# Driving Simulators for HMI Research

PhD. Thesis

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# Abstract

This work presents a compact view on the discipline of driving simulation. It introduces some of world-class research driving simulators and problems of their design and construction as well. A validation of the simulator functions and validation of the experiments to be preformed on the driving simulator are described here. Then the requirements on such a device are analyzed and different approaches to visual, audio and motion cueing are discussed. The thesis in its second part describes using the driving simulators for research purposes. A complex system which involves a simulator incorporated into a set of measuring devices is described in detail, ways of data collection and analysis are shown. The last and most comprehensive chapter illustrates the possibilities of the driving simulator use through the mediation of the complex analyses of four experiments (which concurrently follows main ways of our investigation); the two experiments concerning driver’s fatigue, summarization of a set of HMI related measurements and the experiment focused on influence of an outer environment on driving.

# Content

# Chapter 1: Introduction to driving simulation

The driving simulators give us a wide range of possible applications. They have been successfully used for several decades in research and automotive industry.  We can find first steps of these activities in the 1950s of the twentieth century (VW, BMW, Ford). Their blossoming appears in the 1970's (mainly Ford and VW). Originally, they were being developed to help drivers to train their driving skills. Then, they were mainly used for training of professional drivers of special vehicles to adapt on demanding situations.

Nowadays, the high quality driving simulators are widely considered as valid devices for training 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 car-cockpit and assistance systems optimization.

Their theory, methodology of use, design, construction and operation require a very wide range of knowledge, from neurology, psychology, control engineering electronics, informatics, mathematics and mechanical engineering to transportation sciences.

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

In my PhD thesis I tried to present a compact view on problems related to adaptive simulators design and construction, formulate the background of the necessary theory and verify some of its interesting parts on practical measurements concerning the problem of driver attention decreases. Further I focused on four main directions of the experiments: The measurements of driver's fatigue without any destruction during driving, the measurements of driver's fatigue calibrated with a driver response times on various stimuli, measurements of influence of HMI devices (like navigation systems, communication systems and entertainment tools) on driving safety and driver's comfort and measurements of influence of outer environment (i.e. tunnel driving, etc.) on driving safety and driver's comfort. Some of these investigations were made in cooperation with the Skoda-Auto c.o. and with their kind support.

## *1.1 Fully interactive driving simulators (FIDS)*

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.  Of those some leading ones could be pointed out:

- **In France** [OKT]**,** [CHAA02]

Fig 1-1: Advanced motion based simulators in Renault Technocenter (Right - so called “cross desk”)

- **In Korea** [LEEW99]**,** [LEEW98]

Fig. 1-2: Hexapod based simulator of Kookmin University in Seoul

- **In the USA** [KLEM03], [KUHJ95], [BOUS01]

Fig. 1- 3: Left - Perhaps the most advanced motion based simulation system NADS
Right- The still based Pennsylvania Truck Driving Simulator

- **Sveden** [ADLM04]

Fig. 1-4: A hybrid motion platform for simulator VTI in Linkeping (Right - an inner view)

- **In Germany**

Fig. 1-5: Left – a full car simulator situated on robust hexapod platform in BMW
Right – one of the European latest simulators by Simtec and DLR, Bruanschweig

- **In Japan**

Fig.1- 6: Driving simulators by Mitsubishi Precision (Left) and Honda (Rigth)

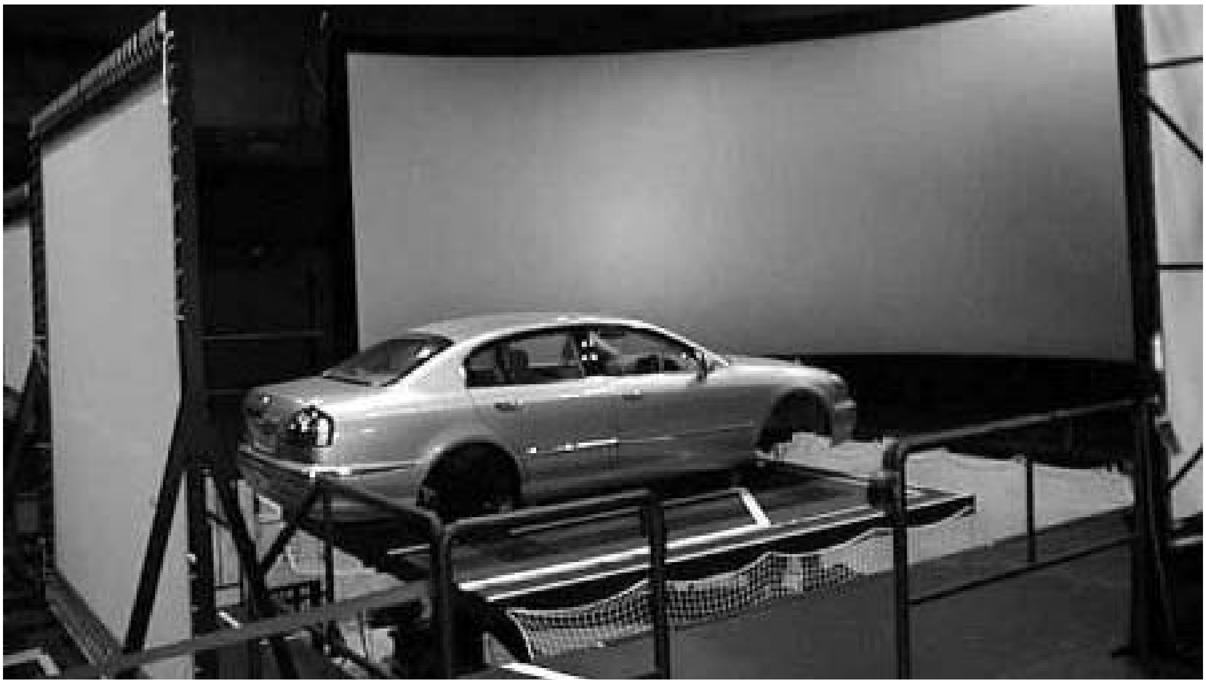


Fig.1- 7: Advanced driving simulator in the Nissan research center [KAZI06]

# Chapter 2: FIDS - constructional and functional designs

An overall system of 'living' simulator (equipped with tools enabling its modifications respecting actual needs of each particular experiment) can be described by a multilayer model [BOUP05/1]. The next figure (Fig. 2-1) introduces the functional structure of our equipment from the point of view of the simulator.

