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Simulator technology for research and training
Simulátorové technologie pro výzkum a výcvik

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Summary

This presentation covers the topic of the simulation technologies used for research tasks and training purposes. It provides a reader with overview of the important milestones and important examples of simulators (and mainly driving simulators) over the world. A special focus is on those devices, which were developed in the Laboratory of Systems Reliability at Faculty of Transportation Sciences, Czech Technical University in Prague.

In the next part there is described in detail the architecture of driving simulators and recently used technologies. It concerns all necessary subsystems of interactive simulators, such as visual, audio and motion cueing system, mathematical model of car dynamics, interconnection module and others. A separate chapter is devoted to a unique approach to enhance the visual system with dynamic interior lighting, which is author's original contribution to the interactive simulator technology.

Souhrn

Přednáška pokrývá témata simulačních technologií používaných pro účely výcviku i pro výzkumné úkoly. Poskytuje čtenáři přehled důležitých milníků a významných příkladů simulátorů (zejména vozidlových) z celého světa. Zvláštní důraz je kladen na simulátorové systémy, které byly vyvinuty v rámci činnosti Společné laboratoře spolehlivosti systémů Fakulty dopravní ČVUT a Ústavu informatiky AVČR.

V další části je detailně popsána architektura vozidlových simulátorů a současné technologie používané k jejich realizaci. To zahrnuje veškeré nutné subsystémy interaktivních simulátorů, jako jsou generátory poskytující vizuální, zvukové či pohybové vjemy, matematicko-fyzikální model vozidla nebo např. modul zajišťující propojení jednotlivých subsystémů. Zvláštní kapitola je věnována unikátnímu systému, který rozšiřuje běžné možnosti vizuálních systémů o dynamické osvětlení interiéru kabiny simulátoru, jež je autorovým původním příspěvkem k modernímu technologickému řešení interaktivních simulátorů.

Keywords

Interactive simulators, simulation technology, cueing, virtual reality, human – machine interaction, operator training

Klíčová slova

Interaktivní simulátory, simulační technologie, simulace vjemů, virtuální realita, interakce člověk-stroj, výcvik operátorů

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1 Interactive Simulation

Modern interactive simulation of transport systems is set up as a model of the vehicle (or other machine or artificial system), both from the perspective of the machine itself, just from looking around, with which the agent interacts in real situations. If the simulated operation of the device includes driver’s interventions, it is a so-called simulation system "driver-in loop”.

Interactive simulation model and a vehicle are equipped with functional models of systems from the perspective of the user (operator) providing the functions necessary for the validity of a particular experiment or a satisfactory training. Since the model is a real system with limited capabilities, it is always necessary to assess professionally whether the simulator system is suitable for each particular experiment or training Moreover, sometimes also validation and comparative experiments are necessary.

Modern simulators usually consist of parts of real vehicles or machines, with which an operator interacts, and the complex system of computer-generated virtual reality, which should cover the widest possible range of operator’s sensor input, so that it can induce a sense of realistic environment. The primary group consists of visual cues, audio cues and the dynamics of self-movement. Other cues are generally neglected, if not directly related to the specific measurement or training.

1.1 History

Very first simulation systems can be found at a very beginning of air force pilots training procedure. Training in real planes meant higher training cost and high danger rate for novice pilots. After such successful launch of pilot training simulators, other vehicles simulators came quickly. The most widespread have become the car driving simulators.

The simulator systems used to be developed for use in three separated fields:

- Training
- Research
- Entertainment

Originally, different ways of use of the simulators in the above noted fields have merged during decades of their use and development.

1.2 Vehicle Simulators

Vehicle simulators are widely used since they cover education of professional drivers (operators) and non-professional ones as well.

1.2.1 Flight simulators

As it has been already introduced, the flight simulators started the era of training simulators in the beginning of the 20th century. Flight training school “Antoinette” developed the first flight simulator in 1909 (Fig. 1).

Fig. 1: Antoinette flight simulator 1909

1.2.2 Space vehicles simulators

Space vehicles are very special systems which construction is quite unique. Besides this, they are very expensive and their operation must be performed faultlessly. Any operator’s mistake can have horrible consequences. Moreover, the training under real condition is almost impossible. From those above listed problems, the use of simulator is easy to come.

1.2.3 Rail engine simulators

Rail engine simulators are often used in developed countries for training of engine drivers. This covers either novice basic training or so called “new track familiarizing” for experienced drivers being prepared for new lines. Such simulators can be differentiated into following categories:

- Rail engines (locomotives)
- High speed trains
- Trams
- Special railroad vehicles and machines

1.2.4 Captain bridges (ships) simulators

As in case of other expensive vehicles, the ship simulators are extremely cost effective. The next picture shows interior of captain's bridge training simulator used to train officers of Dutch Naval Forces (Fig. 2). Although the initial cost of the simulators is quite high, its working cost is incomparable to the real training ship (we must count also work of the whole ship crew).

Fig. 2: Dutch Royal Navy captain bridge simulator

1.2.5 Driving simulators

Under the term of so called driving simulator, we consider the interactive simulator either of car (passenger cars, lories, trucks, heavy tippers etc.) or two-wheelers (i.e. motorbikes). The car driving simulators are discussed in more details thereinafter.

The interactive simulators of motorbikes are now mostly used for entertaining purposes or in the first stages of motorbike drivers training. This is due to the fact that the process of driving is slightly different from for example cars, where just simple rotating of steering wheel forces the car to move in suggested direction. The motorbikes require much more physical interactions to control the machine in appropriate way. This of course puts much higher demands on such responses of the simulator like correct motion cueing and possibility of rocking the machine left and right while turning. On the other hand, the bike, while moving thanks to interties and a gyroscopic effect tends to stay in vertical position. This is very hard to be simulated, in the way the riders would be feel like on the motorbike. However, there are now several research applications even for motorbike simulators.

1.2.6 Special devices simulation

In this group, we can find mainly the training simulators of devices to be operated in various industrial areas. These are mainly mine vehicle or drilling mechanisms or heavy cranes (in ports usually)- see Fig. 3 left. Medical treatment simulators present a special category. There, “operators” (surgeons, nurses, dentists etc.) are trained how to deal with humans (Fig. 3, right).

Fig. 3: Crane simulator (left), human body simulator for nurses (right)

1.3 Operator’s workplace simulators

At the end of the 20th century development of traffic significantly increased, which led to a growing need to build terrestrial road communications as well. The construction of these roads has involved transportation structures such as bridges and tunnels.

