Driver Response to Gear Shifting System in Motion Cueing Driving Simulator

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***Abstract*— Researchers are using driving simulators to design and assess the automated driving and driver assistant systems, due to the safe nature of experimentation in the virtual environment. The motion cues and accelerations felt by the drivers are essential for an accurate perception of the events and the response of the drivers. In this paper, the vehicle dynamic model and the Motion Cueing Algorithm used for the simulation is described in detail, then driver's performance and subjective assessments was studied for the braking, chicane and overtaking maneuver in the 3 different gear shifting scenario. The study demonstrates that the presence of the motion cueing feedback in the driving simulation was satisfactory and gave realistic cues for the participants independent of the gear shifting system, however no significant effect was found from the driver's behavior due to different gear shifting system.**

Keywords-Motion Cueing; Driving Simulator; Driver Behaviour; Gear Shift Response; Vestibular Cues.

I. INTRODUCTION

Driving simulators provide a repeatable safe environment for a wide range of research and industrial applications. The virtual environment in the driving simulator may not be identical to real-world scenarios but should provide the necessary information for the driver to control the vehicle. Most of this information is provided by the visual. However, vestibular stimuli are also found decisive in the perception of distance and steering for the drivers [1][2].

Driving task requires perceptual, cognitive, and sensory systems, which provide information on the traffic and road infrastructure. Therefore, various cueing systems in the driving simulator have to ensure that the participant perceives the correct cues and feedback for driving. Visual cues provide the driver with the information required to detect the road, obstacles, road width and markings, that enables the driver to guide the vehicle during the simulation and generally agreed upon as the primary sensory feedback. However, the driving experience is dominated by the sensation of the motion, which, by providing the correct vestibular cue, can enhance driver immersion in the driving simulator. This feedback offers essential information for vehicle guidance, collision avoidance and road condition [1]. The vestibular cues in driving simulator were found to be crucial for accurate vehicle speed and distance perception in the driving simulator [2]. A study of the motion scaling for the slalom driving task using the human perception limitation of self-motion perception found that reduced or absence of the motion cues significantly degrades driving performance [3].

Motion is the feedback from the simulated vehicle in the virtual environment. The motion feedback can improve driver engagement in the virtual environment by providing motion stimuli on the vehicle states for the driver, while the driver may feel the absence of motion that cause even motion sickness, due to the impaired visual and motion cues for the human vestibular system.

Various types of motion platform can be used to reproduce the movement in driving simulation, but the reproduction of the real vehicle movement needs large movements, and therefore, Motion Cueing Algorithm is being used to control the movements within the platform operative limits. Motion Cueing Algorithm used in the simulator should be selected according to the motion platform architecture and the intensity of the required motion. For example, a classical Motion Cueing Algorithm is used in the 6 Degrees of Freedom (DOF) Renault driving simulator for motion with low frequency, but not including vibrations [4]. While an adaptive Motion Cueing Algorithm is implemented on a low-cost driving simulator with 2 DOF with longitudinal and seat rotation [5]. Other studies suggest using optimized Motion Cueing Algorithm [6] in order to investigate different Motion Cueing Algorithm for driving simulators. Another important cueing system in the simulator is the proprioceptive cue that provides the driver with the control load and feedback on the steering wheel, pedals, and gear change. Investigation in the steering feedback showed that the proprioceptive cue from the steering, gives drivers information about the road and tire dynamics, which helps them in curve negotiation.

The gear shifting behavior studied in the literature was mostly for fuel consumption, since the correct gear significantly influences the combustion engine speed and CO2 emission. The gear shift operation indicates as optimal when the driver senses a comfortable shifting event [7].

In this paper, a low-cost 2DOF motion simulator is used to investigate the driver response. Three gear shifting scenario have been implemented in the driving simulator in order to investigate the effect of the gear changing strategy on users Driver control inputs, such as steering angle, braking pedal, acceleration pedal and gear changed have been observed during the simulation. The motion feedback of the platform evaluated by participants with the use of a questionnaire and objective measures were compared using statistical analysis.