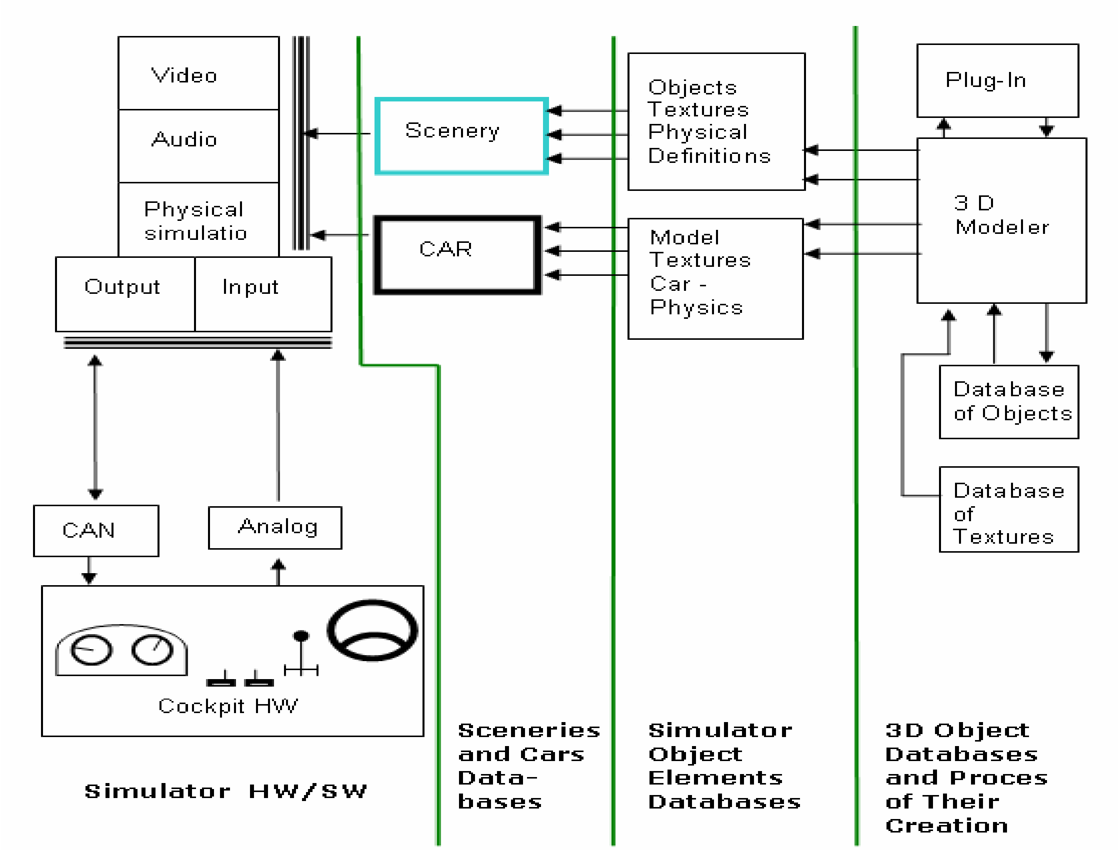


Fig. 2-1: Functional structure of the simulator

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. As the hardware of our "light" simulator we consider cockpit which 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 (generation of 3D graphics and spatial sound) and physical engine. A real behavior of the simulated car is a necessary condition for good results of experiments. For that reason it is necessary to pay big attention to the realistic behavior of the car. The physical engine is always a compromise between a very accurate physical behavior and a very fast (real-time) response.

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. Sometimes we need a curveted road to study driver's ability to keep the car on the road while he/she is forced to fulfill an additional task. On the other hand a scenario for investigation of driver's drowsiness and fatigue is recommended to have a very boring (almost straight) highway road which cannot divert him/her but it let the driver to get into relaxation state. By the same way we should treat with the database of cars. Strong engine with automatic gearbox is suitable for measurement of drowsiness meanwhile a car with manual gearbox and weaker engine with worthier grip  is serves better for classification of one's driving style.

The last layer represents tools for creation of assets constituting scenarios. Those are mainly modeling of 3D objects and tools for automation of such a process and databases (storages) of modeled objects. Each object in virtual reality is accompanied by a texture or a set of textures. The texture is a picture which simplifies the 3D object creation in following manner: The geometry of any real object is very complex, on the other hand it is possible to replace it with a very simple geometry covered by a worked out digital photography (texture). The textures can be of different types; general which are tillable (i.e. repeatable - like grass, road surface…) and the unique ones (houses, signs….). The amount of textures over one scenario could be very high but lots of them could be reused on several different pieces of geometry. For that reason it is also very practical to have apart the database of 3D models (objects) also a database of textures.

## *2.1 Modular architecture*

The above paragraph introduced the simulator system as a layered architecture. In fact the architecture of the simulator itself is usually modular.

Considering the inputs for the simulation device they could be divided into two groups: first one represents the inputs into the simulation like a real geographical data (for example from GIS sources), data from the real of world maps, data from micro traffic simulations and finally the data from external high-end physical simulations and models.

On the other hand, the system should be opened for imports from various devices, which can be contacted into the car. Those could be for example: driver assistance devices, systems of mobile communication GPS systems and many other systems requiring driver's interaction. The basic system setup can be fortunately decomposed into subsystems, which could be treated and solved separately.

The basic modules are as follows (see the diagram Fig. 2-3):

- Graphical engine
- Graphical output system
- Spatial Audio system [LARP]
- Motion platform and vibration system
- Scene handling and generation system [RIEB], [KRAD]
- Car physics engine
- General input system
- General purpose output system
- Communication and interconnection module
- Safety and emergency system

The modular architecture of a system which is required to work in almost real time should be well designed. The interconnection system, which we use in our modular system of our driving simulators, is composed on three levels - see Fig. 2-2 (described in more details in [LALM06]).

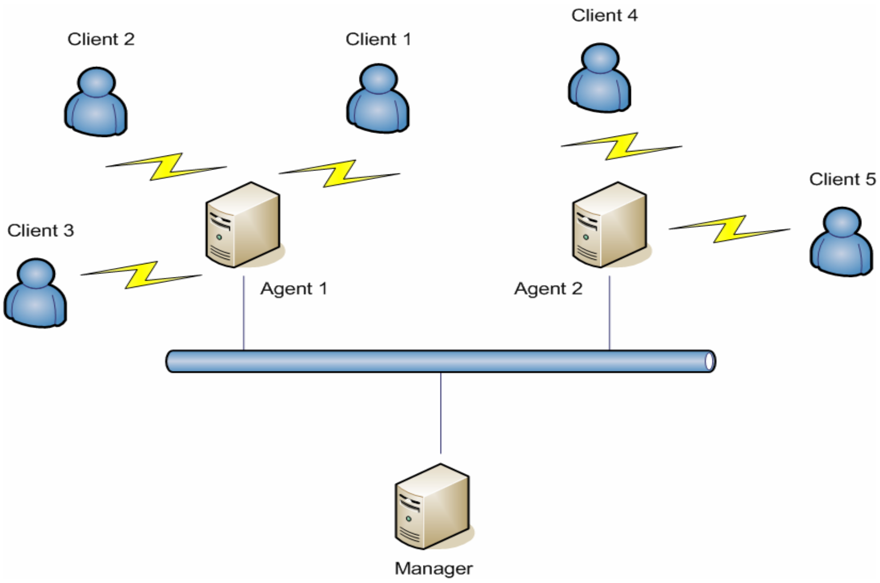


Fig. 2-2: Modular system based on Manager-Agent-Client architecture (by [LALM06])