Tunnels can be affected with numerous critical situations. The standard emergency situations can include failure of transport facilities and equipment related to traffic control. Other critical situation may occur when oversize loads vehicle entering the tunnel, an accident happens or automobile traffic congestion appears. Several times per year they needed to solve such crisis situations, such as car in the opposite direction, it may happen that there is observed a small fire in either a tunnel tube or technical background. Dispatchers must be ready for the extreme cases like tunnel fire or terrorist attacks.

Methods of training may be different. Normal training involves classroom lecturing with explanations of situations, use cases and possible exemplary solutions. It is usually finalized with written or oral exams. There is no possibility for the dispatcher to get in touch with “real” emergencies in this case. As well the performance under the stress is also hard to be trained. Nowadays the simulator of dispatcher workplaces can be used to simulate both, normal operation conditions and critical situations as well. It is possible to teach and train the operators in the regular tunnel maintenance or evoke a “real” emergency. By current experiences, dispatchers have a couple of most important and simulator suitable critical situations, where such training takes place.

1.4 Car Driving Simulators

The driving simulators and the driving simulation technology are said to be a “royal discipline” within the scope of the simulation devices.

The advanced driving simulators are very expensive. First, their technical and spatial demands are very high and second, they are not produced in large series, but mostly developed individually on demand. For this reason its development includes a lot of research effort (it is always expensive).

For the reasons described above, they are usually developed and designed in cooperation with university research institutions, state research institutions and car manufacturers.

The driving simulators are continuously developed in the majority of industrial countries over the world. Their detailed description would require a big amount of space, so this paragraph serves as an illustration only.

The first driving simulator was designed as 3DOF motion based one. It was equipped by one screen in front of the windshield. It was built by Volkswagen in early 70’s. Having experiences from this motion based simulator in Germany, Swedish Road Administration (VTI) in 1977 started to develop a novel and complex design, which has majority of features of nowadays simulators (see next pictures – Fig. 4).

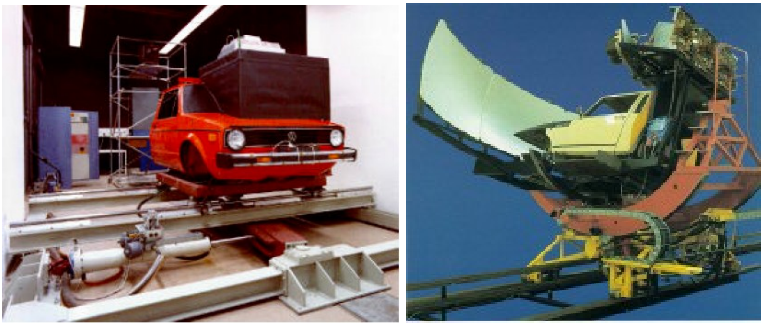

Fig. 4: The first motion based driving simulator VW (left) and its Swedish descendant from 1984 (right)

1.4.1 Non-interactive simulation

In the very beginning of HMI research history non interactive car "simulators" were frequently used. Basic research activities did not necessarily require simulating complex interactive behavior, but rather rely on predefined scenarios. In this case, the feel from real driving is usually simulated with use of car body or mockup and movie projection. Such simulator systems are still used mainly by psychologists.

1.4.2 PC "game" simulators

Such kind of so called serious games can be considered as simulators as far as they satisfy particular experimental conditions for validity. In other words any PC driving game can be used for either training or research purposes in limited cases. Thanks to the rapid development of gaming industry nowadays, these games usually offer stunning graphics but the realism is usually not their intrinsic feature as they rather offer entertainment.

1.4.3 Virtual simulators

Virtual simulators are in fact PC simulators which utilizes virtual glasses as an output and frequently also haptic feedback as additional outputs. Input is usually done via normal gaming steering wheel. This is mostly satisfactory since the “real parts” of the cockpit, the driver can see, are virtual ones.

1.4.4 Light cockpit simulators

Light cockpit simulators take advantage from the fact, that the driver usually does interacts with car cockpit in a limited range. This allows to surround him/her with important parts of the car and save space and weight (which is crucial in case of motion base setups).

Fig. 5: Driving simulators by Mitsubishi Precision (Left) and Honda (Right)

1.4.5 Full body simulators

These simulators are composed of the whole car body (or partially cut off unnecessary parts due to spatial of weight restrictions). They are considered as a top version and are used with and without motion platform.

1.4.6 Motion platform based simulators

The simulators with advanced motion cueing are based on several construction approaches. Since there is in most cases a whole car inside the simulator main body (dome), the most important requirement on moving platform is its adequate bearing capacity.

Some construction approaches emphasize certain motion cues and suppress other ones which are (according designers’ experiences) less important. In addition, the ratio quality/price is here quite high. In the picture Fig. 6, there is possible to see VTI simulators with emphasized lateral linear motion.

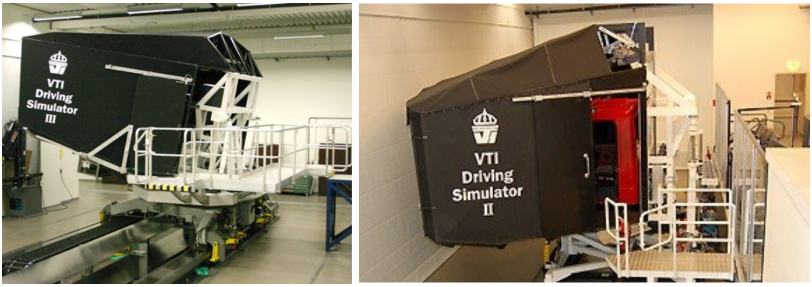

Fig. 6: A hybrid motion platform for simulator VTI in Linköping (passenger car – left and truck simulator - right)

1.4.6.1 Full body simulators with motion platforms 6DOF

Most of the simulators that use full car body mockup are placed on the top of so-called Steward Platform or "hexapod". This system enables to simulate movements in all 3 axes and tilting in all 3 angles. Its main advantage is that they can make a full range of possible motion cues but their range and frequency is limited according to their size and payload. Hexapod construction comes from the field of aircraft simulation, which, maybe, from the first look seems to be more complex (since the aircraft is floating in the air). Unfortunately the situation with car simulators motion cuing is even more complicated due to the fact that the car is tightly bind via wheels to the surface of roads and it still requires regular movements and tilting in 6DOF.

Because of above described problems the hexapod construction is not agreed to be suitable for car driving simulators and it is usually extended to reach higher range movements or enhanced with additional motion actuators.

