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Development of a Mobile Driving Simulator to Eliminate False Motion Cues

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Abstract – *Driving Simulators are a valuable tool for the evaluation of driver assistance systems and analysis of user behaviour. They consist of a vehicle mock-up and a display, motion and an audio system. As, driving is mainly a visual task and the driver receives most of the information through his eyes, so the configuration of the display is very important for accurate perception of surroundings. Important features of a display system are its distance from driver's eyes, field of view, continuity and the picture quality of the displayed image. In order to simulate motion, most of the existing driving simulators consist of a dome, mounted on a Stewart platform, which is either stationary or moves on a rail or a horizontal table. Due to the limiting working space of the motion system of such driving simulators, they cannot accurately simulate longitudinal accelerations so they use scaled vehicle dynamics model or blend the longitudinal movement of simulator with the tilt movement, which the driver perceives as unrealistic motion cues. To eliminate the issues of false motion perception in the driver, a mobile driving simulator is developed, which is to be driven on a planar area and a display system is designed around it. The display system covers the horizontal and vertical field of view of the driver and the distance of the display system from the driver's eyes is chosen in such a way that it takes into account the accommodation effects, which helps in the perception of depth. This results in a display system in the form of 220º cylindrical dome with a diameter of approximately 4.8 meter.*

Keywords: Accommodation, display system, driving simulator, driver, field of view, motion cues

1.0 INTRODUCTION

Driving simulators are physical build-ups aiming to model the real life driving environment and situations as accurate as possible. They are mainly used for the evaluation and optimization of human machine interaction concepts, user training and for the analysis of driver's behaviour and response under different conditions. Driving simulators need to reproduce the driving environment as realistic as possible in order to achieve unaffected driver perception. Different types of driving simulators exist today and every simulator concept offers a different degree of realism with respect to the driving environment, which is called as physical fidelity. The ideal case is to match the simulator characteristics with the actual car and the road experience but this is not possible due to current technological limitations. Besides the physical fidelity, the motivation of driver while driving in a driving simulator should be same as driving in real life and this is called behavioural fidelity. In in-house driving simulator facilities, the drivers have no fear of accidents and their motivation is not same as driving a real vehicle. That's why, while driving in a driving simulator, the driver turns faster around corners than in real life driving.

Driver perceives most of the information for driving using his sense of sight (Hills, 1980), but, in order to improve the physical fidelity of driving simulators, simulation has to be done through multiple sensory channels instead of visual simulation alone (Pinto et al., 2008). During driving, the driver receives information using four senses i.e. sight, hearing, sense of balance and skin sense. Sense of sight is responsible for the visual perception while, the sense of motion is responsible for the perception of motion. With the help of vestibular system, humans can perceive the tilt and acceleration movements in different directions. In order to stimulate these senses, driving simulators consist of a display system, vehicle mock-up, audio and motion system. The layout of the vehicle mock-up affects the sense of presence within a simulator and can be improved by the degree of resemblance with a real vehicle. Some driving simulators use only the driver's seat, steering wheel and pedals while some simulators use complete vehicle to enhance the immersion of the driver in the simulated environment.

Display systems should cover the entire horizontal field of view of the driver. In order to take into account the accommodation effects, the display system should be at a distance of more than 2 meter from the driver's eyes. Increasing the area of display system also improves the speed perception of driver (Negele, 2007). Motion system should be capable of simulating the whole range of motions, frequencies and accelerations occurring in real world driving. The physical and perceptual validity of the motion cues is judged with respect to the actual vehicle acceleration data and human self-motion perception (Reymond et al., 2000). The driver underestimates the speed if there are no audio signals and it is hard to maintain a constant speed unless the auditory cues of engine's speed and acceleration are present (Pinto et al., 2008; Chioma, 2015). All the noises coming from the vehicle and the surroundings must be simulated by the audio system.