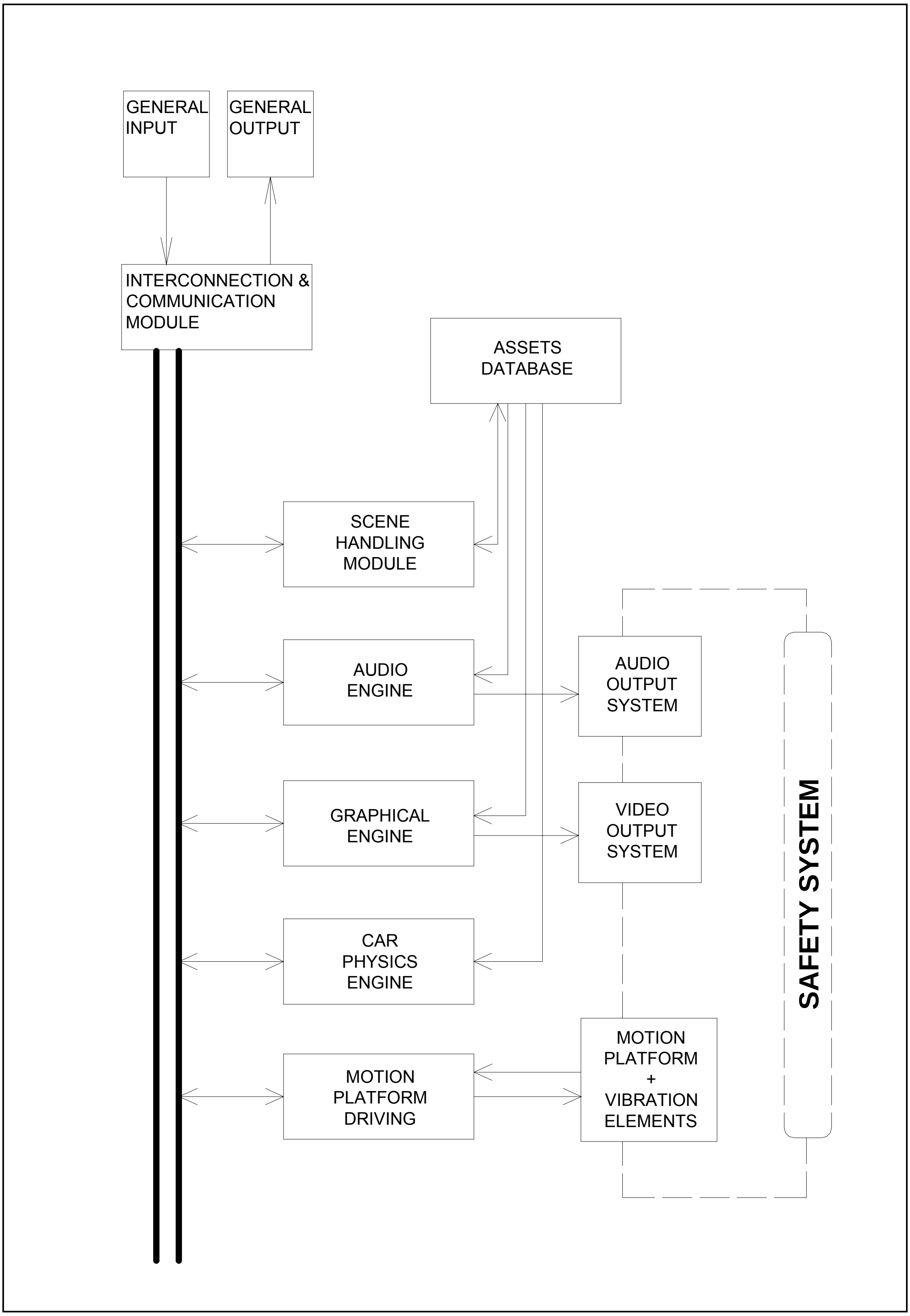


Fig. 2-3: Advanced driving simulation system – basic structure

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. Fortunately, the 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 Scenarios

As a necessary tool for application of the above mentioned driving simulators the advanced driving scenarios were developed. In the LSR, in cooperation with my colleagues Ing. Roman Piekník and Ing. Stanislav Novotny, we subsequently developed a whole set of advanced driving scenarios in VR adapted for specific purposes of performed measuring experiments. These scenarios are ready to be used in multi-parallel projection systems, ensuring a considerably high quality of driver visual perception and impression. They are described more detailed in other sources (see e.g. [PIER05, PIER06, NOVS05]).

Although these scenarios are quite important and interesting, having in mind a danger of too large size of this PhD. thesis I'll not describe them here.

# Chapter 3: Validation

The driving simulators are considered either as research tools or as a basis for a driver's training. Those which we have developed and used in the LSR are used for both of these purposes. Since no simulation device could ever offer a human subject a complete set of cues like they appear in reality, it is necessary to be sure that the stimuli impacting on the human are sufficiently convincing as for the needs of an actual experiment. From that point the necessary condition is the validation for an each experiment or a branch of experiments with the very similar perception cues. To be precise we need to ensure that the proband, who are driving the simulator, will behave in at least a very similar manner like in the case of driving a real car. Even though it is not possible (or sometimes not desirable) to copy simply the responses and behavior of a real car, those measurements are necessary preconditions for quality and valid simulation. From the point of view of usability of measure data, we divide them into two groups: the data used for simulator system design and the data used for experiments validation.

Quality of simulation of any human operated system relies on an ability of simulators to cheat the human senses in such a way that the human driver can accept the simulation to be reality. For this reason it is necessary to have deep knowledge of common behavior of the simulated system. As it was mentioned before, stimulating all the aspects in their full range is almost an impossible task and one should concentrate on those most impressive aspects.

## *3.1 Technical data*

The acquisition of the performance data from car driving used to be a very complex and expensive task. Of course when precise data are necessary such measurements are also complicated even today. Fortunately the modern cars which are equipped with electronic advanced driving assistance devices utilize many different electronic sensors of physical quantities. Data from those sensors are digitalized and transferred to the computational and controlling units via digital buses. It is possible to take advantage from this communication and scan and store the data without any serious intervention into the car itself and without any need of any external measuring devices.

For example a car equipped with ESP and ABS could give us useful information about:

- Linear velocity of each of the wheels
- Angular velocity each of the wheels
- Lateral acceleration on each of the wheels
- Longitudal acceleration on each of the wheels
- Throttle pedal depression
- Brake and clutch activity
- Gear-shifting
- Steering wheel angular velocity and position
- Majority of functional buttons and handlers used by the driver

## *3.2 Experiments with a real car*

Although the experiments were originally focused mainly on obtaining data for development of driving simulators, they have opened for us additional opportunities of their usage (see [BOUP07]). The further usability of this work can be observed from the following points of view:

1. Investigate in possibilities of measurements of a Driver-Car interaction in real cars in real traffic, first approach for future development of so-called “instrumented vehicle”.
2. Obtain data from different testing scenarios which would be used for development and tuning of physical model and motion cuing modules of our driving simulators.
3. Validation of contemporary features of our simulators.

### 3.2.1 Data collection

The measuring car was instrumented with measuring devices to obtain the following quantities:

1. Trajectory
2. Car performance data
3. Camera video recording

***Trajectory***

The path of the vehicle is obtained from GPS signal in 2D coordinates. Unfortunately, correct usage of GPS signal for trajectory is not always enough frequent and the correctness of the immediate localization when moving is also problematic. The range is at about 3-8m and from that reason it serves for car position identification. Average localization frequency is about 3-4 seconds, the points for example in highway segments are in average around 100m from each other. Therefore it was necessary to interpolate within the measured points. A spline interpolation seems to be suitable.

***Car performance data***

All the necessary data were collected via car CAN-bus protocol and CAN diagnostics protocol. They give evidence of car's response to driver's behavior. Those were actual values of:

1. Car velocity in km/h (and proportional speed of rotation of each of car wheels)
2. Vertical - in g - and longitudal - in m.s$^{-2}$ - accelerations
3. Spinning velocity of the car in degrees/s
4. Rotates of the engine, the gear
5. Position of throttle pedal in percentage, depression of brake pedal (here only on/off position)
6. Position of steering wheel in degrees and its velocity in degrees/s
7. Torque, which the driver forces on the steering wheel and force developed by power steering, all in N/m

***Camera recording***

Video record from the ride was recorded using a common digital camera with a high sensitivity and with a wide FOV had to be used, so that it would be possible to record the same visual field and distance as the driver sees even under limited visual conditions.

### 3.2.2 Procedure of the experiments

All the devices are roughly synchronized by a common time clock, the sampling frequency of CAN data is in magnitude of milliseconds. From above described devices it is possible to obtain a complete information about where the car is riding, how the driver behaves, how the car reacts on the driver and on the environment and also about the actual situation around the car (traffic, light conditions, weather).

Fig. 3-1: Complex of measuring devices in the instrumented car

## Analysis and Results

All the collected data had to be synchronized and re-sampled on a common base. Linear interpolation was used for continuous data and nearest neighbor interpolation for discrete data. Then the data from each segment are stored in a big matrix. For manipulating such huge data the scripts in Matlab were created. Those allow selection of different segments in appropriate resolution for further classification. From the set of tested rides it was possible to derive statistical values (e.g. maximal values, quartiles of values, relative occurrences, etc.). Those statistics would be used for determination of either physical limits or mean range of operation of the simulation. From the point of segmentation and with respect to above described intrinsic properties, the data were classified into different segments and treated separately:

1. Highway
2. Rural environment
3. Town environment
4. Starting

5. Stopping
6. Slalom
7. Overtaking
8. Other specific segments

Each of those segments is specified with very different characteristics of driver and car behavior. The next picture shows the development of the car speed during about 200 kilometers on a combined (mostly rural) road environment. It is possible to see for the first look that the segmentation is necessary to be done before any kind of data mining. The picture fig. 3-2 shows an output from GUI for selection of a complex data matrix.