In the next pictures there are three different architectures of full car simulator setups based on hexapod platform:

1. Full car body is placed on the moving platform enhanced with vibration actuators placed beneath the hubs. The simulation system is equipped with very large projection screens. Since the screens are static and the car mockup is moving independently, this setup is necessary to cover the driver sight even if the care is tilted. Due to this fact, it is also easy to come that the simulator is capable of limited range of motion cueing.

2. Full car body is placed on a hexapod with extended size. The visualization system does not need to be so large, because the car body does not change its position with respect to the projection screens. Visualization is frequently realized as a projection dome or a part of it.
3. Full car body is placed inside pensile capsule which is hinged by “giant” hexapod installed upside down. This solution is unique and its architecture advanced the hexapod system with possibility of simulation of lateral movements that are quite limited in conventional hexapods.

Fig. 7: Full car simulator situated on robust hexapod platform in BMW – left and one of the European latest simulators by Simtec and DLR – right

1.4.6.2 Simulators with enhanced movement capabilities (6DOF +)

To simulate realistic feeling from driving it is necessary to assure that the driver is exposed to at least basic spectrum of motion cues. These are beside acceleration and deceleration also centrifugal forces acting on the driver when the car is turning left or right. In certain limited range, it is sufficient to cheat the driver with rocking the car left and right according to the steering wheel movements as it is done for the case of speed up and down changes. However, the driver when controlling the car direction relies on lateral acceleration and motion as a direct response to his steering maneuver. For this case, it was proven that lateral movements are the most appropriate motion cues.

Because of the above described facts, the most advanced motion based driving simulators are often designed as a mixture of motion cueing approaches:

1. motion (vibration) actuators with limited range mounted under each of hubs
2. hexapod with medium range supported car body and frequently also visualization screens or dome
3. cross platform on which the complete system made of both above mentioned parts is moving in XY direction to simulate lateral and longitudinal motion cues

Fig. 8: Perhaps the most advanced motion based simulation systems – NADS in USA (left) and Driving simulator Toyota in Japan (right)

2 Driving Simulators Design

As it was possible to see from the previous chapter, the simulators have different construction topologies. The topology is often connected with the simulation fidelity but they are tightly coupled with the system cost. Although the simulators producing the majority of available cues in the largest ranges are considered as high fidelity simulators, they do not necessarily fit best to all experiment types. Even the most expensive systems still only approximate the real driving experience. As a result there is only a model more or less satisfying needs of each particular experiment.

Generally, nowadays simulators can be differentiated into 6 basic topological setups. In the next picture (Fig. 9), there are illustrations corresponding to setups in order based on approximate cost (from cheapest to the most expensive):

1. Simple cockpit mockup, steady, static projection screens

2. Same as 1, but cockpit is replaced with full car body
3. Same as 2, but placed on simple moving platform (usually 3 DOF)
4. Simple mockup placed together with projection screen on full range moving platform (6 DOF)
5. Same as 3, but equipped with full range moving platform (6 DOF)
6. Same as 5, but the projection screens are moving

Several different variants can utilize more than one topology from those above described. Alternatively, they can have features, which are not covered with such categories. Some moving platforms are enforced with additional movements (sometimes called 6 + DOF) for enhancement of the movement ranges in important directions.

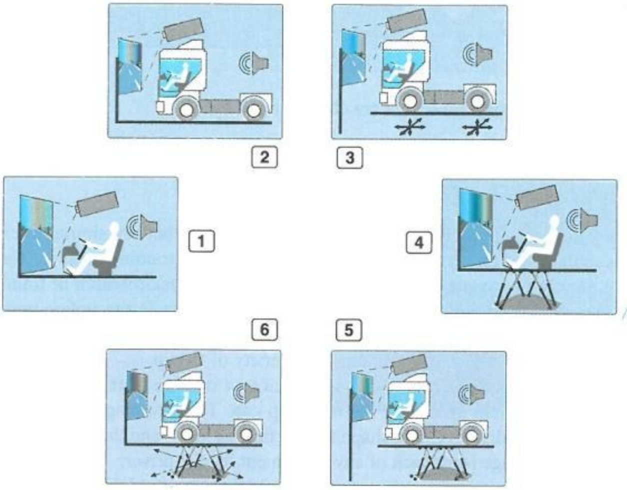

Fig. 9: 6 basic driving simulator setups 1-6, as described in the previous text (adopted from [12])

2.1 System architecture

An overall system of ‘living’ simulator (equipped with tools enabling its modifications respecting actual needs of each particular experiment) can be described as a multilayer model. The next figure (Fig. 10) introduces the functional structure of our equipment from the point of view of the simulator.

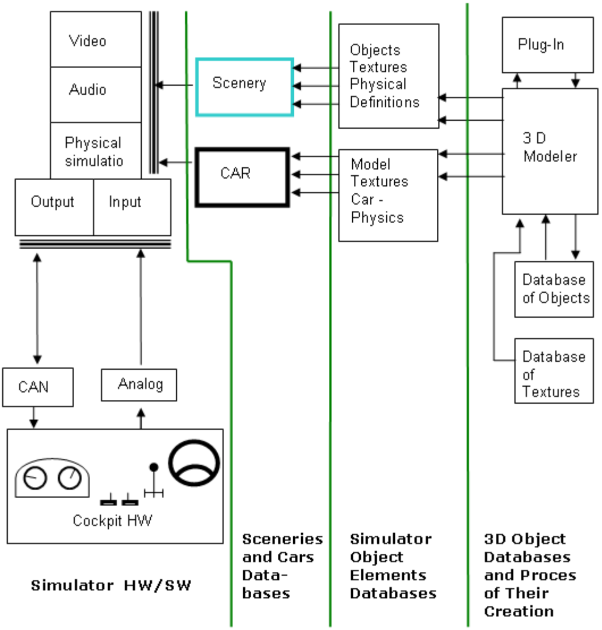

Fig. 10: Functional structure of the simulator

The whole system can be divided into four layers (they are separated with green lines on the picture). The first layer represents the simulator device itself. It consists of software and hardware parts. It is composed from parts of a real car and PCs connected to a network. I/O cards (like CAN bus to PC interface) are also included in this layer. Software of the simulator consists of Virtual Reality engine and mathematical model of the car and environments.

Second layer in fact represents testing/training scenario. The next layer represents a database of testing tracks (sometimes called scenarios) and cars. Each experiment requires a more or less different scenario. To get objective results it is necessary to have precisely defined difficulty of each scenario.