2.0 METHODOLOGY

2.1 Visual Perception of Driver

Most important information for the driving task is of visual nature (Eckstein, 2013). Using his eyes, driver picks information from the surroundings regarding the driving scenario. The visual ability depends on the visual range and the field of view. Visual range is the area that the driver can see (not sharply focused) without any head and eye movements, while the field of view is the area that the driver can see with his normal head and eye movements. Magnitude of the visual range depends on the type of viewing. If a driver is viewing with both eyes at the same time, then the horizontal visual range is 120° and it is called binocular vision. If the driver is viewing with one eye (monocular viewing), the horizontal visual range is increased but the sharply focused area is reduced. Sum of left and right monocular views result in a visual range of 180° and it is called 'ambinocular' viewing (Eckstein, 2013). Average peak angles of cervical spine rotations during driving were 35.7° towards left and 42.5° towards right and around 13% of the driving time, drivers stayed out of the neutral head positions (Shugg et al., 2017).

Perception of depth is also important for driving in a driving simulator. Driver can perceive depth with the help of accommodation of the eyes, which is defined as the change in the optical shape of an eye lens to bring an object into focus. To change the shape of the eye lens, ciliary muscles inside the eye contracts and relaxes and this movement provides depth information to the brain.

2.2 Systematic Design Concept

Most of the high fidelity driving simulators consist of a vehicle inside a 360° projection dome, which is mounted on a Stewart platform and it is either fixed or moves on a rail or an x-y table. Movement of the Stewart platform in 6 degrees of freedom and on the rail or table helps in simulating different manoeuvres experienced in real life driving. However, due to the limited working space of such a motion system, it is hard to simulate sustained accelerations in such driving simulators and have to rely on different techniques to represent such accelerations (Negele, 2007). First technique is to replace the initial translational movement of the simulator with the tilt of the dome, which helps the vestibular organs of the driver to perceive gravitational acceleration as translational acceleration. After the inclination, the simulator has to return to its initial position, which is known as washout. During this manoeuvre, if the angular acceleration is higher than the human perception threshold for spin accelerations, the driver perceives this movement as a false motion cue and it produces a false impression as compared to an actual drive. Some simulators use scaled vehicle dynamics models to simulate such accelerations, but the driver can differentiate between the scaled accelerations and the accelerations perceived while driving on a road. Other simulators use centrifugal forces to simulate longitudinal and lateral accelerations, but in this method, yaw rate is falsified (Negele, 2007).

On the other hand, JARI Augmented Reality Vehicle (JARI-ARV) uses modified vehicle, which is driven on real roads. The instrumented vehicle consists of three LCDs mounted at front of the vehicle, three cameras that record the driving situation and a workstation (Uchida et al., 2017). The video recorded by the cameras is combined with augmented reality objects in the workstation and then displayed on the front display. As, it is driven on test tracks, the dynamic behaviour of the vehicle is real and it is able to simulate sustained accelerations. The display compresses the entire field of view into 110°, which does not cover the complete frontal view of the driver and leads to inaccurate driver head movements at intersections and junctions (Hirsh et al., 2015). The use of multiple LCDs in the display system leads to vertical cuts, which is not good for the immersion of driver into the simulated environment. Additionally, the display system is placed very close to the driver's eyes, which does not provide sufficient accommodation effects for depth perception.

In order to eliminate the issue of false motion cueing in the driving simulators, a mobile driving simulator concept for urban driving conditions is developed in this paper. Unrestricted mobility in a large planar area is the only way to simulate sustained accelerations in a driving simulator and it is not possible with in-house driving simulation facilities. Moreover, as the vehicle is driven on test tracks, the motivation of the driver, while driving this mobile simulator, is improved than in-house driving simulators and hence the behavioural fidelity is improved. For improving the visual perception of the front view than existing mobile driving simulator concepts, an immersive display system is designed around the hood of the vehicle, which covers the complete frontal field of view of the driver and allow for sufficient accommodation effects. For displaying the rear view, LCDs are used at the side mirror positions.

2.3 Definition of Specification

Driver's immersion into the simulated environment is adversely affected if the driver can see the boundaries of the display system of the driving simulator, so the display system should cover the entire horizontal and vertical field of view of the driver with his normal head movements. Objects on the display system should appear at the same location as they appear in real life driving, such that the head movements of the driver, at intersections and crossings, are same as in real world driving. To take into account the accommodation affects, the display system should be at a sufficient distance from the driver's eyes. At a distance of more than 2 meter, 95% of the accommodation is passed through and at a distance of 5 meter, ciliary muscles are completely relaxed (Andersen, 2011; Negele, 2007). NHTSA recommends a distance of at least 2 meter from the display to the driver for providing sufficient accommodation effects (NHTSA, 2012). Moreover, the quality of visual simulation also depends on the picture quality i.e. brightness, resolution and contrast of the displayed images. In case of multi-channel display systems, the use of multiple monitors must be avoided as it leads to vertical cuts and in case of multiple projectors, double illuminated areas must be fixed through edge blending and the resulting images should be continuous. Discontinuous images affect the immersion of driver into the driving simulator.

