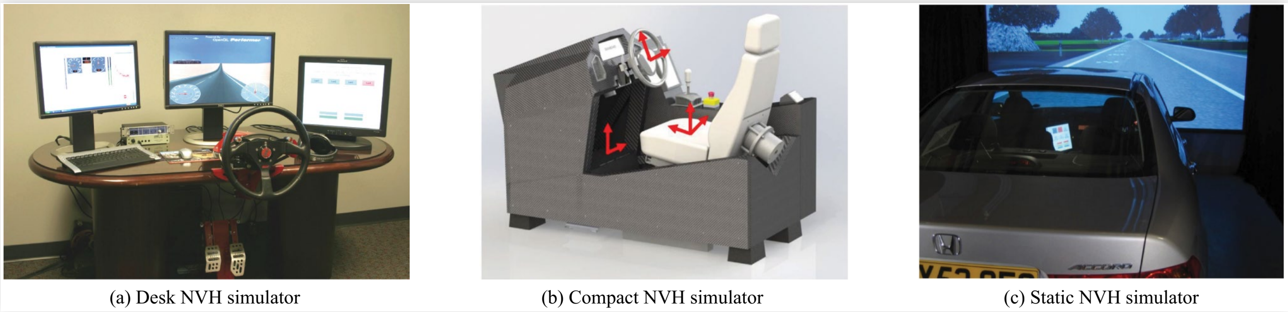
simulator. In some applications, the noise analysis is focused on some specific components. In these cases some specially developed in-lab simulators are employed, in most cases coupled with a physical prototype [141, 142, 143]. Therefore, this type of component simulator requiring a physical prototype is only available at the end of the vehicle prototyping phase.

Interactive NVH driving simulators, contrary to non-interactive simulators, allow the drivers to actually drive the vehicle while computing in real time the sound that drivers would perceive in the corresponding real vehicle. Representative NVH simulators include Desktop NVH simulator [shown in Figure 10(a)], compact NVH simulator [shown in Figure 10(b)], and static NVH simulator [shown in Figure 10(c)]. These simulators can be used for the so-called free-driving mode, allowing drivers to use vehicle controls, such as throttle pedal, brake pedal, steering wheel, and gear selector during the evaluation [25, 26, 91]. In [91] a vehicle sound simulator (VSS) that allows both subjective and objective NVH assessment in free-driving mode has been developed and applied to the NVH assessment in hybrid vehicles design. Although a comprehensive vehicle model that generates noise is still unavailable, by using model-based system testing (MBST) technology [144], the driver's input is converted in real-time to vehicle performance variables (i.e., engine rpm, vehicle speed, CAN output, etc.), which are fed to the virtual prototype assembly (VPA) for vehicle sound live synthesis [91]. Furthermore, by combining the virtual car sound (VCS) synthesis technique [145], which can reproduce typical sound features of the road vehicle, the VSS simulator can enable engineers to subjectively evaluate and live editing of the component NVH performance in a full-vehicle assembly. An alternative approach is presented in [92] where an on-road simulator installed on a real car (shown in Figure 11) is introduced for validation and fine-tuning of the designed sound.

TABLE 3 Benefits of each type of driving simulator toward different vibration aspect (– poor; + good; ++ very good).

	Low-frequency whole-body vibration (below 20 Hz)	High-frequency whole-body vibration (up to 200 Hz)	Harm and hand vibration at steering wheel	Touch points vibration
Single-shaker-based driving simulator	+	+	+	–
Multi-shaker-based driving simulator	+	+	+	++
Hexapod platform	++	–	–	–
Hexapod platform +extra mechanisms	++	–	–	–
Hexapod platform +extra shakers	++	+	+	+

FIGURE 10 Representative interactive NVH driving simulators.


(a) Desk NVH simulator
(b) Compact NVH simulator
(c) Static NVH simulator

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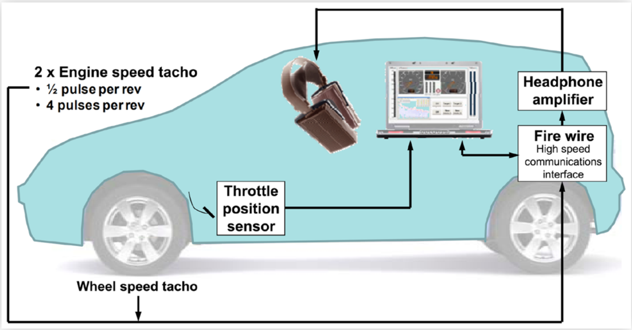
The advantage of this solution is that it can increase the realism of the driving experience as the real car can provide realistic vibrations and steering feeling [92]. Primary features and applications of non-interactive and interactive NVH driving simulators are summarized in Table 4.