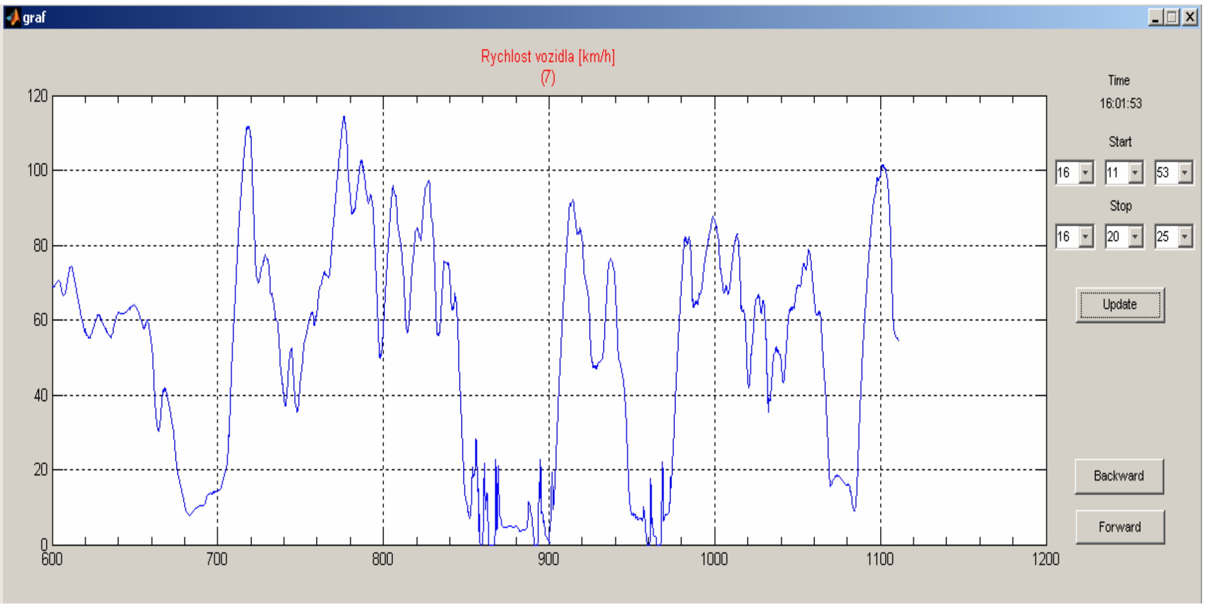


Fig. 3-2: Example of the analytical widow created with use of the Matlab environment

The results of analysis discovered also many limitations. It is not possible to rely on GPS data unless those are corrected by terrestrial reference signals. Also the accelerations obtained form ESP are not of enough resolution and not enough frequent for analysis of marginal situations like hard braking on slick surfaces etc. There is also no relevant information on vertical acceleration which should be gathered using additional devices (preferably with much higher resolution and sampling frequency). The same conclusion is for synchronization of gathered data. Simple synchronization is enough for analysis which was done within this experiment but for a very detailed analysis of marginal situations, this approach is not enough and needs to be treated differently with using of some additional time triggers. The next picture (Fig. 3-3) illustrates examples of possible use of measured data.

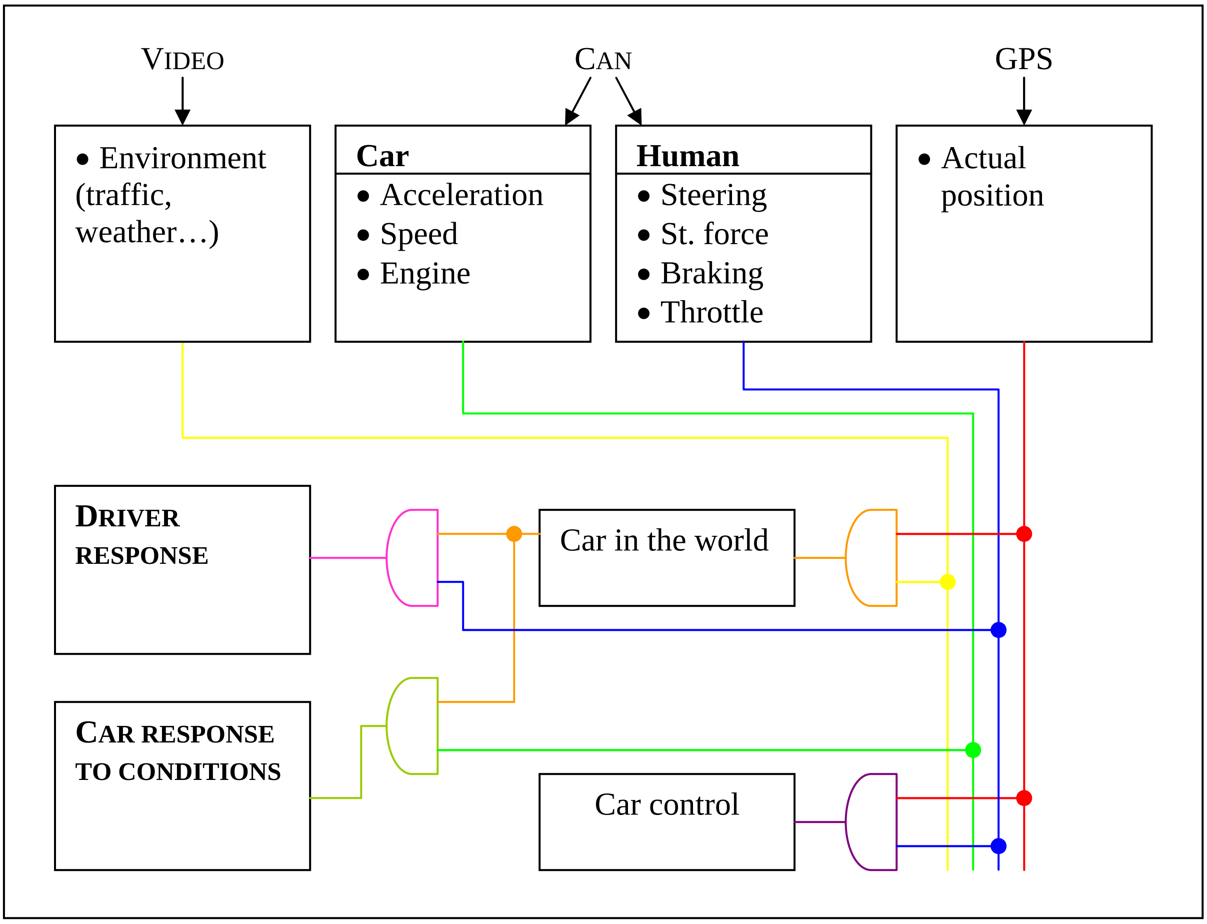


Fig.3-3: Example of certain possibility of data processing of measured data validation procedure

## *3.3 Validation experiments*

Because of the complexity of the interaction between the human subject and the advanced driving simulator there is a strong necessity to consider a set of validation measurements for any experiment at the beginning. These can be done either in the beginning of a measuring set, or at its end or distributed in its course. These validation measurements have to be designed with careful respect to the still valid fact that in any case there are some more ore less significant differences between driving of the real car an a real road and the driving in laboratory on the simulator. In my work I therefore should take this fact into account.

### 3.3.1 Identification of a driver in virtual environment

The training rounds are usually performed at the beginning of each measurement. The aim of this is to allow the testing person (proband) to adapt satisfactorily to the virtual environment and learn how to drive the simulator. This introductory rounds allowed us also to keep the experiment data clean from “noise” appearing usually when a not enough skilled proband is tested. According to our experience these introductory rounds should be of the lengths at least 15-20 minutes, which usually represent 20% of the time of the experiment. Off course this could be considered as a very general recommendation only, because of an extremely high individuality of each one’s brain. We met some probands who learnt the simulator specifics very easily and fast and also some who had to be trained for a very long time with a high care.

Generally, a quality of the experiments is influenced by a depth of driver’s immersion into the virtual environment. Among the most important factors we can count primarily following ones:

- Quality of the projected visual scenario
- Quality of the sound simulation
- Ratio of driver surrounding with presented virtual reality
- Personal ability to accommodate the artificial conditions of the simulator

### 3.3.2 ISO testing scenario

ISO specified some sets of requirements on experiments made on real cars (see [ISO75]). A methodology of those experiments used for our simulators will be very interesting but it was not possible to carry on them out till now. I’m looking forward that this could be possible in my future in this area.