The last layer represents tools for creation of assets constituting scenarios. Those are mainly modeling of 3D objects and tools for automation of such process and databases (storages) of modeled objects.

2.1.1 Modular architecture

The above paragraph introduced the simulator system as a layered architecture. In fact, the architecture of the simulator itself is usually modular. The basic system setup can be decomposed into subsystems, which could be treated and solved separately (see the diagram Fig. 11).

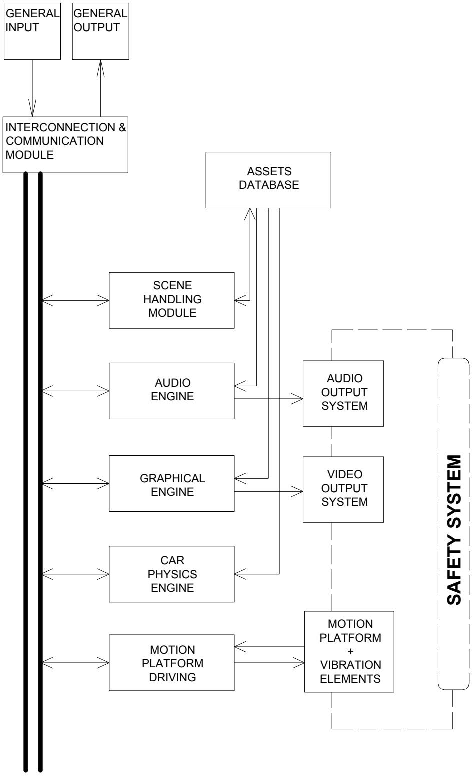

Fig. 11: Advanced driving simulation system – basic structure

The modules can be treated and operated separately but it is very useful to take advantage of their interconnection. The results from tasks computed on one particular module could be utilized in other modules, which process the same (or very similar) data. As an example, we can consider a geometric representation of an area of the virtual scenery. The graphical engine primarily cuts off an appropriate area of the virtual world representing the actual driver's surroundings. Then the geometry should be worked out according to a particular level of detail. Such data then enter into rendering process. Such data could be also reused in other modules. For example, the audio system also needs the geometrical representation of the world to be able to render the sound realistically. Other modules, which can take advantage from such pre-computed data, are for example:

- collision detection subsystem
- traffic management subsystem
- general output subsystem
- car simulation physics engine

2.2 Mathematical – Physics simulation engine

The model of the car is created with the use of linear integral-differential solver. Online processing of input data (signals from the devices representing driver's controlling actions) is a basic requirement on mathematical model of physical behavior of any interactive simulation system. Such inputs, in case of driving simulators, are represented by the following signals (parameters):

- Rate of depression of throttle pedal
- Rate of depression of brake pedal
- Rate of depression of clutch pedal (in case of manual gear shifting)
- Gear shifter position
- Angle of steering wheel deflection

Those are the basic ones, which can be (and in most cases of high fidelity simulators are) accompanied with additional inputs which tell the simulator about the driver's orders and wishes (handbrake, handlers, buttons etc.). The physical "engine" (processing the mathematical car model) should be able to react on additional inputs which are usually realized via direct (manual setting) or indirect (realized via activation of some assistant system) driver's interventions.

Another important source of information upon which the mathematical model decides about future steps in car behavior is an actual state of the objects the car is interacting with. Upon these above described information and information about inner structure of the simulated system (axle architecture, gearbox etc.) the actual behavior (next step) is computed. The following picture (Fig. 12) illustrates a basic arrangement of powered wheel in contemporary road vehicles.

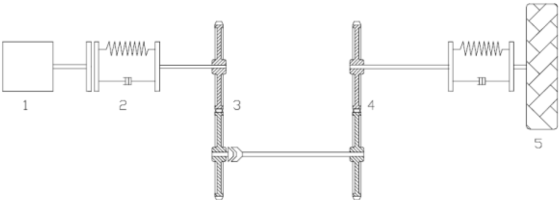

Fig. 12: A simplified transmission of the initial torque from the engine up to the wheel surface (engine with flywheel (1), clutch (2), gearbox (3), differential (4), axle with wheel and suspensions (5))

The mathematical model of vehicle physics makes always a kind of compromise in between physical preciseness and ability of computer to compute online enough short simulation steps.

The core of the physical engine is composed from partial function blocks respecting a real structure and links. In our model these are:

- Engine
- Gearbox
- Wheels (tires)
- Suspensions
- Car body
- Surface of interacting terrain
- Initial parameters of the whole model
- Input parameters from driver and other simulation models
- Inner variables

In the following picture (Fig. 13), there is architecture of our physical engine.

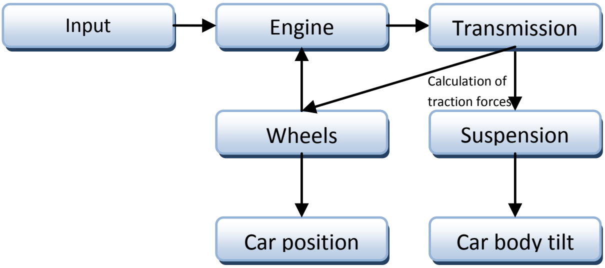

Fig. 13: Architecture of the physics engine

2.3 Visualization system

Most of the information that the driver's brain needs for driving (i.e. correct response to the outer conditions and various stimuli) are visual ones. From the observed virtual scenery, the driver gathers information primarily about:

- Shape and color of the surrounding objects (including the road)
- Distance of the objects
- Self-movement (eventually the relative movement of other objects)

From those primary cues, he/she derives secondary information about:

- Self (car) velocity in all directions
- Limited range of self (car) accelerations in all directions
- Weather conditions
- Road condition
- Surrounding objects (obstacles) and their movement
- Surrounding traffic
- Contextual information (signposts, pictograms, texts, traffic lights, etc.)

2.3.1 3D projection

The driver should obtain correct information about his/her distance from outer objects. A standard projection simulates depth by correction of vertical and lateral coordinates by the portion of depth coordinate, so that there is an effect of "distant junction of parallels". The next equation shows computation of new 2D coordinates:

$$X_{2D} = X_{3D} - \frac{DX}{Z_{3D} + \text{Eye distance}} \times X_{3D} \quad Y_{2D} = Y_{3D} - \frac{DY}{Z_{3D} + \text{Eye distance}} \times Y_{3D}$$

Where $\frac{DX}{DY}$ is the distance between the eye and the 3D point in the X/Y axis, a large positive Z is towards the horizon and 0 is screen. Unfortunately, this does not provide correct and convincing appearance of immediate surroundings.

