A novel method for the evaluation of driving simulator performances

F Cianetti¹, M Cavallaro¹, M Palmieri¹ and F Ambrogi²

¹ University of Perugia, Department of Engineering, Via G. Duranti 93, 06125 Perugia, Italy
² Vi-Grade srl, Via Manzoni 193/A, 06135 Perugia, Italy

E-mail: massimiliano.palmieri@unipg.it

Abstract. The use of driving simulator is increasing wide-spread in the whole automotive sector. The adoption of driving simulator indeed allows evaluating the design choices directly during the design stage through the man-machine interaction, where “man” means the driver while “machine” means the mathematical model of the car translated to the driver through a different machine: the driving simulator. In this research activity a questionnaire was developed to evaluate the performances of a driving simulator focusing on two main aspects. The first one regards the ability of the driving simulator to accurately reproduce the driving feelings without inducing motion sickness sensations. The second instead regards the ability of the driver to objectively judge the vehicle performances throughout a set of parameters. All these aspects were firstly numerically investigated implementing different models showing different dynamics characteristics and successively verified by experimental test at the driving simulator. The drivers scores, about both the accuracy of the mathematical model and the driving simulator, were analysed in order to understand if their feelings match the real behaviour imposed to the car.

1. Introduction

Over the last few years, the most important car manufacturers constantly invest in research and development of new technologies to improve driving simulator performances [1-5]. Driving simulators are tools able to faithfully reproduce the dynamic characteristics of a real vehicle in a virtual environment reproducing conditions and external factors to the passenger with which the vehicle interacts, replicating sounds and landscapes faithfully [6-7]. Driving simulators, in fact, are becoming a fundamental tools both for drivers training and for the design [8-9]. Moreover they are becoming crucial in the development of new technologies such as autonomous driving, active driving aids rather than driver behavior studies during a ride [10-12].

Currently, driving simulators can be split in two categories: static and dynamic [13]. Static systems are the simplest and least expensive ones since do not include moving parts. Dynamic simulators instead are installed on mobile platforms capable of replicating all motions of the vehicle.

But how faithful is the reproduction of driving feelings? The answer may seem obvious, and certainly the manufacturers of simulators are dealing with this question for several years, but the issues to be addressed are many and not easy to solve. Available literature does not contemplate methods for an objective evaluation of driving simulator performances [14-17]. According to this, with the interest of an important driving simulator manufacturer, it emerged the need to...
developed an evaluation questionnaire. An in-depth study on the state of the art about driving simulators leads to identify the main parameters of the investigation leading to a questionnaire divided into two main sections [18]. The first one is regarded to a technical evaluation of the driving simulator whilst the second concerns the perceived characteristics of the driven vehicle model. This, after a submission to users, gives the possibility to evaluate all various aspects supplying, at the end, a final scores.

Once the questionnaire was defined, it was fundamental to test its effectiveness through a test case. For an more objective evaluation of the driving simulator performances, through the proposed questionnaire, it was necessary to choose a vehicle for which a lot of information were available and drivers with sufficient driving experience on the vehicle itself. To overcome these needs, the Formula Student car of the University of Perugia was adopted. Moreover, to increase the objectivity of the evaluation two more models, with imposed bugs, were realized [19-20]. All the models were tested on a static driving simulator by five different drivers of the same team performing certain manoeuvre aimed to stress both the driving simulator and the proposed survey. After each session, drivers had to fill the proposed questionnaire leading at the end, to a final score useful to judge the driving simulator and to find technical aspects to be improved.

2. Theoretical background

To study the handling of the vehicle when cornering, it is necessary to describe the different behaviors that a vehicle exhibits during a curve. The simplest model of vehicle is the one called a single-track, or a bicycle.

There are two types of evaluation for understanding the vehicle performances: open-loop and closed-loop tests [21-22]. In open-loop tests, the driver provides inputs to the vehicle by acting, for example, steps or ramps input, a constant radius turn or an impulse input. In a closed-loop test, the driver must withstand specific tests, such as a slalom or double line change with maximum speed. The vehicle evaluation methodologies can be based either on personal evaluations of the driver, or through objective evaluation of the vehicle.