Besides the specifications of the display system, the overall concept of the driving simulator must be very lightweight. Power demand of the vehicle is dependent on the mass of the vehicle. In this mobile driving simulator concept, the simulator structure is mounted with the vehicle, which increases the power demand of the vehicle, so the whole structure of the simulator must be very lightweight. To decrease the mass of the simulator, cantilever construction should be avoided, which requires very stiff construction and can result in large deformations.

2.4 Design of Projection Surface

A projection surface with a horizontal field of view of 220° was developed around the Toyota Camry Vehicle and it was analysed for the driver's vision at peak head rotations. It was designed symmetric with respect to the vehicle longitudinal axis and hence, its distance from the driver varies along its surface. As shown in figure 1, diameter of projection surface is 4.8 m, which was decided in such a way that the projection surface is very close to the bumper cross rail, which is the front mounting point of the simulator structure. This dimension helps in avoiding the cantilevered structure at the front. Moreover, this distance is more than the recommended minimum distance of the display from the driver and hence, it is capable of providing sufficient accommodation effects.

Vehicle's dashboard and its structure limit the driver's external view, so, the view through the windshield and the side windows is decisive for vertical field of view of the display. Using CATIA human builder workbench, driver's vision was observed while looking straight and at peak head rotations mentioned by Shugg et al. (2011). The height of the projection surface (1.77 m on left, 1.57 m on right) was chosen such that the complete vertical field of view of the driver is covered through the windshield. The driver is closer to the display on the left side and there is less sight obstruction on the left side, due to the small distance from the side window, so the height of the projection surface was increased on the left side to cover the vertical field of view of the driver. Figure 1 shows the driver's binocular vision at peak head rotations. Non-shaded area in the figure represents the binocular vision and the sum of shaded and non-shaded area shows the ambinocular vision of the driver.

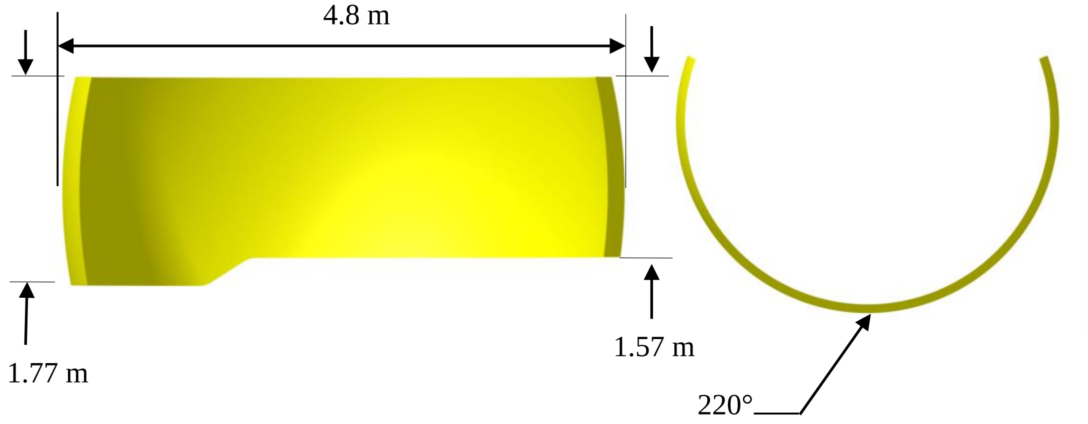

Figure 1: Projection surface design

It is observed in Figure 2 that the designed projection surface covers the entire horizontal field for projection if binocular vision is considered, but for covering the horizontal field for ambinocular viewing, the horizontal field of view has to be increased beyond 220°. Moreover, monocular viewing does not provide depth perception and humans with impairment in one eye only use it, so the current version of projection surface with 220° field of view was deemed sufficient. The vertical field of view of the projection surface covers the complete area through the windscreen while, a very small area is not covered by the display system through the left side window.