A stereoscopic projection gives the solution to this problem. Concerning HMD, the stereoscopy is its intrinsic property, since each eye is served by a separate display. Common projection screens need special solution, which is in principal projection of two images, which should be separated into the appropriate eye, on common projection screen. Two main ways most frequently used (anaglyphic glasses are used really):

- Polarizing filter glasses (passive stereo) - a cheap method that transports correctly the appropriate image into the appropriate eye, based on two differently oriented polarizing filter couples.
- Shutter glasses (active stereo) - an approach is based on principle of shutters synchronized with graphical output providing for each of the eyes only the appropriate frame. Their shutters are frequently limited in size.

Fig. 14: Photo taken from the cockpit where driver is observing the 3D scenario

2.4 Audio system

Besides the visual information, the second most important one is the sound information. It accomplishes or substitutes the visual and other cues coming into the driver’s senses. From the virtual sound, the driver can get information about:

- Car velocity
- Engine velocity and load
- Interaction with different types of road surfaces
- Sound properties of surrounding environment (open road, tunnel, corridor, bridge, forest, etc.)
- Surrounding traffic
- Collisions

2.4.1 Simulation of the engine sounds

The car engine sound is one of the most important audio stimuli for the driver [8]. While driving a real car, the engine is not usually the strongest source of the sound, but it is important for the driver to feel how fast the car goes and how fast the engine rotates. Besides the hearing and the visual sensation there are the haptic perceptions, which cause the feeling of speed. The rumble of moving car is carried from the steering wheel to the driver’s hands, and also to the whole body via the seat and the car floor. These are also very important noises but they are hard to simulate. In the driving simulator it is convenient to simulate much more clear, strong and sharp sound than is present in a real car, especially if it is not possible to simulate haptic perceptions. The audio perceptions partially take over a task of haptic ones, which is very beneficial.

The engine itself produces sound field in the whole acoustic band. It also generates very loud subsonic tremble. The car cab damps the sound of the engine significantly. It filters out higher frequencies more efficiently than the lower frequencies and subsonic ones. Sounds of very low frequencies are carried to the chassis, so the sound level in a subsonic band is higher in a cab than outside the car.

2.5 Haptics, motion cueing

Both of the frequently used simulators - the steady based or motion based - can be equipped with additional feedback devices. They should provide even more realistic feelings from driving. The aim of their use is to stimulate mechanical feedback coming either from the car itself or from the environment (e.g. road, blasts of wind). Motion platforms used in modern simulators are quite complex, mainly from the point of intelligent control, which should give the driver mechanical (based on forces acting on his/her body) responses from driving, utilizing only limited range of accelerations. The problem is roughly illustrated in chapter 1.4 and its detailed explanation is out of the scope of this presentation.

2.5.1 Steering wheel

The system that is necessary to be emphasized is the feedback on the steering wheel. This is actually the most direct way of how the driver feels reactions of the car to his/ her control actions. The correct behavior of a feedback of the steering wheel is essential for correct path keeping. For that reason majority of steady based simulators are equipped with at least certain type of steering wheel feedback.

2.5.1.1 Feedback of the steering wheel

In general, the powered steering behaves in complex way, but it is possible to describe its function much more precisely since it is electronically driven. In the next picture, there are plots of responses measured in a real car equipped with electric power steering (Fig. 15).

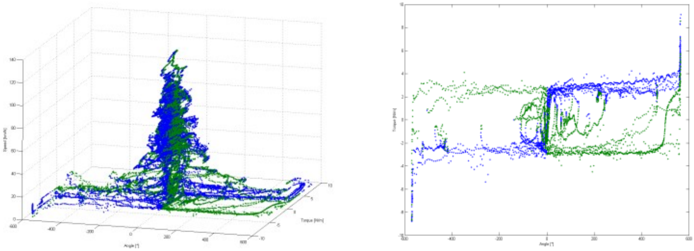

Fig. 15: 3d plot of velocity, steer angle, steer wheel force (left), 2D cut of the same at 0-5km/h (right)

3 Enhanced immersive features

Although the visualization - and computer graphics as a whole - is nowadays the most developed part of the virtual reality, the main point of hi-fidelity simulators lays mainly in its possibility to immerse the tested/trained subject into the virtual scenarios. Majority of contemporary simulators are composed both from virtual and real parts. The system, which is described in the following chapter, was developed in our laboratory just to overcome this problem.

3.1 Shadow-Light projection system (DYICOLIS)

Scenarios with complex lighting - like road tunnels (experiments depicted for example in [9], [10], [11] and light conditions for simulations described in [3]), require more complex approach. The night driving scenarios (for measurements of driver's fatigue [6], where the light changes could either influence the driver's vigilance in positive sense or they can contribute to his/her discomfort) also provide the driver with much more complex light stimuli than common simulators can offer. Proceeding from those proposals in our laboratory, we designed the so-called "Dynamic In-Cockpit Lighting System".

The system idea was first introduced as DYICOLIS in 2007 [2] providing basic functions. The DYICOLIS brought also several enhancements into the field of visual cuing. It can for example help the driver perceive the speed of the car (mainly in slower ranges) more accurately; it can partially solve the problem of inadequate optic flow, because it projects the picture directly in front of him/her. The couple of pictures below shows the simulator without (Fig. 16 - left) and with (Fig. 16 - right) incorporation of the DYICOLIS. We can see that the simulator equipped with inner lights and shadows, which are dynamically projected on its cockpit parts, immerses (or "plunge") the subject deeply into the virtual scenery.

Shadows cast by various objects appearing on the scene and lights coming from various sources (besides changeable light conditions) are just in "touching distance" to the driver and because of that fact they really intensively influence driver's senses.

Fig. 16: Pictures from the simulator cockpit – classical approach (left) and the cockpit equipped with DYICOLIS (right)

3.2 Shadow-light scenarios

3.2.1 Day vs. night light conditions

The main difference, which every driver should notice, is that the car interior appears differently during the day and during the night. While during the day (bright day) the main (better say the most significant) source of light in the car interior is the sun, the night cockpit illumination is composed of complex and dynamic set of artificial light sources. Contemporary simulation systems usually do not solve this problem and rely on the light reflected from the screens, i.e. daylight scenarios possess more light while night less.