In the traditional NVH development process, benchmarking, target positioning, validation, and fine-tuning of interior noise rely heavily on the physical prototype car. Because of the realism and immersivity of NVH simulators, the simulator can provide a realistic driving experience to the driver. NVH simulators give decision-makers and engineers a chance to experience noise without a physical prototype in the initial stage of vehicle development. According to [150, 160], the application of NVH simulators in the whole NVH development can be summarized as explained in Figure 12. NVH simulators provide engineers with a tool able to provide a deep understanding of test or experimental data. The efficiency of the NVH process can be improved by combining interactive jury evaluation, target creation, and sign-off capabilities into one tool and by using a common vehicle database, which can directly link customers, decision-makers, and NVH engineers [150].

FIGURE 11 Schematic of on-road NVH simulator—engine & wheel speed Tacho and throttle position sensor replace the vehicle performance used in Desktop NVH simulator.



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In the next subsections, the application of simulators to evaluate different noise types is described. First, interior noise, i.e., the noise perceived by the occupants such as powertrain noise, tire/road noise, and wind noise is considered. Second, the exterior noise perceived by the other road users is analyzed. Finally, the impact of sound on driver behaviors and active sound design are discussed.

5.1. Powertrain Noise

Powertrain noise, as the predominant source of vehicle interior noise in internal combustion engine (ICE) vehicles, has always been a major concern for companies. How to design a brand-specific and pleasant powertrain sound is an important part of NVH work for many companies. In the early conceptual stages, NVH simulators can be used for target setting and decision-making in terms of powertrain sound quality [26, 87, 151, 152].

In [150], a project targeting the powertrain sound quality is presented. A desktop simulator is used for jury evaluation of competitors and current models to set sound quality targets. After modifying the existing sound design according to the jury evaluation results, experts select the optimal design closest to the target and validated it on an on-road simulator [92]. In [161], a NVH simulator is used to study the acceleration sound quality of a V6 vehicle. Structure-borne noise of the powertrains of the test vehicle and the target vehicle, as well as the airborne noise from the air intakes and exhausts, are analyzed and compared to guide the next step in optimizing the intake and exhaust noise design. In [95], a NVH simulator is used for noise reproduction at idle condition to evaluate the cases of "sound only," "vibration only," and "combining noise and vibration" for selecting the best design.

The optimization of the powertrain mounting system can be performed using full-vehicle NVH simulators to balance ride comfort and powertrain NVH across various frequencies [154, 155]. In these papers, two finite elements models, one modeling the ride comfort of the full vehicle and one the NVH response of the powertrain, are firstly created separately and then correlated with real vehicle measurement data. By using the validated models, a set of modified acoustic and vibration

TABLE 4 Primary features and applications of non-interactive and interactive NVH driving simulators.

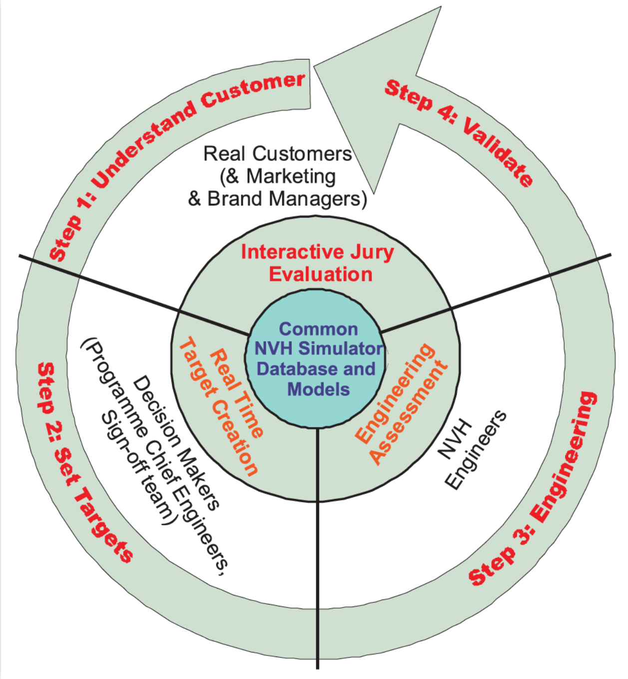
	Feature	Application
Non-interactive NVH simulator	Reproduce previously recorded or synthesized sound through headphones or loudspeakers	• Vibration effect on low-frequency noise [140] • Tire/road noise analysis [141, 142, 143] • Powertrain vibration noise [139] • Human response to pass-by noise [146, 147] • EVs warning sound [88, 89, 90, 148, 149]
Interactive NVH simulator	Can be used for free-driving mode	• Powertrain sound quality [87, 91, 92, 95, 150, 151, 152, 153] • Powertrain mounting development [154, 155] • Tire/road noise analysis [86] • Glass interlayer material optimization [156] • Chassis development (road noise quality) [25] • Active sound design [157] • Driver's behaviors [158, 159]