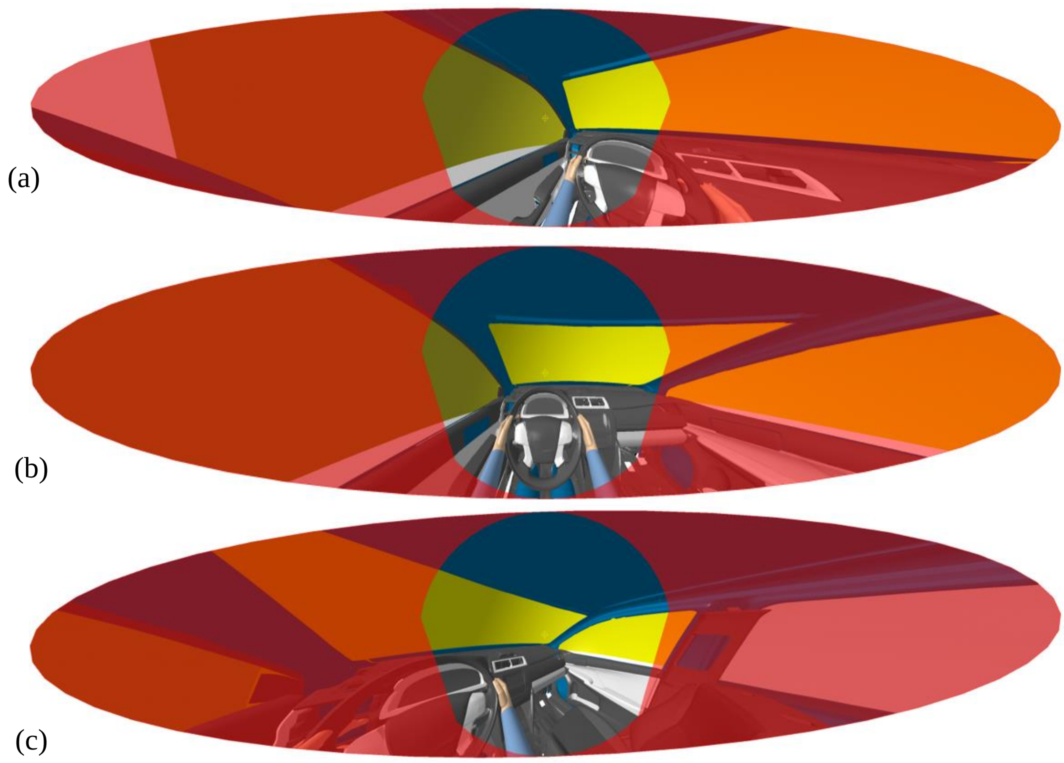

Figure 1: Driver binocular vision: (a) driver looking 35.7° left; (b) looking straight; and (c) looking 42.5° right

2.5 Projectors Arrangement

After the design of projection surface, projectors selection and their arrangement was carried out. Due to the space limitations, short throw projector was required. Barco F22 projector with EN19 lens (Throw Ratio 0.74:1) was selected for this application, as they are one of the lightest simulation projectors available (Barco Lens Calculator, 2018). Using an aspect ratio of 5:4, from a throw distance of 2.1 meter, the projector creates an image size of 2.27×2.84 m^2. Throw distance was selected such that it results in the minimum number of projectors to display on the projection surface and at the same time, there is enough space above the roof of the vehicle for their circular arrangement. Using five projectors in landscape mode, it covers the entire projection surface. Figure 3 shows the projectors arrangement in two layers above the vehicle roof. In order to generate bright images on the projection surface, slight curve along the height of the projection surface was included such that the projector rays hit the projection surface perpendicularly. In this case, as multiple numbers of projectors are used, some areas are double illuminated and the images projected on the cylindrical surface are distorted so multi-image processing box, WB1920 by Barco, were used for edge blending and warping.