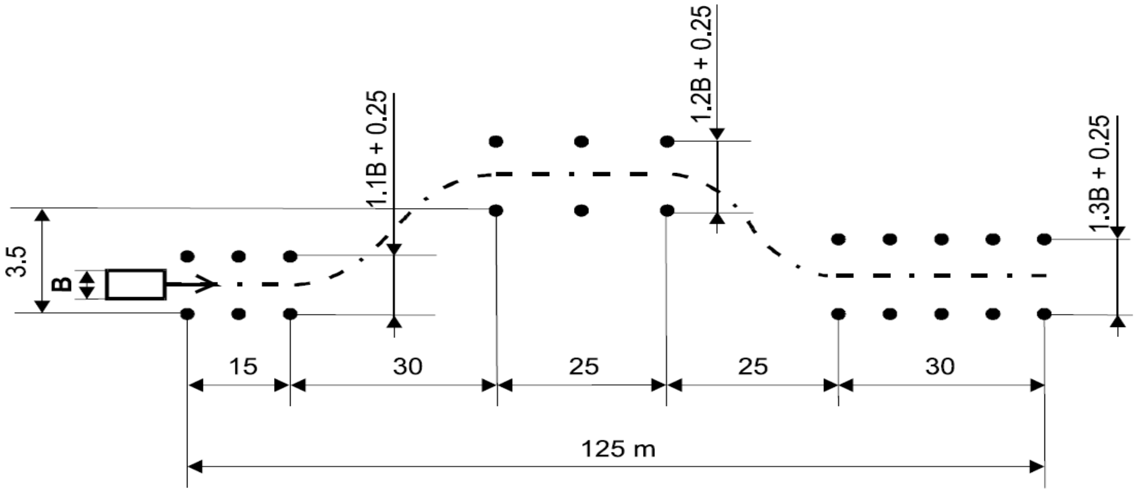


Fig 3-4: The track of the double lane-change maneuver according to standard No. ISO 388-1975 (B…car width)

# Chapter 4: Experience with design of driving simulators in LSR

Car simulation device were used and continuously developed within the Laboratory of Systems Reliability (LSR) for more than four years. We use several different versions (or types) of car simulator design. In the picture (Fig. 4-1) 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 [BOUP04/1]).


Fig. 4-1: Our first approach to FIDS in duty form the year 2002

Currently we have three simulators operating and one in development. All of them are based on body parts of current middle class European passenger cars. The first “compact” simulator was built by a German company VRteinment [VRT], the second type which we called “Light” was built in our laboratory as a prototype. We incorporated a set of measuring devices into the simulation system and created support of creation of sceneries using real (GIS-based) data. The reason to create our own simulation device was that we needed a very flexible system which could react to the sudden requirements of the experiment. A need to be adaptive, forced us to develop car simulators by our hands. O the basis of the experiences with the prototype we designed new simulation device. It is based on distributed and modular architecture, so that it could offer larger field of usage than a micro-sleep research. All our simulators are PC based. See the next table (Tab. 4-1) for rough description of basic features of the driving simulators which are being continuously developed within the DSRG of LSR.

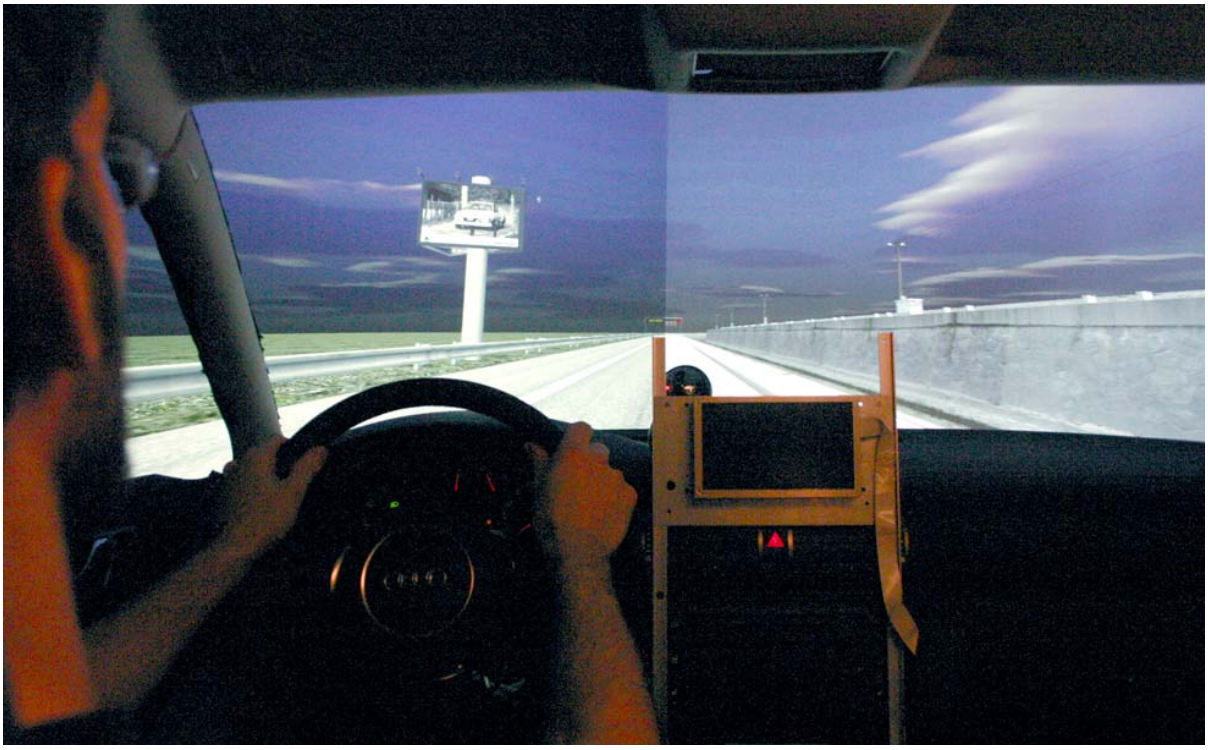
| **System specification** | | **Compact simulator** | **Light Simulator (prototype)** | **Light Simulator II** | **Compact simulator II** |
|---|---|---|---|---|---|
| **Platform** | | PCbased, Win32 | PCbased Win32 | PCbased Win32/64/Linux | PCbased Win32/64/Linux |
| **Physics/Video/Audio** | | Distributed | Single PC | Distributed/Modular | Distributed/Modular |
| **Real scene based scenarios** | | no | yes (via plugins to 3rd party editor) | yes | yes |
| **Projection (FOV)** | **Horizontal** | 60deg120 | 80 planar | 180 semi angular | 360 angular |
| | **Vertical** | Fully covers windshield | Fully covers windshield | Fully covers windshield partially front windows | Fully covers all the windows except of left front door window |
| | **Projection system** | 1-2 projectors<br>Upgraded to 5 | 2 projectors | 3 projectors with LCD mirrors | 7 projectors |
| **moving platform** | | no | no/vibration | 3dof+ | vibration |
| **Audio system** | | spatial | Spatial | spatial | spatial |
| **car** | | full car body | car cockpit + body parts | car cockpit +body parts | full car body |
| **measurement system** | | RS232 connected /synchronized | RS232connected/ synchronized | Ethernet/ synchronized | Ethernet/ synchronized |

Tab. 4-1 Basic features of the LSR driving simulators [BOUP06/1]

## 4.1 Light simulators

This arrangement represents an intermediate step between the totally 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 with the “compact simulator” discussed in the next section) for the implementation of so called “in-car dynamics”, which force the driver percept the driving experience more realistically (see Fig.4-2).

The simulation engine of the car is connected with 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.



a)

b)

Fig. 4-2: A proband driving on the upgraded version of our firs light simulator a), one of the first prototypes of out light simulator b)

## 4.2 Compact simulators

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. 4-3). 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).

The compact simulator provides the driver with restricted field of view (in comparison with light simulator). It is possible to take advantage from this fact when planning a surround screen projection. The critical boundary part is cleverly occluded with A and B columns.

a)

b)

c)

Fig. 4-3: Three versions of compact simulators: a) the original version of Superb, b) Superb simulator upgraded with 5 projectors surrounding projection screens, c) the compact simulator Octavia II with cylindrical surrounding projection supplemented with rear mirror projection (for more detailed description see for example [NOVM06/1])

### *4.3 Virtual devices*

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 proband to immerse himself into the projected scene.

This step is very important to give him a true feeling of the real drive (see [BOUP04/2]). Although this setup has been replaced with a real part of car cockpit (see further sections) we came back to it when incorporating Head Mounted Display (3D LCD glasses). A proband equipped with HMD has now a freedom of view, which off course requires that the cockpit is completely modeled in 3D. A sensor connected to his head scans the proband'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. A disadvantage of using of the HMD is mainly in its non-comfortableness, relatively low resolution (800x600px) and narrow filed of view (see Fig.4-4). On the other hand it is incomparably more flexible. The cockpit design, ergonomics or other setups could be relatively easily changed (tuned up), respecting the requirements of the actual experiment.

a)

b)

Fig.5-4: a) VR simulator - a driver looks at the scene through VR 3D glasses. The movement of the driver’s head is scanned and the information is issued back into simulation. b) Example of the fully virtual cockpit.

