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Driving simulator: an innovative tool to test new road infrastructures

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Abstract

Driving simulators are high-tech and cost-effective tools that allow performing complex tasks such as designing, testing and studying road design and equipment, e.g., road markings and signs, public lighting, specific traffic lanes. For this, IFSTTAR (The French Institute of Science and Technology for Transport, Development and Networks) has developed various types of simulators – static and dynamic car driving simulators, dynamic motorcycle riding simulators, a pedestrian crossing simulator – and is working on a bicycle simulator. As for any methodological tool, driving simulators must be handled in appropriate conditions. This article presents the pros and cons of this type of device based on IFSTTAR's experience of using simulators. The notion of validation of these tools is also tackled.

Keywords: Driving Simulator; validation; road design; road safety.

Résumé

Les simulateurs de conduite sont des outils de haute technicité permettant d'effectuer à coût réduit, des tâches complexes telles que la conception, le test, et l'étude d'infrastructures et d'aménagements routiers. Ces aménagements peuvent être des signalisations horizontales ou verticales, des éclairages publics, ou des voies de circulation dédiées. Pour évaluer ces aménagements, l'IFSTTAR (Institut Français des Sciences et Technologies des Transports, de l'Aménagement et de Réseaux) développe différents types de simulateurs de déplacement : plateformes statiques et dynamiques de voiture, de moto, un simulateur de traversée de rue pour piétons, ainsi qu'un futur simulateur de vélo. Cet article présente les avantages et les inconvénients de ce type de dispositif, en s'appuyant sur certains exemples d'utilisation qui en a été faite dans le cadre de projets de recherche. Comme pour tout outil, les utilisateurs de simulateur doivent en connaître les conditions d'utilisation appropriées. Nous abordons cette question en nous intéressant également à la notion de validation de ces outils.

Mots-clé: simulateur de conduite ; validation ; conception routière ; sécurité routière

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Introduction

Driving simulators are powerful tools which allow achieving complex tasks at a relatively low cost. There are several families of driving simulators which differ in how they are used. The most impressive simulators, developed by car manufacturers, serve to study the dynamics of vehicles and the validation of their components (Watson et al., 2006). In contrast, institutions dealing with driver training and road risk awareness use low-cost simulators to confront the drivers with various traffic conditions and to present them with crash scenarios. Finally, universities and research institutes dealing with transport and focussing in particular on the study of the behaviour of drivers and other road users (pedestrians, cyclists) implement driving simulation to approach a variety of questions such as the influence of medicine, the introduction of new driver assistance systems, the impact of new regulations, or the evaluation of road design solutions, on which we will focus.

Driving simulators indeed allow testing and comparing different existing or new road configurations or equipment. Thus, they allow determining how road design solutions are perceived and understood by the drivers, and which driving behaviour they generate. The managers of road networks are particularly interested in the acceptance of these solutions by the users, in their impacts on the speed and the side position of vehicles, or still in their impact on traffic safety. In the following sections, we begin with the description of driving simulators architecture; then we discuss advantages and limits of the driving simulators as a tool allowing the evaluation of road design solutions; we tackle the question of their validity and the construction of experimental protocols; we also present several examples of experiments which concern road design.

1. Architecture of driving simulators

Driving simulators immerse the participants (i.e., their drivers) into a virtual environment in which they move by controlling an interface (which can be a whole vehicle). The depiction of this virtual environment is generally multisensory, the objective being to bring to the participants the illusion that they are actually moving in this environment. Simulators thus consist mostly of elements of sensory stimulation (figure 1):

- an interface, which may come in various forms, from the simple steering wheel to the complete vehicle with more or less advanced platforms, allowing the participants to move through the virtual environment and to interact with the virtual users;
- haptic and inertial systems to improve the feedback;
- a 3D visual rendering engine to compute the visual road environment, associated with a display system;
- a 3D sound engine to improve the perception of traffic outside the field of vision;
- a populating engine to immerse the participants among virtual users with realistic behaviours.