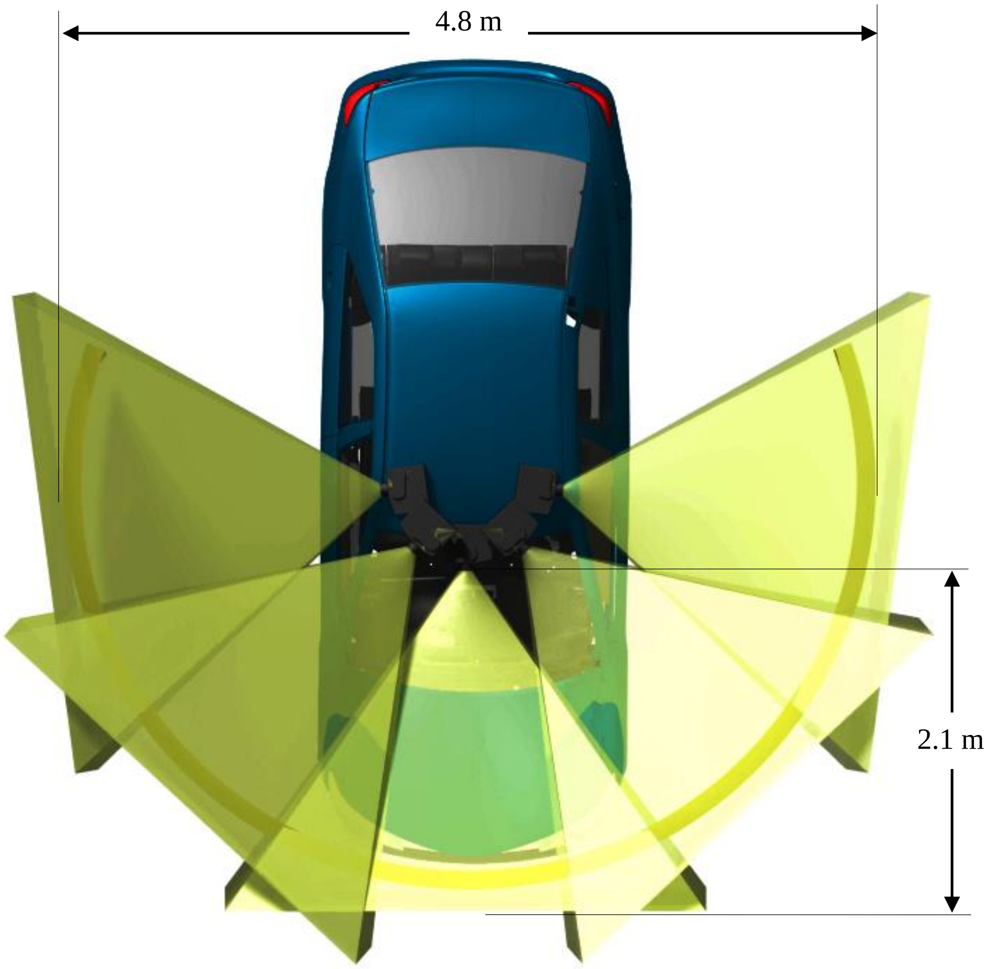

Figure 2: Projectors arrangement

2.6 Driving Simulator Design

Design of the simulator structure, as shown in Figure 4, was carried out with respect to the projectors arrangement and the projection surface design. All the components were designed using best design practices concerning the ease of manufacturing and weight. Projection surface was designed using a 2 mm thin sheet of carbon fibre reinforced plastic (CFRP), which is a high strength lightweight material and it can be manufactured using open mold hand layup process. Volume ratio between the high modulus carbon fibres and the resin was 60:40 and the modulus of elasticity is 220 GPa in the direction of fibres and 6.9 GPa in the other directions. The upper and lower mounts of the projection surface were designed in the shape of L-shaped hollow tubes such that they load the projection surface in compression. That's why, the carbon fibres were oriented along its height, which helps in achieving the maximum reinforcement efficiency of the fibres in the composite.

Projector mounts were designed using aluminium and can be manufactured through the machining process. Projectors were mounted with the roof of the simulator structure and were supported from underneath with rubber mounts. Ratio of the brightness of projected images should be five times more than the ambient light (Negele, 2007), so a sunlight blocking sheet was developed for the top of the driving simulator. It was designed using a thin sheet of Aluminium and rest of the roof structure was designed using extruded low carbon steel profiles.