# Chapter 5: Perception cueing

A development of simulation can be considered as a multidisciplinary task, which encompasses a spread field of possible investigations. The aspects of the simulator design itself and its particular modules are described in the chapter 2. When analyzing needs and proposals for design of those modules it is necessary to have knowledge of what kind of stimuli impact on the driver and in which way it is done.

## *5.1 Visual cues*

Most of the information which the driver's brain needs for driving (i.e. correct response to the outer conditions and various stimuli) are visual ones. The driver 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 primer 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.)

### 5.1.1 Projection

The virtual reality scene, created as a result of reaction of physical models of the virtual world (i.e. car and road in our case), is usually projected via interactive RGB projecting systems. In the case of the driving simulator it should cover big field of view so that the driver can have as much visual information as possible. Generally two kinds of systems are used. First, the HMD which the driver wears just in front of his/her eyes. Second, the systems which consist of wide projection screens designed in such a link that the driver is as much surrounded by the virtual scenery as possible. Using HMD suffers from many problems which do not allow their wide application:

- Relatively heavy weight needs to be supported by driver’s head
- Small screens are very close to the drivers eyes
- The picture can react on the head movements but can hardly react on the movements of eyes
- Field of view is narrow (wide FOV HMD is extremely expensive)
- Many of users suffer from headache and eye pain

### 5.1.2 Depth perception

The driver should obtain correct information about his/her distance form 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”. A next equation shows computation of new 2D coordinates:

$$X_{\mathrm{2D}} = X_{\mathrm{3D}} - \frac{DX}{Z_{\mathrm{3D}} + \text{Eye distance}} \times X_{\mathrm{3D}} \quad Y_{\mathrm{2D}} = Y_{\mathrm{3D}} - \frac{DY}{Z_{\mathrm{3D}} + \text{Eye distance}} \times Y_{\mathrm{3D}} \qquad \text{.....(5-1)}$$

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. Three main ways are frequently used:

1. ***Anaglyphic glasses***

   This approach is very straightforward for implementation; there is no need for some special hardware all the tricks are easily to be done on the software level. The main principle of the depth simulation is in the color filtering of doubled image by glasses pigmented by mutually exclusive colors (e.g. red-blue, green-yellow, etc.). In fact three images are projected at once. The one color for the first eye, the different color for the second eye and the neutral one for the both eyes.

### 2. *Polarizing filter glasses (passive stereo)*

Using the polarizing filters is a relatively cheap method which transports correctly the appropriate image into the appropriate eye without lost of color information. Unfortunately it needs to utilize special non-dispersing screens which preserve angle of light polarization. Main advantages of the solution are as follows:

- Original quality of the 2D picture is preserved with full color information
- Common DLP projectors could be used (using LCD is limited)
- Glasses with polarizing filters are relatively cheap

Unfortunately there are many disadvantages; the most serious are the following:

- Number of projectors should be doubled, which makes the solution twice expensive
- It requires a special projection screen, which is expensive and very demanding for maintenance
- Doubled lost of the light flux
- It is **not** indifferent to change of yaw, the driver should keep his head in the limited range of movements

### 3. *Shutter glasses (active stereo)*

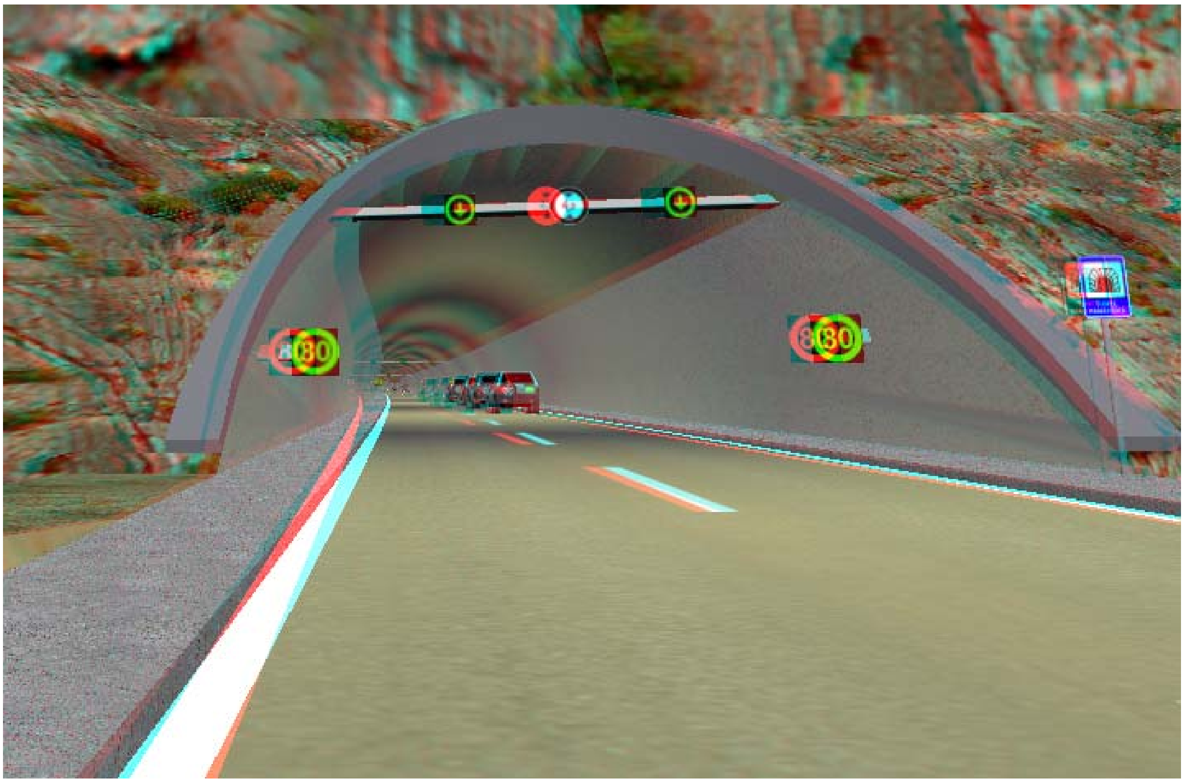
This approach is said to be of the highest quality. Unfortunately it requires shuttering glasses synchronized with graphical output in such a way that each of the eyes percepts only the appropriate frame. This method has several advantages:

- Original quality of the 2D picture is preserved with full color information
- There's no need for any kind of special reflective screen
- It works well with CRT, LCD or DLP displaying or project ink systems
- The relatively low lost of the light flux
- It is indifferent to change in yaw, roll or heading of observers head

It suffers of course from certain disadvantages:

- Relatively expensive and annoying glasses to be used
- Special high speed projectors should be used
- Projection using multiple outputs and multiple projectors is very problematic, since all the projected frames have to be synchronized precisely for each eye

The next two pictures (Fig. 5-1) shows the difference between two approaches (a – type 1, b- type 2 and 3).



a)

b)

Fig.5-1: Photos (2D image) taken from the cockpit when the driver is observing the 3D scenario a) with anaglyphic glasses and b) shutter or polarizing glasses.

All above described methods require wearing active or passive glasses. This off course could be very annoying for the driver. There's one method which can overcome this problem. It is so called auto stereoscopic displays. Those are very expensive and of limited size as they are based on common big LCD monitors equipped with a special kind of mask.

### 5.1.3 Field of view

As it has already been proposed the majority of information that comes to the driver's brain is visual. Because of that fact, it is desirable to provide the driver with as wide angle of view as feasible. Ideally the projection should be fully surrounding the driver.

### 5.1.4 Picture quality

#### *Resolution*

A resolution of the projected image is essential for

- Overall quality of the image
- Ability of recognizing of patterns
- Legibility of signs and pictograms

The matter of fact is that the price of the digital projectors rises non-proportionally with respect to their resolution, but the price of projectors of higher resolution than standard ones is much higher than mainstream. There are systems combining projectors with different resolution.