3.2.2 Daylight and dropped shadows

The daylight is characterized as a relatively strong uniform light source diffused or one directional, in majority of cases it is a mixture of both. Mostly it is of white color, occasionally colored by some large color reflecting surfaces. The main effect of the directional sun light is casting shadows from close tracksides objects (traffic signs, houses, vegetation etc.) and the shadows dropped by the car itself. The shadows casted by the trees around roads are very impressing (Fig. 17). A correct reproduction of car shadows requires incorporating 3D car roof coulisse, which is deformed with respect to the light source position [4].

Weather, which possesses uniform, diffused illumination of static character, presents the simplest environment for in-car lighting simulation model. This can be carried out with a very simple setup with single or multiple monochromatic light sources (usually light tubes) installed around the car cockpit, so that they can on one hand illuminate the interior and the driver's body and on the other hand they do not directly affect driver's eyes (for details see [5]).

Fig. 17: Patterns created on the dashboard the shadows dropped from the trees during the bright day (Left – real car view, Right – simulator view)

3.2.3 Night and tunnel driving

Driving during nighttime and inside tunnels has many common specifics. A series of images (Fig. 18) describes how the illumination patterns affect the cockpit parts and the driver as well. Its dynamic behavior is caused by movement of the car against the light sources. Since they work like obstacles between the light source (street lamp, tunnel illumination…) and the target of light projection (car interior and driver's body), they also create beside the light pattern a shadow pattern which is of the same dynamic properties. If there are multiple light sources which can affect the car contemporarily, each of them creates its effect which is mixed up with contribution of others into the final appearance (Fig. 18).

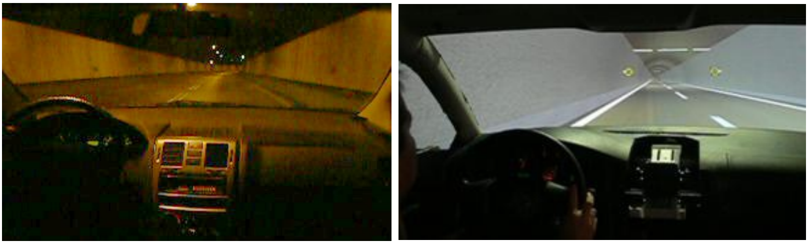

Fig. 18: Dynamic behavior of the light pattern projected onto the car's interior in the tunnel environment (real car - left, simulated car - right)

3.3 DYICOLIS design

3.3.1 Static Elements

For systematic creation of the “shadow” scenario, it was necessary to categorize different elements of the light (shadow). For this purpose, the objects are divided into following subcategories:

1. **Ambient light**
    - Open spaces
    - Tunnels
    - Daytime/Nighttime
2. **Elements of light**
    - Lamps
    - Traffic lights (partially dynamic)
    - Lighted sign tables
    - Reflective planes
3. **Elements of shadow**
    - Bridges, tunnels
    - Shadows of buildings, track side objects
    - Soft shadows of complex objects (trees, bushes fences…)

3.3.2 Dynamic Elements

In general the properties of the objects, casting shadows (which affect the car interior), usually do not change but rather move. Dealing with lights affecting the car cockpit, they could both move their position and/or change their properties. The properties are their color and intensity, frequency of blinking, etc.

1. **Dynamic light elements**
    - lights of emergency cars
    - traffic signalization
    - warning signals on the road
    - surrounding traffic (front, tail and directional lights)

2. Dynamic shadow elements

- moving, rotating or shivering objects (or their parts)
- longitudal shadows (overtaking cars, cars in contra lane…)
- transversal shadows (cars crossing the crossroad, vehicles or trains crossing the bridge)

An example is shown in Fig. 19 - the shadow cast by the truck during the daytime, when shadows are long enough so that they affect the inner cockpit. The shadow is moving and changing with truck position and orientation.

Fig. 19: The shadow cast by the truck moving around the simulated car (left) and dynamic scattered blue light is emitted by police car beacons (right)

3.3.3 Casting maps

Generally, in computer graphics, those textures are made as secondary textures on the objects and they are called light maps or shadow maps. For our purpose, there is no need for secondary textures, the shadows and lights are projected on a real object mapped on its real appearance. Because of that fact we only use the primary textures with gray shadows and color lights mixed together, mapped on simple objects (for simplicity they called them “casting maps”). The casting maps are in fact images obtained as a mixture of the actual ambience expected to persist in particular area and all the active lights, which can affect a volume of the car interior. To achieve a realistic look it is necessary to take into account also the ambient light (the contribution of lights, shadows and ambient lights needs to be computed properly). The picture below (Fig. 20) shows some real situations and corresponding examples of shadows-light maps.

Fig. 20: Examples of the objects, their projection on the real cockpit and their casting maps (from the top to the bottom: Tunnel driving, Traffic lights in the dark environment, Open scenery with trees)

3.3.4 System design and software implementation

The following diagram (Fig. 21) shows a complex way of creation of the final image which is projected onto the car interior. From previous setting, which took into, account only the lights and shadows statically persisting in the scene, now the changeable, movable and deformable shadow-light objects have been introduced. The final image is obtained from the combination of all the components fold up together and mixed with the use of the alpha blending.

The communication between a car physical engine and corresponding visualization software should be as fast as possible. The frame rate of the projected image is expected to be as high as possible because of the fact that the projected shadow and light maps appear in the immediate vicinity of the driver; hence he/she is very sensitive to jerking of the image. When dealing with motion of light and shadow maps which are cast (or projected) on the cockpit and some parts of the driver's body it is necessary to synchronize them correctly with the image, which the driver can see on the screens. In addition, the module working with the car coulisse requires the positions of current light sources and the sun. The arrangement of the programming solution is described by means of the following diagram (Fig. 22).