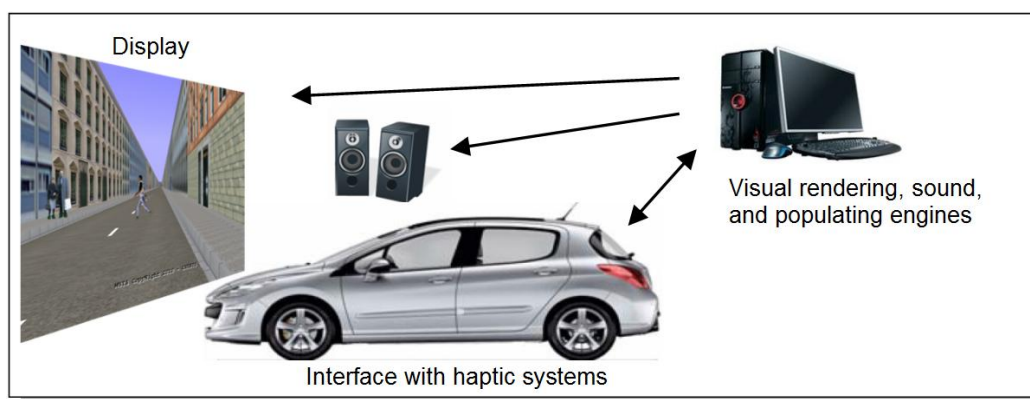


Fig. 1. Simplified representation of a driving simulator.

There are a number of possibilities for research and development towards better sensory stimulation to improve the immersion of the participants:

- high Dynamic Range (HDR) visual rendering for more realistic luminance and contrast levels;
- stereoscopic display for improved distance perception and feeling of presence;



- inertial (on the dynamic platforms) and haptic feedback for improved control;
- 3D sound and the auralization for improved spatial perception of sounds.

Other areas of research deal with populating the virtual scene and aim at improving and at validating the behaviour of autonomous agents (Esp   & Auberlet, 2007).

2. Advantages of driving simulation

There are different tools to study the impact of the road infrastructure and design on the behaviour of the users, such as roadside sensors, instrumented vehicles, and driving simulators. The latter present advantages compared with field systems, especially when it comes to the a priori evaluation of a project. Here are their main advantages in this respect.

2.1. Testing hazardous situations

Because simulators work with virtual environments, they provide total control over the simulated events. Thus, it is possible to present the participants with situations which would be difficult to study on a test track and even more on the road, either because they are hazardous or because they rarely occur. For instance, driving simulators have been used to study populations at risk such as elderly pedestrians (e.g., Lobjois et al., 2013), reduced visibility conditions such as fog (e.g., Caro, 2008), or still situations of traffic congestion.

2.2. Control and reproducibility of the driving situations for all participants

Another advantage of the simulators is to be able to plan and control the events, by acting in particular on the behaviour of the autonomous agents and the elements of the infrastructure (e.g., traffic lights). The driving situations can thus be reproduced as many times as needed, which facilitates behaviour comparisons with various participants.

2.3. Easy scripting of non-existing road features

Simulators allow creating virtual environments supported by the technical information which describe the infrastructure (e.g., alignment, cross section). It can be the mock-up of a real environment or that of a future road project. And it is possible to add or modify road features for the purpose of evaluation (figure 2).



Fig. 2. Sample road configurations and traffic conditions rendered on Ifsttar's driving simulator.

2.4. Recording traffic and vehicle data

To evaluate road design, the experimenters need data concerning the behaviour of the participants and their actions on the commands of the simulator (e.g., driving wheel, pedals, gear lever), as well as data concerning the traffic. The simulation software can supply such information since it manages the moves of the vehicle driven by the participants and as well as the actions of the various autonomous agents populating the scene. Contrary to most roadside or inboard observatories, information can be collected at a high frequency, with the possibility of fine data analysis.

3. Requirements when using driving simulators

Despite its advantages compared to field tests, driving simulators also imply requirements which must be taken into account when addressing the evaluation of road infrastructures. Some of them have to do with technical difficulties; others concern the behaviour which will be observed.



3.1. 3D database

The visual environment plays an essential role in the evaluation of the infrastructure on driving simulators. Therefore, the study of an existing street or highway requires two things. On one hand, the topographic data must be available; it may be obtained from computer aided design software such as Autocad, or from geographic databases such as Google maps (e.g., Auberlet et al., 2010). On the other hand, the surfaces must be textured in order to faithfully reproduce the real environment. When it comes to studying new road features, they must be modelled and rendered as accurately as possible. Generating satisfactory 3D databases is often difficult and time consuming, but it is a necessary first step. Care should also be given to road signs: depending on display resolution, the participants may not be able to read them from as far as in the real world.