The paper is organized into five sections. Section II describes the microsimulation modelling of the vehicle, followed by Section III, where the simulation scenario and the driving task are presented and discussed. The registered variables and questionnaire are reported with the statistical analysis in section IV, and finally, in last section, some conclusions and possible future applications are given.

II. METHODOLOGY

The methodology section describes the "Simu-Lacet" driving simulator model and motion cueing algorithms.

A. Driving simulator Simu-Lacet

The “Simulacet” driving simulator is designed with a 2 DOF motion cueing platform to study the yaw motion vehicle control and simulator sickness in the virtual environment, in PICS-L Lab (Université Gustave-Eiffel) [8]. The choices of the structure and motion platform are motivated by the necessity to produce sufficient motion and while considering financial constraints to develop a low-cost driving simulator. The simulator is designed as a two degree of freedom in motion platform. The cabin consists of a real car dashboard, steering wheel, clutch, brake, throttle pedal, gears change handle, hand break, blinking handle, and a switch. The steering wheel feedback is added with the steering wheel. The cabin provides information such as vehicle speed, engine round per minutes (rpm), fuel indicator and other vehicle states on the dashboard.

The visual image is provided to the driver in the cabin by the means of three fixed screens in front of the driver’s seat. The visual system provides 4K resolution with a capacity of 100 Hz, with 180 degrees of horizontal and 36° of vertical field of view, for the participant in the simulator cabin. A rear-view mirror and two side-view mirrors is implemented on each screen with a frame to isolate the screen from the front view. Visual rendering unit consists of three computers connected and broadcasts the displayed images on three mounted screens. The sound cue is provided by a sound system with four speakers 30 W (50 Hz), reproducing the engine noise, wind sound, rolling noise and other traffic with the possibility to regulate the audio cue intensity.

The acquisition system is composed of an industrial input/output board with the bidirectional information exchange of 1000 Hz. This board is transmitting data in real-time between the cabin and the computer in charge of the vehicle dynamics simulation (XPC Target). The XPC target PC also controls the actuators in the desired position and communicates the position of the vehicle to the visual rendering system. The Traffic simulation PC launches the visual scenario according to the position of the vehicle and simulates the road traffic using Archisim multi-actors traffic simulation model [9].

The motion cueing platform is composed of two separate structure and drivers: the longitudinal rail and the rotating circular platform. The longitudinal upper structure can move linearly along the rail, which is mounted, on the rotating structure. A pulley-belts system is used to move the cabin with a brushless servo motor (SMB 80). The rotating structure provides yaw angle cabin rotation by using a circular platform in which the servomotor directly rotates the upper structure with wheel support in the front of the cabin.

The vehicle model is implemented in MATLAB-SIMULINK, which calculates the vehicle states in real-time using the inputs from the cabin (steering wheel, pedals) [1] [10]. In order to compute the engine torque, we use the measures on throttle pedal percentage and the engine rotation frequency, which is provided from an instrumented vehicle (Peugeot 406) , as shown in Figure 1 [11].

TABLE I. GEAR NUMBER AND THE TRANSMISSION GAIN

Gear	one	two	three	four	Five
Transmission Gain	3.25	1.78	1.19	0.87	0.70

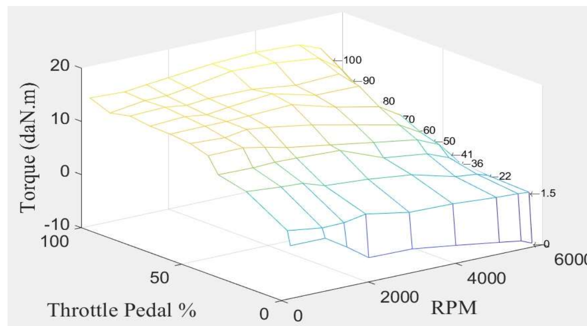

Figure 1. Engine Torque cartography used in vehicle model

The gear shifting system of the vehicle is implemented as a hybrid model that can be used with automatic or manual gear transmission mode. The gear number will apply a gain factor on the torque from the engine model as shown in Table 1.