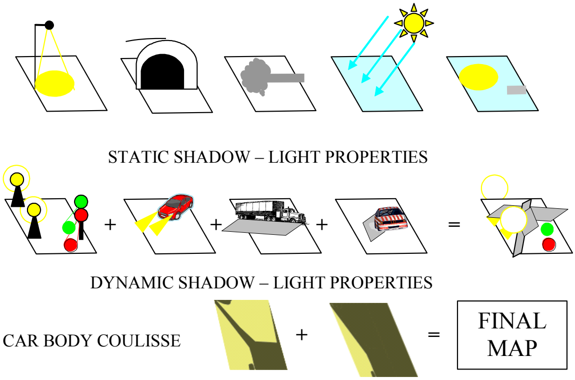

Fig. 21: Mixing of the casting maps on three levels allowing dynamical shadow-light behavior

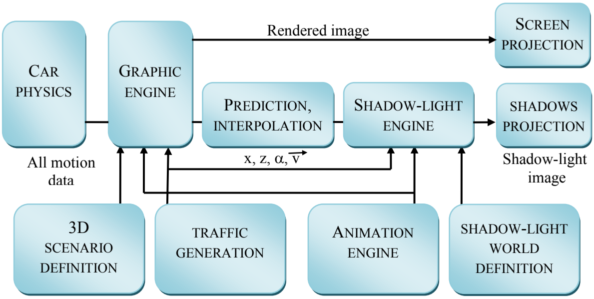

Fig. 22: Schematic diagram of interconnections between the modules

4 Laboratories and Simulator Systems at FTS CTU

Car simulation devices (FIDS – fully interactive driving simulators) are used and they have been continuously developed within the Laboratory of Systems Reliability (LSR) for more than eight years. We use several different versions (or types) of car simulator design.

4.1 Non-interactive simulation for rail engine-drivers

These kinds of simulators are still used mainly by medical institutions. We used such arrangement for sleep onset detection with the use of EEG. Railway drivers were tested just in front of the screen shoving a record from the regular line.

4.2 PC simulator Favorit

The very first arrangement of our simulation device used a common PC steering wheel with two pedals with a sequential gear shifter (or automatic shifting was applied). Now we use a special three pedal system (including a possibility of involvement of the clutch if required) and an H-pattern gear shifter. The realistic three-dimensional cockpit lets the driver immerse himself into the projected scene. In the picture (Fig. 23) there is depicted our very first approach to the driving simulation technology. The experimenting driver uses a big TV screen and common game steering wheel and pedals (see [7]).

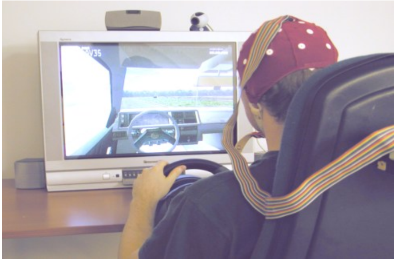

Fig. 23: Our first approach to FIDS in duty form the year 2002

The simulation systems described in the next chapters (4.3-4.7) were developed in close cooperation with Skoda-Auto a.s.

4.3 Light simulator Superb

This arrangement represents an intermediate step between the virtual conception and a usage of a real car body. It comprises advantages of both of these approaches. For example it is much more convenient (in comparison to the “compact simulator” discussed in the next section) for the implementation of so called “in-car dynamics”, which forces the driver to percept the driving experience more realistically (see Fig. 24).

The simulation engine of the car is connected to the car parts via the CAN bus. Connection into CAN is bidirectional; functional parts are the speed and RPM needles (plus other information on a central display), a steering wheel, a gear shifter, a throttle and other pushbuttons and handles.

Fig. 24: One of the first prototypes of out light simulator (2003) – left and contemporary look of our light simulator Superb (2007) - right

4.4 Full simulator Superb

This version is most close to the reality concerning the driver's ergonomics because it uses a complete real car body (see our compact simulators illustrated on the Fig. 25 - left). The tested person sits in a real cockpit and the virtual scenery is projected on the screen walls in front of the car hood and/or around the car depending on the particular design. Results from measurements using such a device should not be loaded with an error caused by the difference between a simulator and a real car cockpit. On the other hand, this setup is rigid and very hard to reconfigure (for example when the experiments require several different configurations of function buttons handlers and/or dashboard instruments).

Fig. 25: Superb simulator upgraded with 5 projectors surrounding projection screens (2006) – left and driving simulator Octavia II (2008) - right

4.5 Full simulator Octavia II

The compact (or full-bodied) simulator is based on the compact middle class car Skoda Octavia II (Fig. 25 – right) equipped with an automatic gearbox. The projection screen of the simulator is cylindrical, covering about 210° (horizontally) of the driver’s frontal field of view. The image in all three mirrors is reflected from a planar projection screen staying behind the car body. The tested driver is surrounded by an almost complete, all-around image of virtual reality. Such an arrangement maximizes immersion into the testing scenarios and consequently the validity of the measured data.

4.6 3D light simulator Octavia II

The latest simulator is our flagship. It is based on cockpit of Octavia II. It offers cave-like visualization system enhanced with polarized 3D projection. The light version of the simulator is based on cockpit parts cut just behind the driver seat. The cockpit is fully equipped like normal car (including roof, mirrors, co-driver seat, etc.). The simulator system is placed on specially designed 3 DOF moving platform (Fig. 26).

Fig. 26: Cockpit of the light simulator Octavia II 3D (2010) (left) and 3DOF moving platform, specially designed for use with light simulator (right)

4.7 Fully Virtual simulator

The use of VR in product design significantly reduces the production cycle, cuts cost and improves quality. Because there is no need to produce expensive physical models, their use is fast and very cheap. The experimental driver, equipped with HMD, has now a freedom of view, which of course requires the cockpit completely modeled in 3D. A sensor connected to his head scans the driver`s head turns. This data primarily serves for evaluation of turn/move of the projected picture or it could be stored for further analysis of driver's head movement. Such a set up presents a good competition to a compact simulator because it could retract the observer deeply into the scene. The cockpit design, ergonomics or other setups could be relatively easily changed (tuned up), respecting the requirements of the actual experiment.

In the picture (Fig. 27 – left), it is possible to see image the driver observes in HMD. Drive's hands are observed by IR motion tracking system and right hand fingers are connected to sensor glove. Thanks to such arrangement, a driver can interact with elements of virtual world. Except of interaction with basic cockpit controls (steering wheel, pedals and gear shifter), he /she can also touch other virtual buttons and handlers. In the following picture there is a real driver sitting in a virtual simulator trying to manipulate with inner middle mirror (Fig. 27 - right)

Fig. 27: VR environment seen in HMDs (left) and driver in virtual simulator, HMD - real parts of the cockpit wearing high resolution, extra-large FOV HMD (right)

5 Conclusion

The simulators give a wide range of possible applications. Nowadays, the high quality simulators are widely considered as valid devices for training of drivers, training situations under demanding conditions for professionals, but also for research and investigations concerning the reliability of driver-car interaction, for solving the large variety of human-machine interaction problems (HMI) and assistance systems optimization.