signatures are obtained by modifying the powertrain mounting system. Engineers thus can subjectively assess tactile point vibrations and acoustic responses by testing all powertrain mount variants on the full-vehicle driving simulator. Following the subjective evaluation, based on the obtained information, engineers were able to understand the behavior of the system and identify the necessary changes to meet the project targets.

In [139], a dedicated simulator is designed to study sound and vibration of an engine. A simulacrum of the engine equipped with several loudspeakers and shakers is installed in the engine bay of a trimmed car. Loudspeakers are used to generate pure airborne noise, while shakers simulate pure structure-borne noise. The benefit of this engine simulator is that the vibro-acoustic FRFs measurement relative to the engine can be moved to a stationary vehicle rather than a moving one. In addition, during the component design process, this kind of simulator can be used to verify the design results before a physical prototype of the engine is available.

With the development of vehicle electrification, the powertrain noise of hybrid electric vehicles (HEVs) and electric vehicles (EVs) has also received attention. The sound of these powertrains is completely different and NVH simulators are a viable way to assess their sound [91, 153]. In [153], the participants are situated in a simulator realized by a real car equipped with immersive 3D ambisonic sound capabilities and exposed to stimuli from 11 EV cars in five scenarios to investigate the driver's perception of e-powertrain noise. Conclusions indicate that subjective perception of EV sounds can vary widely from individual to individual, even when presented with the same stimuli. Although the EV cars are much quieter, participants still expect feedback in certain situations (e.g., full acceleration).

FIGURE 12 Using NVH simulators in NVH development process.



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5.2. Tire/Road Noise

Tire/road noise is another important source of interior noise, especially for EV where there is no internal combustion engine to mask other noise sources and tire/road noise becomes the primary source of interior noise. Tire/road noise is generated by the interaction between tires and road surface and is transmitted to the occupant's ears by both the vehicle structure and air [162]. To investigate the effect of tires on NVH performance, some high-fidelity CAE models [163, 164] and some in-laboratory component simulators, summarized in a literature review [141], are developed. This kind of tire/road component simulators, such as drum facility at the Technical University of Gdansk [142] and Tire-Pavement Test Apparatus (TPTA) [143], usually places the tested rotating tire in contact with the road material and places a microphone near the contact area between tire and road to measure the noise generated by the tire. These simulators perform very well in measuring the noise of different tires on different roads, but due to the complexity of the sound transmission mechanism to the cockpit, are unable to simulate the noise of tires to the driver's ears.

Interactive NVH simulators combined with a high-fidelity model or measured data can help engineers evaluate design options and even optimize the component in the concept stage. In [86], eight types of road noise are simulated on the dynamic simulator VTI Simulator III and participants are invited to evaluate the realism subjectively. The results show that the simulator could provide a very realistic driving experience.

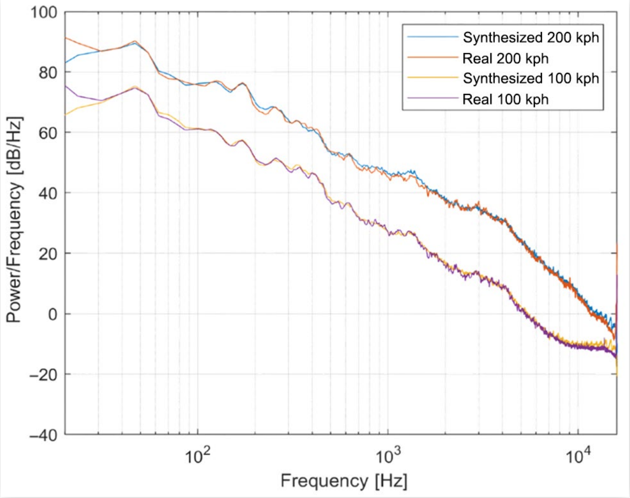
In [156], the optimization of a windshield realized by laminated glass with interlayer material by using NVH simulator is presented. The proposed process consists of an interactive NVH evaluation of the optimized windshield. A driving simulator is employed to reproduce vehicle interior sounds without actually installing a new windshield on the vehicle. Since airborne tire/road noise and wind noise are the most affected by interlayer materials, the structure-borne tire/road noise and powertrain noise functions related to speed and engine RPM are assumed to remain constant. The windshield contribution, specifically its sound transmission loss, can be evaluated by estimating the effect of changes in glass material on the transfer functions between airborne road noise and wind noise and the driver's ears.