3.2. Interaction with different actors inside the virtual world

To favour the immersion of the participants, the simulated traffic and the agents in interaction, such as the pedestrians, have to behave in a realistic way. So, when investigating road features in connection with traffic (such as congestion signalling) the behaviour of the virtual road users ought to be realistic enough not to influence the behaviour of the participants. This also involves an important preparation.

3.3. Lighting

Among the different channels of the human sensory system, vision is the main source of information for a driving task (Sivak, 1996). Therefore, the computer graphics element of the driving simulation must receive special attention. Recent studies have been investigating the use of lighting systems, such as road lighting or pavement-embedded signals which provide information to the drivers. For such studies, photometrically calibrated HDR rendering and display enables accurate simulation of luminaires and headlamps (e.g., Petit & Brémond, 2010).

3.4. Simulator sickness

One of the constraints when using simulators is the syndrome of simulator sickness (kinetosis). A common hypothesis concerning the origin of motion sickness is a conflict between visual and somato-sensory information. This syndrome appears particularly for urban driving (e.g., left- or right-turn situations) and concerns more particularly elderly drivers, a privileged target for our studies in road safety with the ageing of the population. Reducing simulator sickness is strategic, because it modifies the behaviour of those participants who feel it. Some solutions have been proposed, such as a questionnaire to identify those participants who are susceptible to motion sickness, or participant training to reduce the effects of kinetosis (Werneke & Vollrath, 2012).

3.5. Speed evaluation

On a driving simulator, it is easy to know the speed adopted by the participants all along the course. It is one of the reasons why speed is frequently used as an indicator to assess the impact of road design on the drivers' behaviour (Chrysler & Nelson, 2011). There are several such examples of a priori evaluation of road configurations on a driving simulator (Denton, 1980; Godley, 1999). Let us note however that the perception of speed can be biased on a simulator, so that we cannot consider that the practised speeds will be the same in real conditions (Chrysler & Nelson, 2011). Indeed, the main information used by the drivers to estimate their own speed of travel lies in the variations in size and position of the objects in the road environment, as well as the level of texture (Evans, 2004; Manser & Hancock, 2007). Peripheral vision is the main source of this information (Evans, 2004), which explains the decrease of performance of the participants when estimating their own speed of travel with a limited field of vision (Evans, 2004; Manser & Hancock, 2007).

As we have just seen, driving simulators offer advantages but also imply requirements. These may ban certain researches or impose the use of specific material and software configurations. In order to better comprehend these constraints with respect to the possible uses of driving simulators, we now approach the question of the validity of the simulators and of the experiments which they serve.



4. Simulators and experiments validity

4.1. Several definitions of validity

To our knowledge, there is no standardized method to validate driving simulators; the validation process is sometimes limited to checking the conformity with the technical specifications from the designers or to an expert's opinion. We propose several definitions of the simulators' validity and discuss the consequences about the experiments' setup. We think it is essential to assess simulators based on the sensations they provide or on the behaviour they lead to. However, few works have been undertaken in this direction.

Malaterre & Fréchaux (2001) distinguish four levels of simulators' validity, which correspond to different kind of similarities between driving in virtual environments and driving in the real world: the physical, experiential, ethological, and psychological validity. Physical validity refers to the similarity between the sensory stimulations generated in the real environment and in the virtual environment. Perfect physical validity would imply, among other things, to be able to submit participants to prolonged accelerations, to be able to display images with high levels of luminance and contrasts, and to play a perfectly spatialized sound whatever the subjects' position. Since current systems are not technically able to produce such stimulations, the simulators' designers have to produce illusions, relying on detection limitations and ambiguities in the human sensory system. Researches are thus conducted to tune motion rendering algorithms (e.g., Colombet et al., 2010) or computer graphics algorithms (e.g., Petit & Brémond, 2010) in order to generate sensations "similar" to those that would be experienced in real situations. This concept of sensations' similarity corresponds to the experiential validity, defined by Malaterre & Fréchaux (2001). Beyond the stimulations produced by the simulators and the sensations they provide, we can focus on the behaviour they lead to. Malaterre & Fréchaux thus defined the ethological validity, which deals with the similarity between the behaviours adopted on the simulators and in real situation, and corresponds to the absolute validity defined by Törnros (1998). Absolute validity means that all the observables of the behaviour, such as speed, are identical to those observed in real situations. When variations in the driving conditions induce the same change of behaviour in the simulation as in the real world, we speak of relative validity (Törnros, 1998). The results can then be interpreted qualitatively. Most (if not all) ethological validation studies deal with relative validity. By design (comparison with a control condition), experiments conducted on driving simulators generally presume the simulators' relative validity. Finally, psychological validity concerns the underlying processes which lead to the behaviour; however, it is difficult to identify these processes.