As shown in Figure 5, driving simulator was mounted with the bumper cross rail at the front and on the sides; it was connected with rocker panels of the vehicle. In order to avoid cantilevered structures at the left and the right side, roller supports in the form of rubber wheels with in-built suspension systems were added under the projection surface. All the components were designed using extruded profiles of low carbon steel and were welded together.

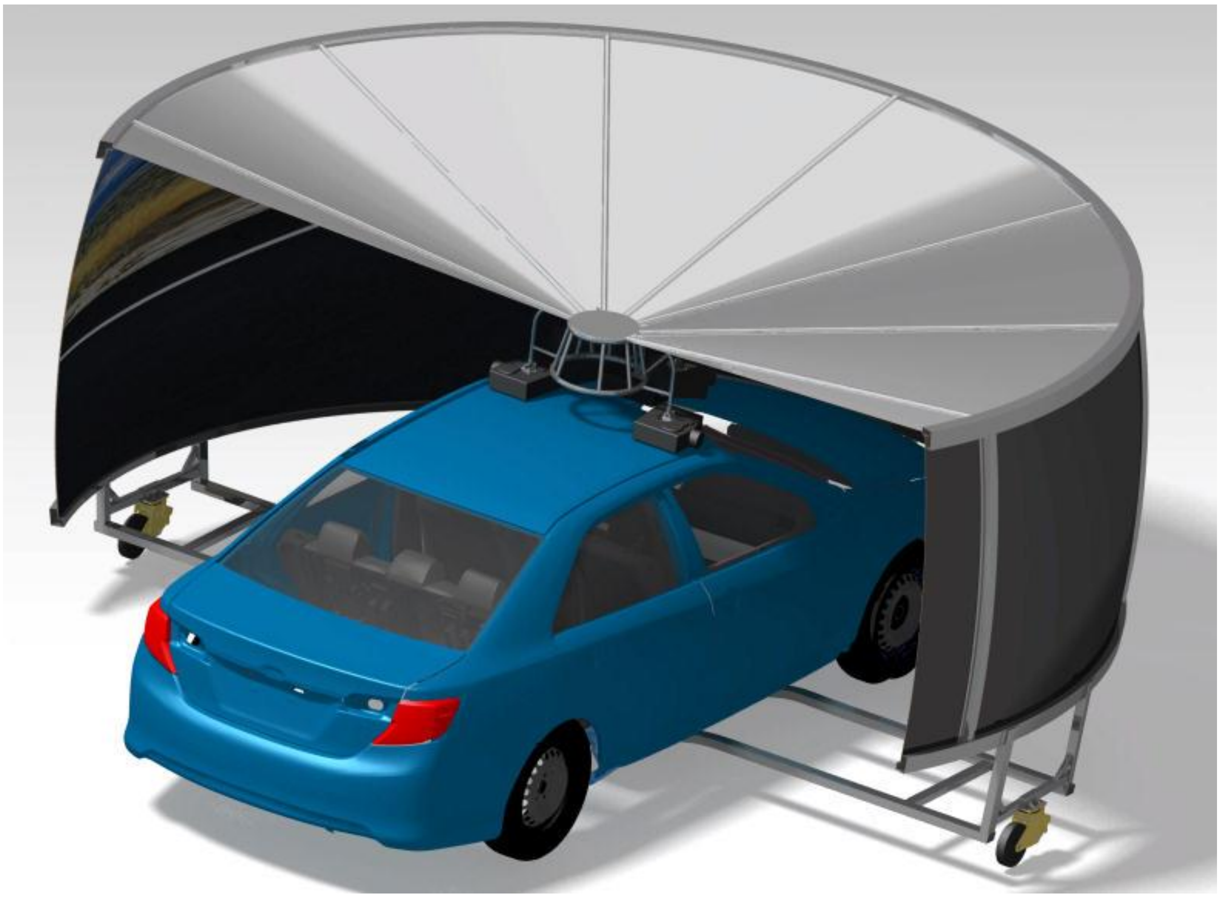

Figure 3: Mobile driving simulator concept

As shown in Table 1, total weight of the driving simulator structure is 204 kg and the weight of 50th percentile male is 78 kg. Total weight allowed inside Toyota Camry is 410 kg (M-Sedan, 2018). The total weight of the simulator and the driver sums up to 282 kg, which is less than the allowable weight inside the vehicle, i.e. 410 kg. Weight can be further reduced by removing spare wheel from the luggage compartment and the rear seats from the passenger compartment. The complete structure of the driving simulator is shown in Figure 5.