In [25], an interactive sound simulator is used in conjunction with a CAE model of a suspension system to evaluate different design concepts for a new suspension design. A validated CAE model of the current vehicle suspension is used as baseline for the evaluation of the new suspension system. The model provides structure-borne road noise for the original vehicle and for the new designs to be tested. The new vehicle design can be driven on the driving simulator and evaluated before the first physical prototype is available, minimizing the risk of bad decisions resulting in poor designs that need to be reworked later in the program.

5.3. Wind Noise

Wind noise is highly speed-dependent and dominates vehicle interior noise at speeds above 130 km/h [32, 33]. Moreover, wind noise could be more annoying in an EV car due to the lack of powertrain noise masking. In the traditional development process, wind noise analysis, especially sound quality, heavily relies on wind tunnels and physical prototype vehicle on-road tests. NVH simulators can be employed to simulate and analyze wind noise before the physical prototype stage. In [156], wind noise is estimated by the difference between the total measured noise and the contribution of powertrain noise and road noise. The utilization of NVH simulators allows engineers to evaluate wind noise individually. Koch et al. [165] proposed a wind noise synthesis method for NVH simulators in which wind noise is modeled as a stationary colored noise. As shown in Figure 13, synthesized noise signal is highly consistent with the real one, and evaluators can barely hear the differences.

FIGURE 13 Comparison of the PSDs of synthesized and real wind noise.



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5.4. Vehicle Exterior Pass-by Noise

Vehicle exterior pass-by noise has become a major health and environment concern in recent years. ECE R51.03 Noise Emission Regulation [166] defines the limits for vehicle noise emissions and ISO 362-1: 2005 [167] standard specifies the method for measuring pass-by noise. As a result, the reduction of pass-by noise has become a key element of NVH development for OEMs in recent years. Morel et al. [146] proposed noise annoyance indicators that take into account acoustic factors and determined a total annoyance model for combined noises. In this study, participants were asked to make a subjective evaluation of two scenarios (vehicle pass-by noise only and pass-by plus industrial noise) in a quiet room equipped with two loudspeakers and a subwoofer. Results show that the proposed indicators overcome the drawbacks of noise maps that only consider exposure levels but do not take into account the combined effects of multiple noise sources.

The upcoming electrification of vehicles will eliminate one of the major exterior noise sources, the internal combustion engine, but low noise levels may pose a safety issue for pedestrians. Due to exterior noise being able to provide pedestrians with information about the position and movement of the vehicle, pedestrians are less likely to receive such information from EVs, especially when the vehicle is driven at a low speed [168]. In [147], a headphone-presentation virtual environment is used to study how moving vehicles perceive distance and velocity. The result shows that an increase in distance results in a decrease in perceived speed. The exterior sound simulator (ESS), which can provide pedestrians with a virtual-world traffic scenario in a 3D audiovisual space, is introduced to EVs warning sound design [88] and exterior noise evaluation [89, 90]. This virtual-world methodology can offer an accurate prediction of pedestrians' evaluation and their impression to the EV sounds. In terms of sound design, a common approach is for the evaluators to use a simulator to subjectively evaluate a variety of different generated or tested sounds [148].

In [149], experts and novice users were surveyed about the sound design of EVs by means of subjective experiments. The majority of experts and users agree that there is a strong need to add sound to EVs. There is a disagreement between users and experts as to what the sound of an electric vehicle should be. Due to psychological inertia, novice users believe that electric cars should sound like ICE cars, while experts' answers are design-oriented such as "electric motor association" or "frequency varying with speed."