Research investigating driver behaviours, or the impact of road design on these behaviours, require simulators to have an ethological and experiential validity. In other words, these studies rely on similarity in both the behaviour of drivers and their experience, rather than the stimulations they are presented with. To our knowledge very few data are available regarding explicitly the validity in relation to the different types of driving simulator. A recent study (Rosey & Auberlet, 2014) showed the same trends in participants' behaviours on two different driving simulators, but higher speeds on the desktop simulator than on the full-cab one. Other studies (Auberlet et al., 2010; Auberlet et al., 2012) showed that there is a correspondence between the effects of perceptual treatments on driver's behaviour, when studies are conducted with a static simulator, a dynamic simulator, and in a real situation, which goes in the way of relative validity.

Beyond the validity of the simulator as a tool, it must be emphasized that the processes which underlie the behaviour of drivers are particularly complex (e.g., Michon, 1985) and may be influenced by many factors other than those related to the "driving simulator tool". Therefore, attention must be paid to such factors when experimenting on a driving simulator.

4.2. Relevant factors

In this section, we propose an inventory of the factors that influence the behaviour of the participants in a simulator experiment, whether or not these factors are related to the operation of the simulator. We propose to classify them in the following four levels: (1) access to information, (2) speed and trajectory control, (3) representative character of the situations, and (4) factors related to the individual and the context.

The first two levels concern those factors which affect the physical validity of a simulator. For the first level (access to information), it is the information provided to the participant under different sensory modalities in the



virtual environment and the movement in this environment, including information provided by the cab of the simulator or device, through the speedometer or dashboard lights for instance. The second level (motion control) concerns the interface which enables participants to control their movement, i.e., their path, speed, and position relative to other vehicles. This level is based primarily on the dynamic model of the vehicle which is implemented in the simulator, the haptic feedback provided by the various commands (e.g., hardness of the pedals and steering wheel), not to mention the use of different actuators in the cab.

The third level (representative character of the situations) no longer concerns the simulator as a physical object but rather scenarios and virtual environments that are planned and presented. This level includes several components such as the richness of the visual scene, the way the virtual world is populated (density and behaviour of other users), or the frequency of extraordinary events. These are meaningful components which address processes at the highest levels for the participants. Thus, the behaviours of the participants tend to differ according to traffic density or in unusual situations.

Finally, the fourth level (related to the individual and the context) refers to anything that is outside the driving simulation itself. Participants are indeed required to drive a simulator in an environment that is foreign to them and under the scrutiny of the experimenter. This laboratory setting is totally different from the normal context of driving. The emotional state of the participants (Jallais et al., 2011) and the events they have previously gone through in the near or distant past are also likely to influence their behaviour. Note that a large part of the boundaries of simulation experiments also applies to studies aboard actual vehicles and more broadly, to all experimental contexts.

4.3. Consequences for experimenters

Insofar as each of the previous factors is likely to influence the behaviour of the participants, they can affect the validity of the experiments carried out in terms of ethological validity. Experimenters must pay attention during the construction of the experimental protocol, and evaluate the potential impact of each factor depending on the purpose of the experiment. We could consider building a checklist to assess the potential impact of each of these factors, depending on the experimental conditions and objectives of the experiment. However, this approach involves having prior knowledge of the behaviour of the participants and of the parameters which are expected to influence it. Such precautions generally come with the methods used in experimental psychology, which we will not detail in this paper. Nevertheless, we list several components of the experiment the importance of which should be emphasized: the pre-experiment(s), the instructions given to participants, how participants are familiarised with the simulator, and the post-experimental interview.

The pre-experiment(s) and instructions given to the participants contribute to a common goal: to ensure that the participants actually encounter the studied driving situations and to verify that these situations were properly set up (proper choice of experimental conditions). For example, if for the purpose of the experimentation, the participants are expected to pass a vehicle in a specific area, the experimenter must make sure that the participants catch up with a vehicle, that they have the opportunity to pass it in the targeted zone, and that they understand that the manoeuvre is allowed, like in real life. This simple goal requires both a fine focus of the scenario and the choice of appropriate instructions. The instructions also provide the participants with some background on the driving situation, when the experimenter wants to draw their attention to a particular context (e.g., category of the road, day and time, passengers in the vehicle) which is likely to influence their behaviour.