Table 1: Weight and materials used for driving simulator structure

Components/Assembly	Weight (kg)	Material
Projectors	14.5	
Projection surface	108.4	CFRP and steel
Projector mounts	5.6	Aluminium and steel
Driving simulator roof structure	27.3	Steel and aluminium
Front mounts	4.3	Steel
Side mounts (left and right)	25.1	Steel
Caster wheels	18.8	Steel and rubber
Total weight of simulator	204	
Weight of 50th percentile male	78	

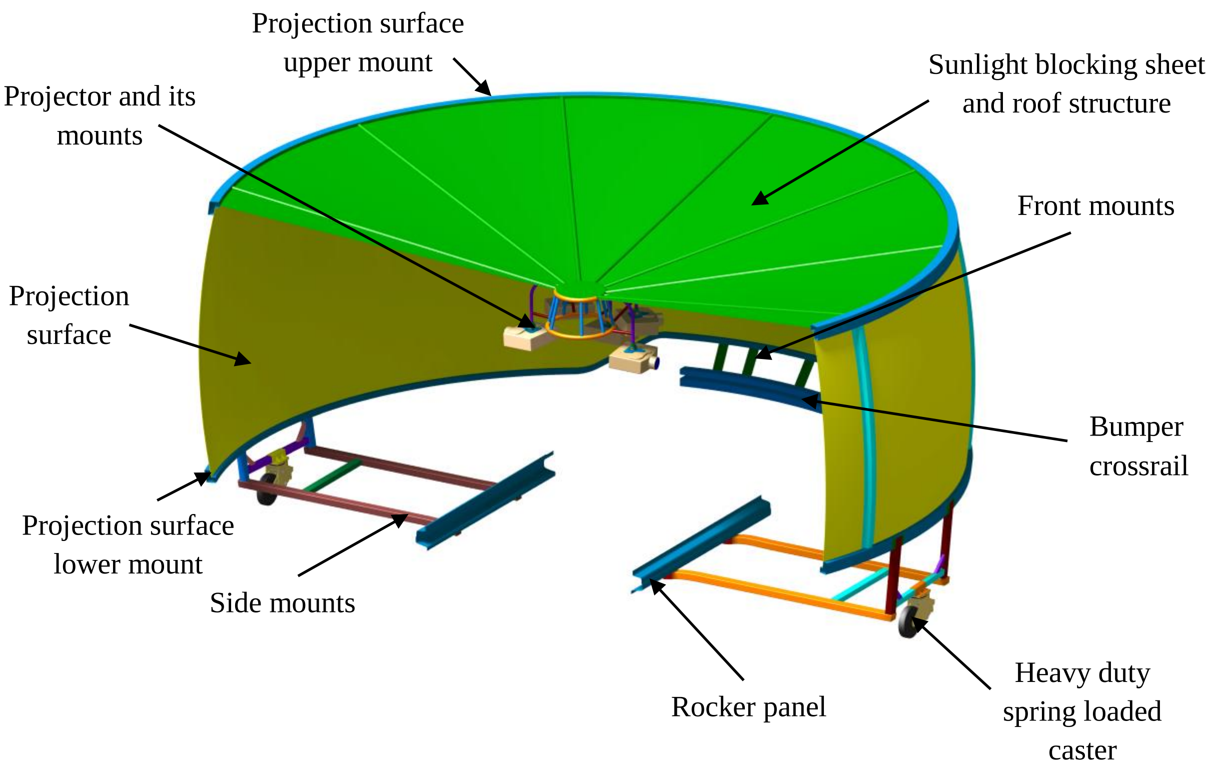

Figure 4: Driving simulator structure

3.0 ADVANTAGES

This section discusses the advantages of the new simulator concept, developed in the previous section, over existing driving simulator concepts.

3.1 Behavioural Fidelity

One of the major issues of the driving simulators is that due to the lack of real danger and no consequences of actions evoke a false sense of safety in the driver and he tends to do rash driving than real world driving, which leads to inaccurate research outcomes and the behavioural fidelity is compromised. As this mobile driving simulator is driven on test tracks, the vehicle can become unstable upon rash driving and hence, the driver's motivation is enhanced than in-house driving simulation facilities.