2.1. Circular test in steady state

The objective of this test is to determine the response of the vehicle’s direction control in steady state. A circular track is traveled with increasing speed or with a constant steering wheel angle, referring to a steady state manoeuvre in terms of steering angle as function of lateral acceleration. The vehicle outputs can be the side slip angle and the roll angle.

2.2. Lateral transient response test

The main objective of this test is to determine the behavior of the vehicle during transient phenomena. The typical monitored parameters for this test are the delay time, the response time, lateral acceleration. Figure (1) shows a typical response for a J-curve. The vehicle, after a straight line, should face a constant radius curve: the step from a straight line to a constant radius cornering condition required a certain time, generally called ”overshoot”.

The random steering input test is aimed to evaluate the frequency performance of the vehicle with lateral acceleration values up to $4\text{m}/\text{s}^2$. The response of the vehicle to a random steering input is generally expressed through the Bode diagram, thus in terms of magnitude and phase (figure (1)).

The simplest model to evaluate the handling of a generic vehicle is the single track vehicle model (often referred as ”the bicycle” model) shown in figure (2).

In figure 2, $\alpha_1$ and $\alpha_2$ denote the slip angle for the front and rear axle respectively whilst $F_{y1}$, $F_{y2}$, $M_{z1}$ and $M_{z2}$ are the total lateral force and aligning torque for front and rear axle respectively. The horizontal behaviour of the vehicle is described using a local lateral velocity
Figure 1. Typical responses for transient response test. (a) Response to step steering input. (b) Response to random steering input

Figure 2. Single-track vehicle model

\( v \) at the CoG, a local forward velocity \( u \) and a body slip angle \( \beta \). \( V \) denotes the total vehicle velocity that, for small body slip angle, coincides with \( u \).

Starting from the single track vehicle model shown in figure (2), it is possible to write the handling equation (equation (1)):

\[
m \cdot (\dot{v} + u \cdot \dot{r}) = F_{y1} + F_{y2} + F_{ye} \\
J_z \cdot \dot{\alpha} = a \cdot F_{y1} - b \cdot F_{y2} + M_{ze}
\]

In equation 1, the terms \( F_{ye} \) and \( M_{ze} \) are the external forces and moments respectively, for example, due to aerodynamic source. The solution for the steady-state case are considered [18]. The stability of the vehicle can be expressed as the response in steady state condition at the time instant after a disturbance from previous conditions. In steady state case, for a constant radius curve of radius \( R \), it is possible to obtain:

\[
F_{y1}(\alpha_1) + F_{y2}(\alpha_2) = \frac{u \cdot r}{g} = \frac{u^2}{m \cdot R} = \frac{F_y}{m \cdot g}
\]
The later acceleration $F_y = m \cdot g$ is function of the ratio between the wheelbase and the curve radius $R$, thus it is possible to write the following equation:

$$\frac{F_y}{m \cdot g} = \frac{u^2}{g \cdot \frac{L}{R}} \quad (3)$$

From previous equation it is possible to write:

$$\delta = \frac{L}{R} + (\alpha_1 - \alpha_2) \quad (4)$$

2.3. Oversteer and downsteer

By analyzing the handling equation in steady state condition, assuming a linear behavior of the tire, it is possible to obtain:

$$\frac{u^2}{g \cdot \frac{R}{\alpha_1}} = \frac{c_{\alpha_1} \cdot \alpha_1}{F_{z1}} = \frac{c_{\alpha_2} \cdot \alpha_2}{F_{z2}} \quad (5)$$

Thus:

$$\left[ \frac{F_{z1}}{c_{\alpha_1}} - \frac{F_{z2}}{c_{\alpha_2}} \right] \cdot \frac{u^2}{g \cdot \frac{R}{\alpha_1}} = \eta \cdot \frac{u^2}{g \cdot \frac{R}{\alpha_1}} = \eta \cdot \alpha_y(g) = (\alpha_1 - \alpha_2) = \delta - \frac{L}{R} \quad (6)$$

where $\eta$ is the understeering gradient. Previous equation clearly expresses the dependence of the vehicle’s performance when cornering on the tires characteristics. For very low speeds, the angle needed to make a curve is function of the ratio $L/R$ (Ackermann angle) [20]. Increasing the speed along the same curve with constant radius $R$, it becomes necessary to change the steering angle according to the understeer gradient, which depends on the characteristics of the tires. For a positive understeer gradient, the steering angle must increase, while for a negative understeer gradient, the steering angle must decrease (figure (3)).