5.5. Active Sound Design

Active sound design (ASD) technology is used to modify or enhance the sound inside and outside the vehicle. ASD not only can reduce interior noise, but can also tune the noise spectrum to improve interior sound quality [169]. Mordillat et al. [91] combine VPA technology with NVH simulators to provide human-in-the-loop tests ASD tuning. The vehicle performance calculated from the driver's behavior is fed into the VPA model to generate interior noise synthesis and active noise generation. In order to tune the ASD of engine sound, a real-time binaural synthesis method (shown in Figure 14) based on Binaural vehicle impulse response (BVIR) functions is employed to synthesize the sound fed by multiple speakers to a two-channel binaural signals headphone. In addition, by incorporating the binaural synthesis method into the simulator, the tuning process is moved to an in-lab environment rather than an on-road test [157].

5.6. Driver's Behaviors

NVH simulators can be applied for capturing the driving patterns of customers exposed to noise [170]. With noise reduction technology and electrification, cars will be quieter and the sound quality will change dramatically. To explore the effects of interior noise on the sense of speed and how much noise reduction is acceptable for keeping accurate speed perception, Merat et al. [158] asked participants to drive in an NVH simulator and to maintain a certain speed in the absence of a speedometer, with and without interior noise. A similar work conducted in [159] requires participants to accelerate from initial to target speed and maintain the target speed, with different noise modes, which are internal combustion engine vehicle interior noise, electric vehicle interior noise (wind and tire/road noise), and no sound in day and night scenarios. A similar conclusion drawn by both these two studies shows that drivers tend to underestimate the vehicle speed in the absence of vehicle noise. In particular, the lack of engine noise in EVs may make it difficult for drivers to maintain a certain speed. However, in terms of acceleration to a specific speed, the engine noise increases the underestimation of the target speed relative to the EV sound [159].

Different simulators can be employed for evaluating different noise aspects. Table 5 shows the benefits of each type of simulator with respect to different noise aspects. The interactive driving simulators demonstrate a strong capability in simulating vehicle interior noise. To further enhance NVH evaluation by using driving simulators, a potential next step is to integrate a static NVH simulator for noise response with a full-motion dynamic simulator for vibration response.

6. Future Developments

Driving simulators have already shown their powerful capabilities in NVH development. However, there are still areas

FIGURE 14 Process of the real-time binaural synthesis method for active sound design applied to an NVH simulator.

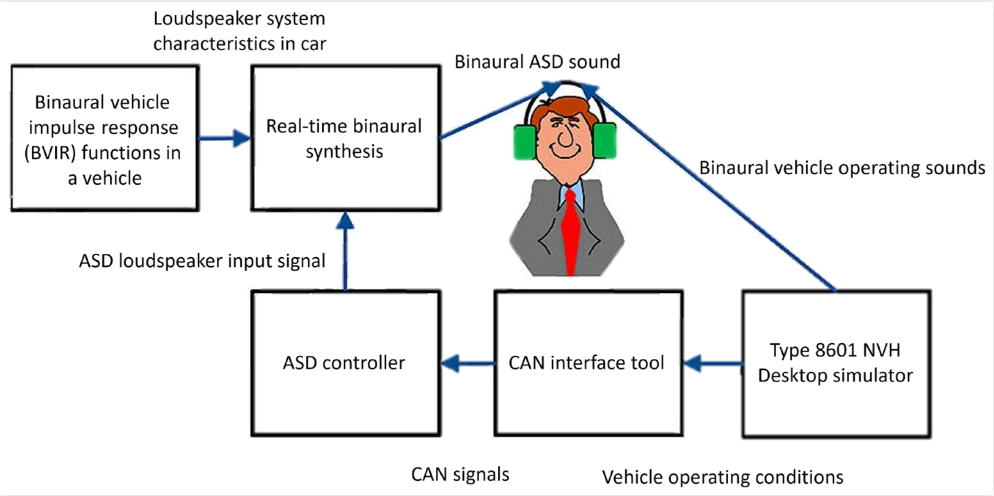

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TABLE 5 Benefits of each type of simulator toward different noise aspect (– poor; + good; ++ very good).

	Powertrain noise	Tire/road noise	Wind noise	Pass-by noise
Non-interactive desk simulator	+	+	+	++
Powertrain component simulator	++	–	–	–
Tire/road component simulator	–	+	–	+
Interactive desk simulator	+	+	+	–
Interactive static simulator	++	++	++	–
Interactive on-road simulator	++	++	++	–

where driving simulators need to be developed. In this section, the future trends of driving simulators in NVH are discussed.