3.2 Elimination of False Motion Cues

Unlike existing driving simulators, this simulator does not involve motion-simulating base, instead the vehicle is driven on a planar area. Unlike in house driving simulation facilities, there is no space limitation to simulate sustained accelerations, which eliminates the use of scaling factors and acceleration perception through tilt movement for the simulation of sustained accelerations and this eliminates the issue of false motion cues in this driving simulator concepts.

3.3 Immersive Display

Mobile driving simulators are affected by the use of LCDs, which are placed closer to the driver, so, they do not provide sufficient accommodation effects for depth perception. Moreover, using multiple LCDs results in the view obstruction and the resulting image is not continuous, which affects the immersion of the driver into the virtual environment and it also does not cover the complete horizontal field of view. The display system designed for this driving simulator covers the complete horizontal field of view of the driver for binocular viewing and there are no sight obstructions. In addition, the display system is placed at a distance of more than 2 m from the driver, which allows for over 90% of the accommodation to pass through.

3.4 Low Cost

In order to simulate roll, pitch and heave movements, driving simulators use motion systems and the cost of the simulator mainly depends on the motion system (Blana, 1996). High cost driving simulators consists of extensive motion platforms, which can simulate motion in multiple degrees of freedom. As this driving simulator consists only of a display system and a vehicle and there is no motion system other than the vehicle and the road itself, so, the cost of this driving simulator is less than the simulators with extensive motion bases.

3.5 Simulator Sickness Reduction

Simulator sickness can arise due to multiple reasons. One of the major reasons of simulator sickness is due to the mismatch of signals provided to brain by different sensory organs. In stationary driving simulators, the eyes can perceive the motion through the visual data on the display system, but due to the absence of motion cues, the vestibular organs cannot perceive any motion, so, such conflicting signals provided to the brain by different organs results in simulator sickness. Simulator sickness can be avoided by providing harmonic cues to the brain through different sensory organs. Another reason for the simulator sickness is that due to the involvement of hydraulics and pneumatics involved in the motion systems of existing simulators, there can be delay between the driver's action to the visual data and the motion system response, which also enhances sickness (Pinto et al., 2008). In this driving simulator, as the dynamic response of the vehicle is not dependant on the motion system and the vehicle is driven on the test track, so there is no simulator sickness due to non-corroboration of vestibular and visual information.

3.6 Lightweight Design

Lightweight design is very important for mobile driving simulators as the vehicle has to carry the extra weight of the simulator structure and electronics, which can change the power demand of the vehicle. Criterion for the lightweight design was decided such that the total weight of the simulator and the driver must not exceed the total weight allowed by the manufacturer of the vehicle. Moreover, the weight of the simulator and the driver is less than the weight of four 50^{th} percentile male humans sitting inside the vehicle.

4.0 LIMITATIONS

The mobile driving simulator concept is designed for a specific vehicle and as the dimensions of the vehicles are different, the designed simulator structure cannot be mounted on other vehicles. Moreover, the frontal area of the vehicle is increased four times after mounting the simulator structure and aerodynamic drag on the vehicle will increase. As the simulator structure is mounted at the front of the vehicle, the weight distribution between the front and the rear is affected, which can lead to over-steer effect at cornering. In order to avoid such handling issues, the suspension system of the vehicle should be tuned for new weight distribution.

5.0 CONCLUSION

This paper has shown the need for a mobile driving simulator to eliminate the false motion cueing methods to simulate sustained accelerations and to improve the behavioural fidelity of the driver. Afterwards, the driver's visual perception was discussed and on its basis, the projection surface for the mobile driving simulator was developed which covered the horizontal field of view of the driver and was placed at a sufficient distance from the driver to account for accommodation effects. Later, a lightweight design of the mobile driving simulator concept was developed, which does not involve motion base to simulate motion, but instead it is driven on a planar area. It was also shown that this simulator concept helps in improving the behavioural fidelity of the driver and can reduce the simulator sickness. Additionally, it has an immersive display system, while the aerodynamic drag on the vehicle is increased.

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