The calculated torque was then transmitted to the wheels. The angular velocity of the wheel is calculated as follows:

$$J_w\dot{\omega}_i = (T_i - T_{bi}) - F_{ix}\cdot R_e \quad (1)$$

where T_i is traction torque from the engine, T_{bi} is the breaking Torque, J_w is the wheel rotation inertia, R_e effective rolling radius of the wheel, F_{ix} friction force and $\dot{\omega}_i$ is the wheel angular acceleration. The wheel slip coefficient was found using Burckhardt formula [12]:

$$S_L = \frac{\omega_i \cdot R_e\, cos(\alpha_i) - v_i}{v_i} \quad \forall\,(v_{ix} > \omega_{ix}\cdot R_e)$$

$$S_S = \frac{\omega_i \cdot R_e\, sina(\alpha_i)}{v_i} \quad \forall\,(v_{ix} > \omega_{ix}\cdot R_e)$$

$$S_L = \frac{v_i - \omega_i \cdot R_e\, cos(\alpha_i)}{v_i} \quad \forall\,(v_{ix} < \omega_{ix}\cdot R_e) \quad (2)$$

$$S_S = tan(\alpha_i) \quad \forall\,(v_{ix} < \omega_{ix}\cdot R_e)$$

$$S = \sqrt{{S_L}^2 + {S_S}^2}$$

with S_L and S_S are the side sleep and longitudinal wheel slip and S_{tot} is Burckhardt friction coefficient, ω_i is the wheel velocity and v_i is the wheel contact speed. The tire forces shown in (3) are calculated by using Burckhardt model for each wheel(i):

$$\mu_i = (C_1 \cdot (1 - e^{-C_2\cdot S}) - C_3 \cdot S) \quad (3)$$

$$F_{xi} = F_{zi} \cdot \mu_i$$

where (C1=1.28, C2=23.99, C3=0.52) are dry asphalt coefficients and F_{zi} is the normal force on each wheel.

The "single-track" model or "bicycle model" is used for lateral vehicle behavior [12]. The equilibrium must hold in lateral, longitudinal and yaw direction with the force applied on tires and the moment acting on the vehicle, therefore (4) derived from equilibrium:

$$\begin{aligned} m(\dot{u} - v.r) &= F_{xf} + F_{xr} \\ m(\dot{v} + u.r) &= F_{yf} \cdot \cos\delta + F_{yr} \\ J_z \cdot \dot{r} &= l_1 \cdot F_{yf} - l_2 \cdot F_{yr} \end{aligned} \tag{4}$$

Where F_{xf} , F_{xr} are the front wheel and rear wheel longitudinal force, F_{yf} and F_{yr} the front wheel and rear wheel lateral force, l_1 distance from COG to front axle, l_2 distance from COG to rear axle and m is the mass of the Peugeot 406.

$$\begin{aligned} \alpha_F &= \delta - \left(\frac{v + \dot{r}}{u}\right) \\ \alpha_R &= -\left(\frac{v - \dot{r}}{u}\right) \\ \beta &= \arctan\left(\frac{v}{u}\right) \end{aligned} \tag{5}$$

where δ is the steering angle, α_F front side slip angle, α_R rear side slip angle, β body slip angle, $\dot{r}$ is the yaw rate, v and u are respectively longitudinal and lateral speed.

TABLE II. VEHICLE MODEL PARAMETERS

Vehicle parameters	Value	Unit
m	1714	Kg
l_1	0.944	m
l_2	1.756	m
J_z	3015	Kg.m2

The outputs of the vehicle acceleration and rotation in the center of gravity coordinate are used to reproduce the longitudinal movement and rotation of the cabin, in real-time, with the use of the Motion Cueing Algorithm. In Figure 2, the inputs of the vehicle dynamic model (pedal, gear, and Steering angle) from one driver during the experiment is shown and in Figure 3, some output of the vehicle model, such as vehicle speed, longitudinal acceleration, and yaw rate are represented.