#### *Color presentation*

Fidelity of the color information presented to the driver in a respective visual virtual scenario is one of the most significant factors influencing the quality of performed simulation. One has to take into account that the dominant part of visual information transferred to human subject is expressed by a color element placed in space. (Actually it is a Cartesian product of two space coordinates and one color information coordinate, projected on spherical surface). In our experiments we were therefore very careful to approximate this fidelity as well as possible. We have subsequently replaced the originally used simple and cheap digital projectors with more advanced products (which are more expensive) and we replaced the single projection with multi-parallel projection. This off course requires a lot of effort with parallel projection control and a very careful selection of the particular projectors (if all of them are of the same type, from the same manufacture and from the same production series. Regardless to these considerably hard requirements we still have to face the problem that the color tone of two neighboring projectors differs – even though slightly.

### *Performance*

The performance of the visual system is essential for immersive effect of a virtual environment. Actually there is no restriction about the frame rate of the projection but generally it is possible to say that the faster is the better. It is possible to say that the lowest limit is somewhere about 30 frames per second. The optimum refreshing rate should be at least about 60 frames per second. Unfortunately there's always a compromise between the quality of the picture and the performance. It should be expressed in general terms as a reciprocal value of each other.

Especially the higher performance projectors should be considered for stereoscopy (i.e. emulating the perception of depth of the picture) which requires twice faster performance since each frame should be generated for an appropriate eye individually. The frame rate is also proportional to the actual virtual self speed of the observer. When moving slowly the observer's eyes are not so sensitive to the slower frame rate but in the case of higher speeds of the driven car, it is necessary to supply the driver with much more visual information during the same amount of time.

The performance depends either on the speed of the digital projector and/or on the power of the graphical rendering subsystem. The refresh rate of the common digital LCD or DLP projectors ranges from 60 to 100 Hz, which is practically enough for smooth movements of the virtual scenery where the car rides (a little more demanding is a case of the flight simulation). The problem could appear when performing depth projection using shutter glasses. In this case the real refresh rate for each of the eyes is a half of overall refresh rate. In this case the peak performance of 60Hz becomes only 30Hz which meets the lower bound of acceptability range. Furthermore the stock projectors interpolate the frames supplied by the graphical hardware and their real frame rate is mostly lower and it is not even synchronized.

***Photo realistic look***

The aim of designers of the graphical subsystem of driving simulators is to achieve as much photo realistic look of the rendered image as possible. The quality (or veridicality) depends on many factors from which it is possible to emphasize following ones:

- Quality and resolution of used objects
- Quality and resolution of used textures
- Variety of textures and objects used in the scene
- Quality of the lighting and shadows
- Physically based motion of the objects appearing in the scene

As in the case of the performance also the photo realistic look is proportional to the hardware demands. Highly dense meshes of 3D objects and higher resolution textures require high memory capacity; working out of huge amount of triangles requires high computational power.

There are many other aspects which can influence the visual quality and consequently the overall quality of the simulation. In principle it is possible to say that the simulated picture is always an imperfect image of reality allowing almost infinite and continues improvements of its quality.

## 5.2 Audio cueing

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. The driver can have from a virtual sound the 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

### 5.2.1 Simulation of the engine

The car engine sound is one of the most important audio stimuli for the driver [HAJM06]. 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 drives and how fast the engine rotates. Besides the hearing and the visual sense 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 the seat and a car floor. These are also very important ones 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.

The sound pressure level slightly rises with revolutions of the engine and with speed of the car. The engine sound itself is very complex and it can be generated only on basis of recordings of the real car. It is necessary to record the car engine in a high quality. The most suitable for this recording are small condenser microphones with low sensitivity, because the sound pressure levels around the car engine can be very high, there is the high risk of overload.

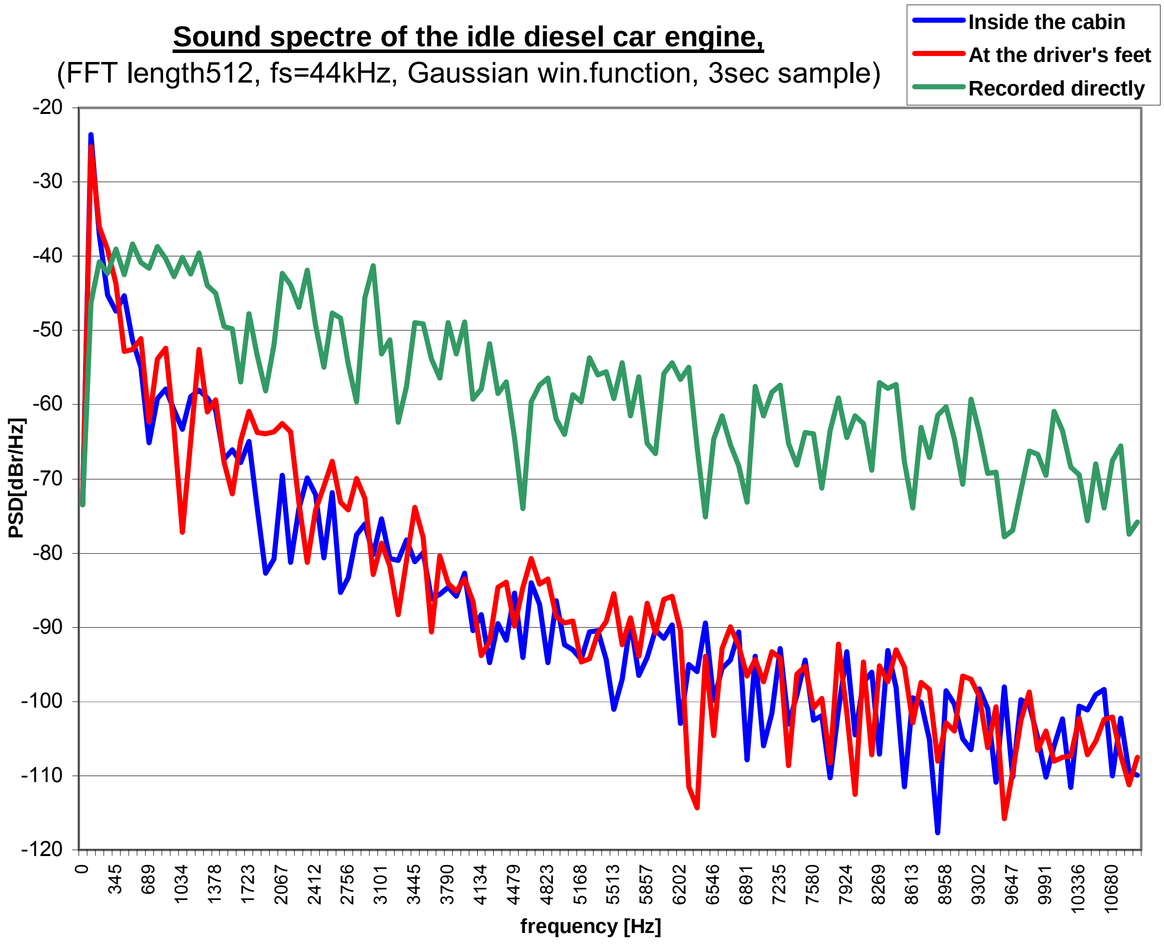


Fig. 5-2 Example of the sound spectral analysis of the real car (see [BOUP05/4])

### *Synthesis of the car engine sound*

Because we cannot record the car sound in every situation we have to render it in real time within the system of a car simulator [michal2]. Probably the best way to render this sound in real time is to use multiple loops cross fading system. It uses multiple samples of recorded real car engine. Each sample is recorded on specific state (like actual revolutions per minute and load). The simulator has a physical model, which sends actual state (RPM and load) to the audio system. The audio system qualifies the sample with the nearest state as the most suitable. The sample is slightly adapted to the exact state and played. This sequence is repeated in a loop and the attributes of the sound are updated several times per second.