Driving simulators have been successfully used for several decades in research and automotive industry. We can find first steps of these activities in the 1950's (VW, BMW and Ford). Their blossoming appears in the 1970's (mainly Ford and VW). Originally, they were developed to help drivers to train their driving skills, and during time, they maturated for use in training of professional drivers of special vehicles to adapt to demanding situations.

In the very beginning of 2000's, in the Joint Laboratory of System Reliability of Faculty of Transportation Sciences CTU and Institute of Computer Science ASCR (LSR), the investigations in drowsiness of rail engine operator began. Based on EEG brainwave analysis with use of advanced non-linear analysis colleagues started to detect sleep-onset of engine drivers after long shifts.

During almost a decade, this research blossomed out rapidly and the original experimentation split into more than one discipline. Beside the original research activities investigating the operator drowsiness, now we have several branches covering the whole field of so-called HMI discipline. During this time, a research group (Driving Simulation Research Group) has been formed as well as new student projects and subjects where problems of HMI and interactive simulations are lectured. .

Several novel approaches have been developed and implemented during almost 10 years of continuous building up of our laboratories. This concerns e.g. the DYICOLIS, which provides the driver with realistic light conditions inside the car cockpit allowing overcoming the border between reality surrounding the driver and virtual world surrounding the simulator. Thanks to such conception, also two of the well-known problems of driving simulators – problem of optic flux and underestimation of self-motion velocity - have been significantly improved.

6 List of References

[1] Bouchner P., Novotný S.: *System with driving simulation device for HMI measurements*, 8th WSEAS International Conference on SYSTEMS (part of the 8th CSCC Multiconference), Athens, 2005, ISBN 960-8457-29-7.

[2] Bouchner P., Novotný S., Piekník, R.: *In-cockpit dynamic lighting system for driving simulators and its impact on quality of driving immersion*, Driving Simulation Conference - North America 2007, Iowa City, Iowa, 2007

[3] Bouchner P., Novák M., Přibyl P., Vysoký P., et al.: *Optimization of design and maintenance of road tunnels*, annual reports 2004, 2005, 2006 (in Czech), National project supported by Czech ministry of transportation

[4] Bouchner P., Novotný S., Jirkovský V., Piekník R., Pěkný J., Kozumplík M.: *Enhancement of DYICOLIS (Dynamic In-Cockpit Lighting System)*, Driving Simulation Conference 2008, Monaco 2008

[5] Wenzel G., Dangelmaier M., Marbeger C., Becirovic S.: *Daylight simulation for driving simulator interior*, Driving Simulation Conference 2004, Paris, 2004

[6] Bouchner, P. - Hajný, M. - Novotný, S. - Piekník, R. - Pěkný, J., Valtrová K.: *Analysis of technical and biological outputs from simulated driving, focused on driver's fatigue detection*, Proceeding of Driving Simulation Conference Asia/Pacific, National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba, 2006

[7] Bouchner, P.: *VR Simulation Device as a Support for Research in Driver's Micro-sleeps and Attention Decrease Detection*, TRANSTEC 2004, The Transport Science & Technology Congress [CD-ROM] vol. 1, pg. 65-72 Athens, Greece, 2004

[8] Hajný M.: *Module of Audio Subsystem of Car Simulator*,(in Czech), Diploma thesis, FEE CTU, Prague, 2006

[9] Ceci R., Högman L., Patten C.: *Measures of driver behavior and cognitive workload in a driving simulator and in a real traffic environment*, Driving Assessment 2001, Snowmass Village at Aspen Colorado

[10] Amundsen F. H.: *Studies of driver behavior in Norwegian road tunnels*, Tunnelling and underground space technology, 1994, 9(1), p. 9-17, 05051101

[11] Toernros J.: *Driving behavior in a real and simulated road tunnel - a validation study*, Accident analysis and prevention, 1998, 30(4), p. 497-503, 05051103

[12] Kappler W.D., Smart Driver Training Simulation, Springer-Verlag Berlin Heidelberg, ISBN: 978-3-540-77069-5, 2008

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- E-safety, member, eSOP revision of basic document HMI in cars, activity of EU committee (2008-2009)
- LSS (Joint Laboratory of System Reliability of CTU FTS and AS CR) – depute head, work in the field of Research of Driver's behavior, implementation of virtual reality tools into the experiments, design of experiments and their analysis
- CTU FTS, Education (teaching), supervisor of bachelor, master and doctoral theses, founder of 3 subjects thought in bachelor and master track at CTU FTS
- DSRG (Driving Simulation Research Group) - Foundation and Leading of research group

- Member of editorial board of scientific journal Neural Network World

Publications:

Since 2003 several tens of papers, chapters in journals, research report with topics on driving simulation, human factors in transportation, especially on driver's attention and fatigue; H-index = 2 (WoS)

Selection of most important recent publications:

- Novák, M. et al., Road Accidents Reduction, Aracne editrice S.r.l. 2010, ISBN 978-88-548-3550-4
- Votruba, Z. - Novák, M. - Brandejský, T. - Fábera, V. - Bouchner, P. – e tal., Theory of System Alliances in Transportation Science, Praha: Ústav Informatiky AV ČR, v.v.i., 2009. 162 p. ISBN 978-80-87136-08-9.
- Jiřina, M. -Bouchner, P. - Novotný, S., Identification of driver's drowsiness using driving information and EEG, In: Neural Network World. 2010, vol. 20, no. 6. ISSN 1210-0552.
- Faber, J. - Pěkný, J. - Piekník, R. - Tichý, T. - Bouchner, P. - et al., Simultaneous recording of electric and metabolic brain aktivity, In: Neural Network World. 2010, vol. 20, no. 4, p. 539-557. ISSN 1210-0552.
- Bouchner, P. - Novotný, S. - Faber, J. - Tichý, T., Driver's Attention Level Improvement with Use of Biofeedback Stimulation Incorporated into Driving Simulator,In: Neural Network World. 2009, vol. 19, no. 1, p. 109-118. ISSN 1210-0552.
- Novák, M. - Votruba, Z. - Svítek, M. - Bouchner, P., Improvement of Bus and Truck Driving Safety, In: 2006 IEEE International Conference on Systems, Man, and Cybernetics [CD-ROM]. New York: IEEE - Systems, Man, and Cybernetics Society, 2006, ISBN 1-4244-0100-3.
- Bouchner P., Novotný S., Piekník, R.: In-cockpit dynamic lighting system for driving simulators and its impact on quality of driving immersion, Driving Simulation Conference - North America 2007, Iowa City, Iowa, 2007