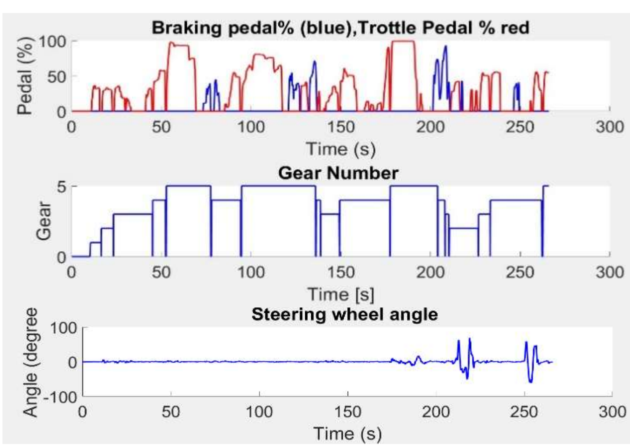

Figure 2. Input of the vehicle dynamic model

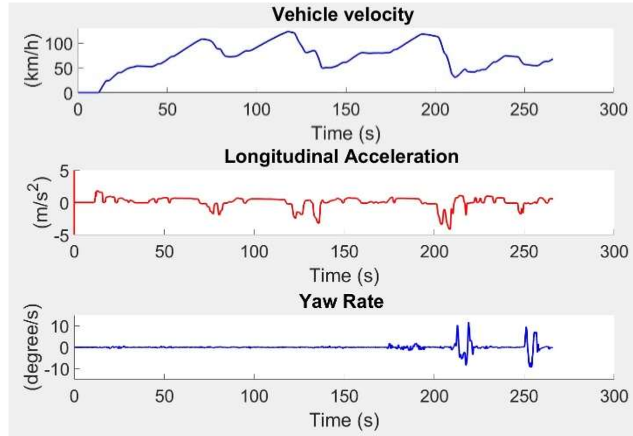

Figure 3. Output of the vehicle dynamic model

B. *Motion Cueing Algorithm (MCA)*

Motion Cueing Algorithms (MCA) reproduce the motion cues of the simulated vehicle from the accelerations and rotations. However, since the motion cueing platform has limitations, MCA has to filter the movements and reproduce some movement that gives the driver the perception of the movement. Therefore, during the simulation, The MCA goal is to:

- Keep the platform within the physical limitations.
- Reproduce movement.
- Return the motion platform to zero position for the next movement

In Table III, the limitations of the platform and the actuators are shown.

TABLE III. MOTION PLATFORM AND ACTUATOR LIMITATIONS

Motion cue	Maneuver Limits	Maximum Speed	Maximum Acceleration
Surge	±0.3 m	2.45 m/s	0.41 g
Yaw	±23°	29.07 °/s	51.15

In order to produce the motion cues, the classical Motion Cueing Algorithm is used (Figure 4). The developed MCA reproduces transient components of the vehicle acceleration with the use of the high pass filters. The tilt rotation is not used due to the platform architecture. The Motion Cueing Algorithm takes as inputs the longitudinal acceleration, yaw rate rotation, and calculates the position of the actuators, which are responsible for reproducing yaw rotation and longitudinal motion of the platform.

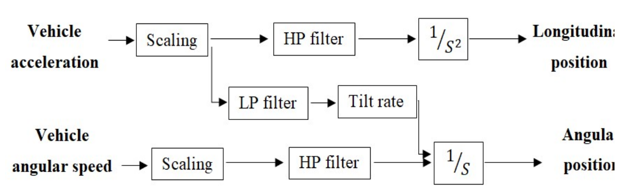

Figure 4. Classical Motion Cueing Algorithm

$$\frac{\ddot{x}_s(s)}{a_x(s)} = \frac{s^3}{(s^2 + 2\xi_1\omega_1 + \omega_1^2) * (s + \omega_2)} \quad (6)$$

The Motion Cueing Algorithm is developed for longitudinal and yaw motion cue with the use of two high pass filters (third order). The cutting frequency "ω_1" in this algorithm controls the acceleration or yaw rate frequency to be filtered with damping coefficient "ζ1", while the cutting frequency "ω_2" regulates the speed of the platform to return to the initial position, which is essential for the reproduction of the next motion. The parameters for the experiment are shown in Table IV.