![Figure 3. Example of understeer gradient](image)

3. The proposed method

With the aim of evaluating the performances of driving simulator, a questionnaire has been found to be the best choice. According to what already available in literature it was needed to propose a new questionnaire able to deeply analyze all the technical features of driving simulators. In such a way, a quasi-objective evaluation was possible. The proposed questionnaire is divided in two main parts: the first one is aimed to the evaluation of driving simulators characteristics, while the second is voted to judge if the simulator is able to supply the right feelings to the driver.
The followed approach allowed a complete view of all aspects link to driving simulations with the possibility to adopt the proposed questionnaire for whichever existing driving simulator. It is obvious however that it is mandatory to extend questions regarding mobile platforms on which driving simulator are installed on. In this study, dealing with a static simulator, these section has been omitted.

3.1. Evaluation of driving simulator performances
To cover all the main technical aspects of driving simulators, the section of the survey was divided into 7 sub-sections each of them aimed to cover every single aspect.

3.1.1. Driving experience
First questions are regarded to the evaluation of driving experience, both real and simulated. It is easily imaginable how the adaptation of experienced driver with no experience in driving simulation may result complicated while driver, also with only experiences in driving games, can manage themselves easily. The following questions where asked to drivers:

- Indicate the level of experience in using virtual driving platforms
  - High
  - medium
  - low
- Indicate the level of driving experience
  - High
  - medium
  - low
- Indicate which of the following driving experience you have:
  - Drive on the track at an amateur level
  - Driving competition cars with open wheels
  - Driving competition cars with covered wheels
  - Driving of Formula Student race car
  - Driving of Go-kart
  - Driving in regional or national challenges
  - Driving in international challenges
  - Driving of Go-kart
  - Other

3.1.2. General behavior of driving simulator
The second section of the survey is aimed to general evaluation of the simulator behavior which will then be analyzed in detail in the following sections. Questions of a general nature are presented allowing drivers to express a general assessment of the driving experience they have undergone. In particular, the questions are the following:

- How do you judge the general feeling provided by the driving simulator?
- How do you evaluate the general correspondence between the handling of the real and simulated vehicle?
- How do you evaluate the simulator’s ability to recreate the micro irregularities of the asphalt?
- How do you evaluate the simulator’s ability to recreate the macro disconnections of the asphalt?
- How do you rate the simulator’s ability to recreate the curbs?
• How difficult was to learn the use of the driving simulator?
• How long did it take you to adapt to the driving simulator?

All questions are graded from 1 to 10 as specified in the introduction to this chapter.

3.1.3. Evaluation of steering feedback  The steering feedback, especially for static simulator is fundamental. Omitting the visual and acoustic effects, the steering input represents the only link between the human driver and the vehicle. It is therefore necessary that the torque exerted by the specific actuator connected to the steering system supplies the correct amplitude to replicate the torque required for the steering of the real vehicle and that, based on the behavior of the vehicle, it provides correct and consistent feedback with the model. The evaluation of the feedback also concerns the ability to replicate the vibrations due to the irregularities of the asphalt and from the curbs, making the driving experience as more realistic as possible. In particular, the asked questions are:

• How do you evaluate the perception of the micro irregularities of the asphalt at steering wheel?
• How do you evaluate the perception of the macro irregularities of the asphalt at steering wheel?
• How do you rate the perception of the curb at the steering wheel?
• How do you rate the force feedback at the steering wheel in relation to the real vehicle?
• The torque at steering wheel results to be:
  – Too high
  – Too low
  – Appropriate
• How do you rate the perception of oversteering?
• How do you rate the perception of understeering?
• How do you evaluate the response of the simulator to a steering input?

3.1.4. Evaluation of acoustic effects  In order to ensure the most realistic driving experience possible it is very important to not neglect any aspect of the simulation. The sound effects are very important for a full immersion in the simulation. Poor sound effects replication necessarily results in an annoying driving experience [23]. To make the driving experience as more realistic as possible, the drivers must wear technical clothing. In fact, for the evaluation of the acoustic effects it is necessary to wear the helmet. In such a way, the sound achieved the driver with the right frequencies and intensity.