The familiarisation phase appears to be an important part of each experiment with the simulator and the driving situation (Auberlet et al., 2010; Rosey & Auberlet, 2014). It comes at the beginning of the experimentation, and should enable the participants to integrate the relationship between their actions on the controls of the simulator and the sensory and cognitive feedback that they receive. Their ability to control the simulator must therefore first improve, and then stabilize. Ideally, participants should have reached stability before the start of the test phase (where data will be collected) to prevent behaviour changes during the experiment. Therefore, it is desirable for the participants to face different types of stress (curves and speed changes more or less pronounced) during the familiarization phase, and for the nature and magnitude of the stresses to be adapted to the content and purpose of the experiment. For example, the participants should be confronted with sharp curves or narrow lanes during familiarization if the course of the experiment contains such features.

Discussion with the participants at the end of the experiment helps understand the mechanisms that they believe have dictated their behaviour, and point to possible misinterpretations. Without the absolute validity of the driving simulator, looking into the underlying mechanisms is necessary to make sure that the results apply to the actual driving, and to generalize to other driving situations.

5. Examples of simulator-based studies

This section presents several projects where Ifsttar's driving simulators were implemented to test new road features. In each case, it was necessary to improve the physical validity of the simulation platform with specific modules and technical developments in order to address the particular characteristics of the studied features.

5.1. Audio-tactile markings (ROADSENSE)

The ROADSENSE project aimed at defining and at optimizing the technical characteristics of warning audio-tactile systems (e.g., rumble strips). The purpose of these systems is to prevent run-off-road accidents by warning the drivers with vibrations (Rosey, 2011). Trials were conducted on a driving simulator, on a test track as well as on a road open to traffic in order to rate the performance of different systems (figure 3), and to evaluate drivers' perception. Since audio-tactile markings produce a warning when the tire of the vehicle runs over them, it was necessary to provide visual, vibratory and acoustic feedback to the participants. This called for a new vibro-acoustic rendering module. Rendered vibrations and sounds were measured with accelerometers and microphones and compared to measurements in the field; agreement between these measurements indicated satisfactory physical validity.

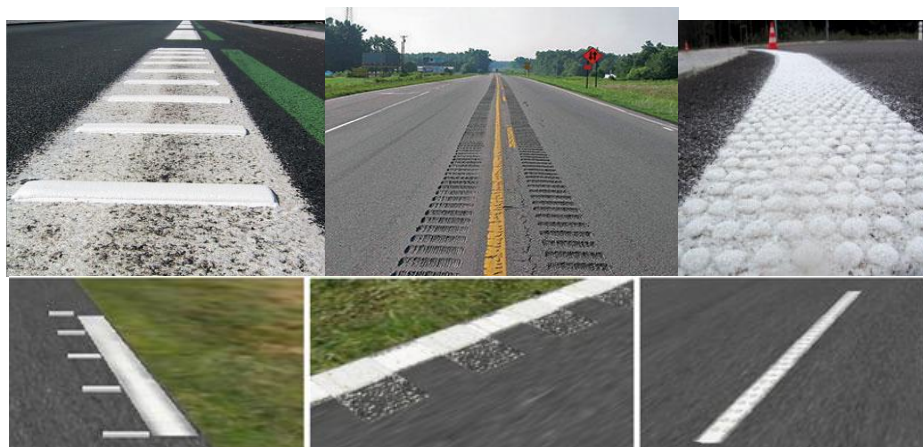


Fig. 3. Illustrations of the audio-tactile systems tested: the first line contains pictures of systems in the real world; the second line shows snapshots of their virtual reconstruction.

5.2. Intelligent road studs (INROADS)

The aim of the FP7 project INROADS (INtelligent Renewable Optical ADvisory System) is to improve the efficiency of the road network through the development of an intelligent LED road stud system, with integrated communication and sensor systems, which can get some or all of its power needs from renewable sources*.

Again looking for physical validity, we determined the photometric characteristics of the studied LED road studs as well as the operating rules of the automaton which controls a group of those LEDs. Then, we simulated these particular signals so as to produce luminance levels on a calibrated display system that were similar to those in the real world; we also simulated other lighting sources in the scene such as the driver's and oncoming vehicle headlights, as well as road lighting. Finally, we modelled the automaton of this device, the one which allows controlling colour, display frequency, activation/deactivation of one or many LEDs.