TABLE IV. MOTION CUEING ALGORITHM PARAMETERS

MCA	ω_1	ω_2	ξ_1
Surge	2.65	0.2	3
Yaw	0.1	0.25	1

III. SIMULATION EXPERIMENT

The experiment is carried out with 19 subjects (16 male and 3 female) with an average age of 32 (SD= 10). All participants had a valid driving license, five of them have experience with a car featuring an automatic gear change system and they had on average driving experience of 11 years (SD = 9) and drive 4600 km/year on average (SD= 6300). Six of the participants were affected at least once by motion sickness on car, bus, or boat.

A. Familiarization

The familiarization took ten minutes for each participant. In the first five minutes, the subjects familiarize with the motion of the simulator and cabin controls. The participants asked to try brake and acceleration pedals and to get familiar with the visual, auditory, and motion cues. The subjects are also asked to overtake some cars in the scenario and to familiarize with the yaw motion. The second familiarization is dedicated to experiment the scenario, which lasts 5 minutes.

B. Driving task and scenario

In order to study the driver's behavior and response to the gear shifting system, three different gear-shifting scenarios were implemented:

a) *Manual gear Change*

b) *Sound Assisst Gear change*

c) *Automatic Gear shift*

The manual gear change scenario was a five-gear shifting system, which the user had to use the clutch for changing the gears. The sound assisted gear shift session aimed to assist the driver when the wrong gear is being used based on the rpm. Therefore, if the driver is using low gear with rpm value more than 4800, a warning sound is sent to the driver, asking him to upshift the gear. In the automatic gear scenario, the driver does not need to change the gears and only use accelerator and braking pedal.

The driving task was implemented in a two-lane motorway section, with 3.5 meters width and an emergency line. At the beginning of the simulation, the driver was located in the highway as shown in Figure 5, with a lead vehicle in front, located at 70 meters of distance. Vertical cones placed along the road at every 15 meters that prevent the driver from taking over the lead vehicle. Driving task includes three braking phases with different speeds in section A. The participants asked to follow the lead vehicle and brake or accelerate while maintaining a safe distance with the lead vehicle.

After the third braking phase, the participants were asked to take over the lead vehicle in section B, by a takeover command that pops up on the screen. As it is shown in figure 6, in this section, there was two ISO chicane implemented in the scenario with vertical cones. Before the chicane, two trucks with amber lights and direction sign are implemented in the scenario in order to guide the vehicle through the chicane. The participants were asked to perform the chicane at speed of 50 km/h.

Figure 5. Simulator Cabin and Visual

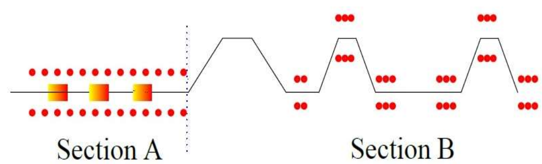

Figure 6. Driving task and sections

An example of the motion platform feedback for the yaw angle and longitudinal motion platform position is shown in Figure 7. The cabin reaches the minimum platform limitations at the end of each braking phase and returns to the zero position for the next maneuver.

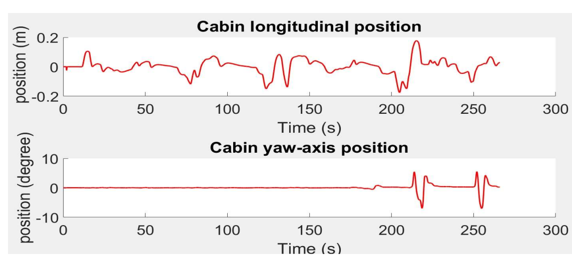

Figure 7. Simulator motion platform position

C. Driving task and visual scenario

The participants evaluated the simulation session with reference to motion cueing feedback using a set of questionnaires. The first one asked the participants to specify their satisfaction level for the motion cues, during specific

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maneuvers. Then, participants filled in a simulator sickness questionnaire developed by Kennedy [13], in order to investigate motion sickness on the participants. The 4-point Likert scale used for the simulator sickness questionnaire and the 5-point Likert scale for driving simulation session evaluation are shown in Table V.