To evaluate the acoustic effects, the following question are asked:

• Is the driver wearing full technical clothing? (gloves-suit-helmet)
  – Yes
  – No
• How do you rate the quality of the sound effects while driving?
• How do you judge the quality of the engine’s audio reproduction?
• How do you rate the quality of the audio representation of the tires?
• How do you rate the noise of external sound sources?
3.1.5. Evaluation of visual effect  Also visual effects are important. An incorrect representation of the track environment and its outline is immediately noticed and generates disturbances in the driving experience. Precisely for this reason, the technologies of representation are evolving more and more towards a photo realism that makes the visual representation extremely realistic [24]. It is also important that the visual effects are able to provide an adequate perception of distance as well as the perception of speed. An incorrect representation of these aspects actually reduces the level of immersion of the driver, conditioning the perception of driving. Also in this case it is asked to specify if the riders wear technical clothing as the use of the helmet, since also in this case, can even improve the driving experience.

To evaluate the visual effects, the following question are asked:

- Is the driver wearing full technical clothing? (gloves-suit-helmet)
  - Yes
  - No
- How do you rate the quality of image reproduction?
- How do you judge the vehicle speed effect recreated on screen?
- How do you evaluate the distance effect recreated in the video?
- How do you evaluate the visual noise of the surrounding environment?

3.1.6. Evaluation of response speed  The response speed of the driving simulator is definitely essential for a good realism and to avoid driver’s discomfort. From a technical point of view, it is obviously essential that the model responds quickly to the driver inputs, reducing latencies until they become imperceptible. In addition to the reactions of the driver, visual, physical and acoustic stimuli must also be synchronized each other. If these latency phenomena were too evident, the actions of the driver and the reactions of the driving simulator would be out of phase and it may cause discomfort on the driver.

The questions posed to each driver are the following:

- How do you evaluate the delay between visually identifiable disconnections (ex. curbs) and reaction feedback?
- How do you evaluate the delay between the steering input and the related force feedback?
- How do you rate the delay between the steering input and the video shown?
- How do you evaluate the delay between the braking input and the relative feedback on the steering wheel?
- How do you judge the delay between the braking input and the video shown?
- How do you rate the delay related to the reproduced visual and sound effects?
- How do you generally rate the response time of the vehicle to the driver’s inputs?

3.1.7. Biometric evaluation  The last section of the survey concerns the monitoring of the main symptoms due to simulator sickness [25-26]. These parameters are very important since any discrepancies between the cognitive inputs may be sufficient to induce feelings of unease that after long driving sessions can become dangerous for the health of the drivers. The main symptoms are evaluated both during and after each driving session.

In this part of the survey, each driver will evaluate, with a score from 1 to 10, the presence of one or more symptoms among those listed in the following list:

- dizziness
- Headache
• Nausea
• Eye strain
• Difficulty to focus
• Salivation
• Sweating
• Concentration difficulties
• Blurred vision
• Stomach pain
• Others

3.2. Evaluation of general characteristics of the mathematical model
The first part of the questionnaire is aimed to identify and evaluate the behavior of the vehicle through scores expressed by the drivers. The results obtained from these investigations are then compared with those obtained from offline tests in order to verify whether the simulator is actually able to provide the right feelings.

Each driver is asked to evaluate the specific behaviors during the various phases of driving on the track with a vote from 1 to 10. Each driver must fill this section of the questionnaire as many times as the number of the tested models. For an accurate evaluation of driving simulator performances, this part of the survey was divided into specific sections for each maneuver addressed.

4. Test case
Before performing a test session it was necessary to define both the model of the vehicle to be tested and the maneuvers to be made. It was decided to model three variants of the formula student race-car of the University of Perugia. The first model is a faithful reproduction of the 2018 model while the other two models have been created imposing deliberately defects with the aim of a better evaluation of the driving simulator. In particular an evident understeering and a sudden loss of grip at the rear were introduced (figure (4)).