6.1. Future Trends for Immersion and Realism

The previous sections show how driving simulators enable engineers to conduct experiments and subjective evaluations. Dynamic driving simulators perform better at reproducing head movements than static driving simulators [70]. Moreover, in [110], a subjective NVH evaluation is conducted on a simulator and a real car. The subjective rating result shows that the noise in the simulator is close to real car noise, while vibrations at steering wheel and seat have a similar trend but a significant difference. Dynamic driving simulators for NVH assessment are primarily used to study low-frequency vibrations, such as motion sickness and ride comfort. Their performance at higher frequency has not been demonstrated. The future work will therefore be devoted to the accurate reproduction of the response of not only low but also high-frequency vibration.

The majority of vibration studies using driving simulators have been performed through offline experiments that usually do not provide a solid interactive experience for the driver, i.e., the driver cannot drive the simulator by means of the pedals, steering wheel, gearshift, and the like. Hence, a key component of future research will be the integration of high-fidelity models that describe the relationship between driver behavior and vibration response. In addition, as stated in [94], NVH phenomena involve both sound and vibration simultaneously and the vehicle is a multi-attribute system. Human perception in the driving simulator is multidimensional, encompassing vision–auditory, tactile, and even psychological aspects. Therefore, the next step should involve further enhancing multi-attribute simulations, not only for NVH evaluation but also for various other activities, in order to provide a more immersive and realistic experience that engages the driver across multiple dimensions.

6.2. NVH in Intelligent Cockpits

Autonomous and intelligent vehicles are expected to become more common in the near future. These vehicles will bring about new forms of human–machine interaction. Vehicle cockpits will incorporate various communication, information, and human–machine interaction technologies, giving rise to what are known as intelligent cockpits. In [171], four factors influencing the comfort of intelligent cockpits are identified: acoustics, optics, temperature, and the human–computer interaction environment. All of these factors can be simulated in a driving simulator.

Traditional noise control aims to provide the driver with a comfortable driving experience. From the perspective of human–vehicle intelligent interaction, noise can also provide the driver with information about the driving state and environment. Sound source localization technologies can detect approaching vehicles, making a significant contribution to accident prevention and providing timely driver alerts [172, 173, 174]. The need for constant driver alertness in complex auditory environments can be resource-intensive. By implementing sound source segmentation technology [175], vehicles can effectively eliminate non-essential sounds for improving driver sensitivity [176]. Additionally, advancements in predicting driver behavior and emotions within cabin environments have led to discussions about adjusting noise levels to create a safe and pleasant driving experience [177].

Considering the vital role of predictive behavior analysis and the challenges of testing autonomous vehicles on public roads, the integration of a sophisticated driving simulator will be increasingly important. Driving simulators, capable of simulating diverse scenarios while immersing drivers in multi-sensory experiences, have the potential for testing and refining NVH within intelligent cockpits.

6.3. “Infusing Sound” Design

As previously described, the electrification makes cars quiet, but this quietness may lead to many problems, such as the safety of pedestrians and the inability of drivers to perceive the speed of the cars. In addition, due to psychological inertia, some users still expect EVs to sound like ICE cars [149]. Thus, in order to achieve market positioning and capture target customers, it would be essential to provide customized services such as downloadable and uploadable acoustic packages, which can realistically portray a specific vehicle sound by infusing sound into EVs as well as autonomous cars in the future. Driving simulators that can immerse drivers in the driving environment and reduce development costs will make a significant contribution to this topic.

7. Conclusion

NVH of road vehicles is strongly dependent on the subjective perception of the occupant. Driving simulators, which can replace the physical prototypes, give engineers the opportunity to validate the virtual models, and subjectively evaluate the design at the concept stage and has demonstrated a strong potential to reduce development cycles and save costs.

In the literature, several papers describing the application of driving simulators to NVH problems can be found. As NVH is a vast topic strictly related to comfort, steering feeling, and sound quality, according to different objectives, various driving simulators can be used. Hexapod-based simulators can provide the whole vehicle motion and low-frequency vibration of the cabin. Shaker-based simulators are more suitable for high-frequency analyses with, in case, emphasis on touch-point vibrations. Additionally, the combination of hexapod platforms and on-board shakers has the potential for a full-spectrum vibration, although the design of effective control system able to fully exploit their potential is still under development. Currently, the NVH evaluation by using driving simulators is still mostly focused on a single attribute at a time. Multi-attribute and more immersive and realistic simulators can be envisaged and will provide more effective tools for NVH evaluation and contribute to the research in intelligent cockpits and cockpit sound customization. This article provides a concise review of the applications of state-of-the-art driving simulators in NVH development, and may help inform engineers and researchers in this rapidly developing field.

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