* <http://www.fehrl.org/?m=320>

Thanks to these improvements in the visual rendering engine of our simulator, we were able to investigate potential applications of intelligent LED road studs at night (see Shahar & Brémond, 2014). The focus of this study was on the visibility, the legibility and in general terms the benefits of such LED-based systems. We used a simulator having three Full-HD 47-inch screens. The central view of the driving simulator (figure 4) was a HDR (High Dynamic Range) screen which provided a luminance range much wider than classical screens (Seetzen et al., 2004). Luminance was measured with a luminance meter and calibrated in order to match the real situation. Moreover, subjective judgements (questionnaires) indicated a good experiential validity. This new functionality of Ifsttar's simulator will allow us investigating night-time driving conditions.



Fig. 4. High Dynamic Range rendering of night-time driving conditions with road lighting (left) and LED studs (right).

5.3. Lateral position at crest curves (VIZIR)

A study of the impact of different perceptual countermeasures on the lateral control of passenger cars on a straight rural road, especially when driving on a crest vertical curve, was conducted in the framework of the VIZIR project (in association with CETE-NC, LAMIH, SETRA). Perceptive difficulties were hypothesized because most of the accidents involve human errors and because almost half of all fatal collisions in Europe are classified as single-vehicle run-off-road or head-on collisions, which related them to trajectory control (Rosey et al., 2008).

The mock-up of an existing two-lane rural road was created for the purpose of the experiment. Ifsttar's fixed-base driving simulator served to test various types of treatments at a crest curve (figure 5), in order to evaluate their impact on lateral positioning (Rosey et al., 2008).

This experiment showed that the two treatments which best helped the drivers stay at the centre of their lane, with the lowest variability in lateral position, were the rumble strips (although they were rendered without vibration feedback) and the paved roadsides. Their influence was observed upstream and downstream of the crest curve. The same experiments, with the same 3D database, were conducted with the motion-base simulator of LAMIH (Auberlet et al., 2010); measurements were also made on a real highway (Auberlet et al., 2012). The agreement between the results of the different conditions showed that relative validity had been achieved.

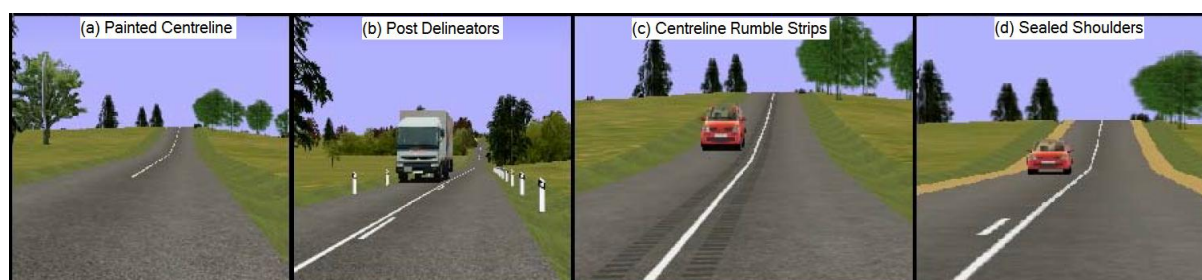


Fig. 5. Snapshots of four experimental perceptual treatments investigated on a driving simulator.

6. Conclusion

This paper recalls the advantages of driving simulators, particularly for the purpose of evaluating road design and treatments, compared to road-side or in-vehicle behaviour observation devices. It also raises some questions about the validity of driving simulation, which is seldom tackled, despite the fact that it determines the ability to generalize the results of the simulator experiments to the real traffic situations.



In order to have similar behaviours on a simulator and on the road, we need to target ethologic validity (ideally, psychological validity would allow exploring the processes which determine the behaviour). This is often done indirectly by assuming that it will derive from experiential or physical validity (e.g., section 5.1 & 5.2). It is also done by comparing behaviours on a simulator with behaviours in situ for a limited number of controlled reference conditions, assuming that the validity applies to other conditions (e.g., section 5.3). Even when a driving simulator is validated, the capacity to obtain valid results with it still depends on the manner in which it is implemented. This aspect is even less documented than validity itself for applications in the field of road safety and operations. However, driving simulators have proven their worth (Keith et al., 2005), and given that the demand is still high for testing innovative road configuration and equipment (see for example Transportation Research Circular E-C110, 2007, related to new technologies for highway design) – probably thanks to the development of the systemic, user-centred approach of road safety, further research into driving simulator validity and operation should be encouraged.

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