![Figure 4. Comparison between understeer gradient of the three mathematical model](image)

Once vehicle models were defined, appropriate test cases were chosen. Starting from standard manoeuvre described in reference standards [21-22], and considering the characteristics of the
modelled vehicle, it was chosen to test the models in 5 different manoeuvres. First two are regarded the verification of the model in stationary conditions (constant radius cornering). The radius cornering are equal to 10m and 30m. Such test were made increasing constantly the speed of the vehicle until it was possible to follow the impose trajectory anymore.

After, the behavior of the vehicle was monitored in transient condition, thus performing a slalom maneuver around cones spaced 15m as shown in figure (5).

For a complete evaluation of the driving simulator, it was imposed moreover to perform some laps in two different tracks. The first one is typical track of formula student racecar for the endurance test. This track, as shown in figure (6) is characterized by a rapid succession of tight curves. Moreover, since the FSAE track is totally flat, to evaluate the accuracy of the simulator in the reproducing all the aspherity, the Hockeneim short track was used as second test (see figure (6)). The track was obtained through a laser scan, showing in such a way all the typical defects of real track.

The different tests were carried out by 5 drivers, selected within the team of the University of Perugia, with different level of experience. This was crucial for the purposes of the statistical survey since, in such a way, it was possible to verify if and how different skills affect the adaptation to driving simulators. To avoid influences on the evaluation, drivers were not aware of which model they were going to test, thus making their evaluation as more objective as possible. Each driver underwent an initial adaptation phase of about 10 minutes, during which he was left free to drive around the virtual test area (proving ground) familiarizing with the
various controls of the driving simulator. After the adaptation phase it was possible to proceed with the established maneuvers.

4.1. Results and discussion

After each session, drivers had to fill the proposed survey. Firstly, it was certified if all driver was able to recognize the proposed model of the vehicle, distinguishing its characteristics. In such a way it was possible a first screening of the driving simulator performances. Figure (7) shows the results of each driver to two appositely questions voted to understand the feelings of drivers in driving one mathematical model with respect to another. Question "a" asked:

*By setting a constant radius cornering of 10m and increasing constantly the vehicle speed, does the loss of grip manifest itself by increasing the understeer character of the vehicle?*

The question "b" instead asked:

*By setting a constant radius cornering of 10m and increasing the speed of the vehicle, does the loss of grip occur abruptly in the rear?*

According to the questions, from figure (7) it is clear that all drivers recognize easily all the driven model, thus certifying a good correspondence between driving simulator feedback and driver perception. Analyzing the scores expressed by drivers regarding the evaluation of the performance of driving simulators the average scores, shown in figure (8), were obtained for each technical section.

In order to reach the final score that characterizes the simulator under all technical aspects, weights, from 1 to 5, have been assigned for each technical characteristic. Indeed, not all technical characteristics have the same importance, therefore the different weights will be assigned according to the effect of the single characteristics on the overall performance of the driving simulator. In particular, the weights shown in table (1) have been assigned.

All weight assigned and shown in table (1) was given according to the most important aspects of a driving simulator according with the manufacturer.
Once all sections have their own weight, it was possible to obtain a final score (FS) by a weighted average as shown in equation (7).

\[ FS = \frac{\sum_{i=1}^{n} x_i \cdot p_i}{\sum_{i=1}^{n} p_i} \]  

(7)

The final score of the investigated driving simulator results to be equal to 8.2 over ten thus certifying a high level of reliability of the tested simulator.

5. Conclusion

Due to wide-spreading use of driving simulators, it was necessary to find a method able to evaluate the performance of this technology and, if possible, to compare different driving simulators in order to have an overall judgment. From a literature analysis it emerged the need to develop an evaluation survey able of achieving the intended purpose in the most objective manner possible.

For this reason, an evaluation survey was drawn up, divided into different sections, capable of evaluating each specific technical characteristic of a generic driving simulator, getting a final score. The survey, which can be used for both static and dynamic driving simulators, as well as evaluating the performance of the simulator, allows keeping track of the developments of the system itself and to identify any critical issues to be optimized in subsequent developments.

The proposed survey was tested with an experimental test campaign using a static simulator, providing a very high overall evaluation, proving to be capable of getting the intended purpose.
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