TABLE V. LIKERT SCALE

Simulator Sickness Questionnaire	Driving simulation evaluation questionnaire
None: 0	Totally Disagree: 1
Slight: 1	Disagree: 2
Moderate: 2	Undecided: 3
Severe: 3	Agree: 4
-	Totally Agree: 5

IV. RESULTS

The results of the experiment are presented in three sections. The first two sections are the results of two questionnaires. While in the last section, simulated vehicle data and motion platform cues were used to compare participants' gear shifting behavior.

A. Participants Simulation Evaluation Questionnaire

The driving simulation evaluation questionnaires with 14 questions and the median of the answer to the 5-point Likert scale are shown in Table VI. The questionnaire designed to evaluate the subject's motion perception in the driving task, which may be subjective to the experience and expectation of the drivers. The answers to the session evaluation questionnaires shows that the participants were satisfied with the motions in the simulator for the automatic session, while for the movement on the second chicane higher speed and helping the control of the vehicle for the manual and assisted scenario most of the users were undecided.

TABLE VI. SIMULATION EVALUATION QUESTIONNAIRE

Questions	session		
	1	2	3
1. I had a realistic driving experience	4	4	4
2. I drove as I normally would	4	4	4
3. Cabin movements were realistic	4	4	4
4. Cabin movements helped control the car	3	3	4
5. In the overtaking maneuver, the movements of the cabin were realistic	4	4	4
6. The movements of the cabin did not cause me any problem when I had to go back to the straight line after the chicane	4	4	4
7. The movements of the cabin in the first chicane were realistic	4	4	4
8. The movements of the cabin in the second chicane were realistic	3	3	4
9. The movements of the cabin in turning were not exaggerated compared to those of a real car	4	4	4
10. While accelerating, the movements were realistic	4	4	4
11. While braking, the movements were realistic	4	4	4
12. When accelerating and braking immediately, the cabin movements were realistic	4	4	4
13. When braking and accelerating immediately, the cabin movements were realistic	4	4	4
14. The movements were pleasant and not troublesome	4	4	4

B. Motion Sickness

The registered the simulator sickness questionnaire (SSQ) calculated with SSQ scoring described by Kennedy [14] are shown in Table VII, where the sub scores for three sickness symptoms of Nausea(N), Oculomotor disturbances(O), Disorientation (D) is shown together with the Total Score (TS). All Sessions belongs to no symptom's category regarding the median. Considering the mean, the, "Assisted" and "Automatic" Sessions makes negligible symptoms, whereas the "Manual" session illustrates more simulation sickness symptoms.

TABLE VII. SIMULATOR SICKNESS QUESTIONNAIRE

Manual				
Score	N	O	D	TS
Mean	9.04	9.57	19.8	13.6
Median	0	0	0	0
Assisted				
Score	N	O	D	TS
Mean	5.02	3.19	2.93	4.33
Median	0	0	0	0
Automatic				
Score	N	O	D	TS
Mean	2.01	1.20	2.20	1.97
Median	0	0	0	0

C. Vehicle dynamics and motion platform results

The simulated vehicle data are used to investigate the effect of different gear change scenario for the requested driving task. The within-group variation analysis conducted by disregarding the outliers for braking, take over and chicane maneuver. Figure 8 shows the revolutions per minute (RPM) of the engine when the vehicle is entering to the chicane, although there is no significant difference using Wilks Lambda test (Table VIII). The variations of the rpm is much lower in automatic gear shifting system comparing to the other sessions. However, the Wilks' lambda test is not showing a significant difference between sessions.

TABLE VIII. MAXIMUM ENGINE RPM IN SECTION B

Variable	Within subjects (Wilks' Lambda)			
	DF	e. DF	F	Sig.
Max engine rpm	2	16	1.698	0.214

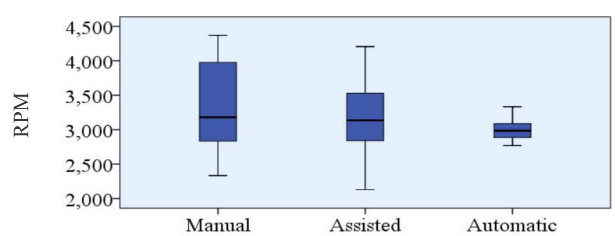

Figure 8. Maximum engine RPM in section B

The maximum deceleration in the first braking phase was found significantly different between the scenarios as shown in Table IX with the Wilks Lambda test. The results suggest that the maximum deceleration is different in the first braking phase (Fig. 9). Therefore, the participants brake harder when using automatic gear change in the first braking phase, but then user adopts to the vehicle, and therefore for the other braking phases the maximum deceleration is not different and remain in the same range.

TABLE IX. MAX LONGITUDINAL DECELERATION IN SECTION A

Variable	Phase	Within subjects (Wilks' Lambda)			
		DF	e.DF	F	Sig.
Maximum deceleration	1	2	17	3.870	0.044
	2	2	13	2.464	0.124
	3	2	15	1.036	0.379

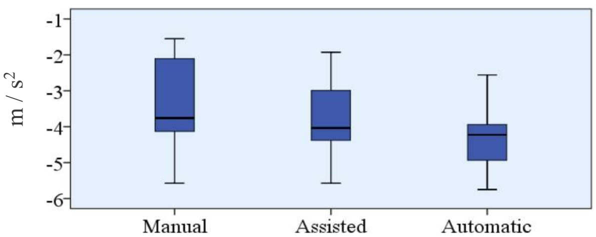

Figure 9. Maximum deceleration in braking in Section A

The maximum lateral acceleration in section B with chicane maneuver investigate using the within-subject Wilks' Lambda test (Table 10). However, in this case, no significant difference observed between sessions. Figure 10 shows the maximum lateral acceleration and variations during the chicane maneuver at section B.

TABLE X. MAXIMUM LATERAL ACCELERATION IN SECTION B

Variable	Within subjects (Wilks' Lambda)			
	DF	e. DF	F	Sig.
Lateral acceleration	2	10	1.406	0.29

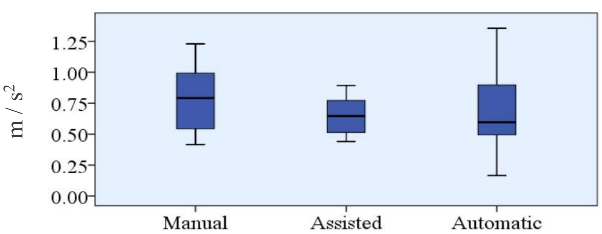

Figure 10. Maximum lateral acceleration at chicane in Section B

V. CONCLUSION AND FUTURE WORK

The increasing demand for driving simulation in the design of vehicle and driver assistant systems needs powerful simulators that can provide full stimuli for the drivers. This study aimed to investigate the motion cueing feedback in the driving simulator with different gear changing system. The developed vehicle dynamics model in MATLAB-Simulink described in detail together with the specifications of the 2DOF simulator and the Motion Cueing Algorithm.

Driving simulator experimentation with 19 participants was conducted in the car following/braking scenario, overpassing and chicane maneuver. The subjective evaluation of the motion feedback on participants is carried out with the use of the simulator evaluation questionnaire and the simulator sickness questionnaire. The simulator sickness scores showed no symptoms of sickness during the sessions, and the result of the session evaluation questionnaire showed that the motion cueing feedback was favorable by most of the participants and increased the immersion in the virtual environment.

The investigation of the motion platform accelerations showed no significant difference in driver control input and output of the vehicle model with different gear shifting scenario. Only the maximum deceleration for the first braking phase found different by comparing three scenarios. But this effect did not continue over the whole simulation. From the results of this study, one may conclude that different gear change system did not significantly affect the driver's behavior and the perception of the motion cueing feedback.

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