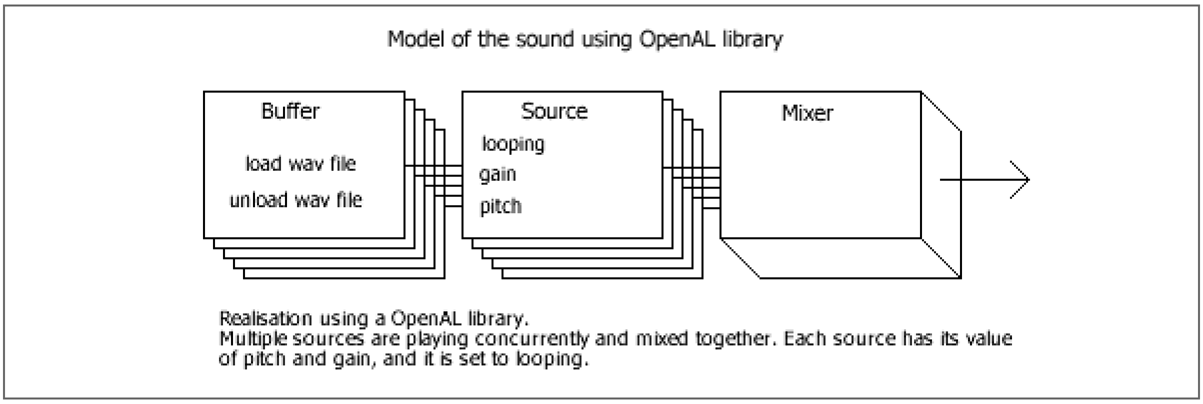


Fig. 5-3: Pricipal of artificial sound creation

The simplest simulation can be performed by single sample played (looped) and real-time adapted to the actual conditions. But this system has high fidelity only in very small adjustements of rpm. When the actual ones differentiate from the recorded, we hear the sound distorted because the adjusted sound does not correspond with the reality. And of course load of the engine is not covered at all.

If there are more samples used, we have to define when each sample should play. It is necessary to define area where two or more samples play together. Where the first sample smoothly rolls off and second swells. This transitional band should be of an appropriate length. Too narrow transition causes us to hear ugly alteration of the sound color while revolutions changes. On the other hand, too wide transitional band causes degradation of the sound. The reason is that the multiple samples are played concurrently which does not sound soft to the listener.

## *5.3 Motion Cues*

Perceptions of motion (i.e. moving in all 3 main axes, yawing and rolling, vibration coming from various sources and directions) and perceptions of an arbitrary acceleration play a very important role in the process of car controlling. The driver gathers the information from these perceptions and immediately reacts. On the other hand he/she gets the information about the car reactions as a feedback.

### 5.3.1 Steady based simulators

Since the motion base for the car simulators presents usually the most expensive part of the whole system, the steady based simulators are frequently used. Majority of the experiments do not necessarily need full motion feedback.

### 5.3.2 Active feedback

Both of the frequently used simulators - the steady based or motion based - can be equipped with additional feedback devices. These can provide 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).

### 5.3.3 Steering wheel

The system which is necessary to be emphasized over all about described systems 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. From that reason majority of steady based simulators are equipped with at least certain type of steering wheel feedback. It is possible to differentiate three basic approaches:

1. ***Mechanical feedback***

   The feedback is provided with certain kind of mechanical spring. Actually the aim of this system is made to keep the steering wheel in the center so that the forces maintaining the car in a straight direction are emulated. This approach is cheap to be implemented to any kind of the car simulator system but it is passive and can not interact with environmental conditions or driver's behavior in any way.

2. ***Electronic servo engine***

   In its simple version (not connected to physics of the car) its behavior is in principle very similar to a mechanical spring. Its main advantage is that it could be controlled and the force of the spring can be generated arbitrarily. From this point it is possible to create any kind of curve of the forces acting on the driver's hands through a ring the steering wheel. This overcomes the main drawback of the mechanical feedback – where the weakest force is generated at the zero position of the steering angle.

3. ***Interactive electronic servo engine***

   Electronic control of the feedback on the steering wheel provides the opportunity to simulate realistically real physical processes coming from the wheel-road interaction. The feedback force does not need to rely on predefined curves but it can take advantage of detail computation inside of the physical engine. It can take into account also the actual velocity and rolling forces the front wheels. It is necessary to keep in mind that modern cars equipped with the power steering progressively change the amount of compensating force, which is influenced by the actual speed of the car.

The steering is the most direct way how the human driver interacts with a car. A driver is very sensitive to a speed and correctness of the response of the steering. Realistic behavior of steering wheel can increase significantly immersion of the driving. On the other hand inadequate response of the steering wheel can disappoint the driver and degrade the overall quality of the simulation. From that respect it is advisable to use high quality angular sensors with resolution of at least a half of degree and no drift. Both factors (insufficient resolution and/or drifting off the zero position) can make the experimenting driver confused and the results of experiments loaded with a big error. Unfortunately sensors available in common steering wheel of the real car are not precise enough.

### *Feedback of the steering wheel*

The steering wheel of a common car can be divided into two groups:

- Classical "crest" steering which directly transfers torque generated by the driver on front wheels
- Powered steering which produces additional torque, using hydraulic, electric or an other method

In general the powered steering behaves in more complex way, but it is possible to describe its function much more precisely since it is electronically driven. The feedback of the servo can be realized either mechanically or electrically. Mechanical realization lays in use of springs (preferably rubber made) and dumping material. Behavior of such solution is static and cannot take into account an actual physical behavior of the car and/or any interaction with a road surface. can do this job.

A torque generated by the electronically driven servo motor can be expressed basically by a following symbolic equation:

$$MotorTorque = TorqueSetValue + Friction + Damping*Speed + SpringStiffness*Position \quad (5\text{-}2)$$

This equation expresses only a static behavior of the steering wheel regardless of an actual dynamics of the moving car. We also need to take into account a progressiveness of power steering which depends on the instant car speed. Since the real time controlling processors could not compute any complex functions, our first approach to the response function should be simple:

$$\tau = \frac{-1}{abs(\omega + p1(\omega)) + p2(v)} + p3(Hv) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(5\text{-}3)$$

This equation of the responding torque $\tau$ generated on the steering wheel, takes into account an actual angle ($\omega$) of the steering wheel in parameter ***p1***, an actual velocity ($v$) of the car - approximating physical behavior of the front wheels - in parameter ***p2*** and stepwise progressive enforcing effect ($Hv$) of power steering in parameter ***p3***.

Some experiments require additional feedback on steering wheel originated by the road surface or different types or accidents (i.e. tire blow up). Those fast movements and vibrations should be also included into final behavior, but it requires a direct connection to the physical module, which can provide information about real behavior the front wheels.

### 5.3.4 Moving platform

In this paragraph I'll briefly describe some known constructions of simulator moving platforms:

***Haxapod (Steward's platform)***

The Stewart Platform is a classic example of a mechanical design that is used for position control (see [SMIM02]). It is a parallel mechanism that consists of a rigid body top plate, or mobile plate, connected to a fixed base plate and is defined by at least three stationary points on the grounded base connected to six independent kinematic legs. Typically, the six legs are connected to both the base plate and the top plate by universal joints in parallel located at both ends of each leg. The legs are designed with an upper body and lower body that can be adjusted, allowing each leg to be varied in length.

The position and orientation of the mobile platform varies depending on the lengths to which the six legs are adjusted. The Stewart Platform can be used to position the platform in six degrees of freedom (three rotational degrees of freedom, as well as three translational degrees of freedom). Most variants of the Stewart Platform have six linearly actuated legs with varying combinations of leg-platform connections. This is mainly because of the system's wide range of motion and accurate positioning capability. It provides a large amount of rigidity, or stiffness, for a given structural mass, enabling the Stewart Platform system to provide a significant source of positional certainty. The design of the Stewart Platform supports a high load-carrying capacity. Because of the design, the legs carry compression and tension forces, and will not succumb to the undesirable bending force found in other designs. The six legs are spaced around the top plate and share the load on the top plate.

### ***Cross-platform***

This type of platform is typical for larger assemblies, because it requires extremely large space for its useful operation. The largest known implementation of such platform is in Iowa in the USA (see for example [BOUS01]). The reason for using of such expensive and demanding construction can be seen in the fact that it can simulate the horizontal movements of the whole simulator with a high fidelity. It is know that such movements can help the partial impression of vertical movements too, if these are combined with simulator declinations.

### ***Hybrid solutions***

The hybrid solutions combine the advantages of above mentioned types. Because of our natural finance and space limitation our prepared moving platform which I hope will be finished soon, is designed to be also of a hybrid conception. Naturally its detailed description I cannot present here, just because it is still under construction.

# Chapter 6: Data collection and Analysis

## 6.1 Driving simulator equipped with set of measuring devices

The whole system of the measurement device is very complex [BOUP05/1]. It consists of many particular devices which need to be synchronized. The next picture (Fig. 6-1) sketches a general view on it.

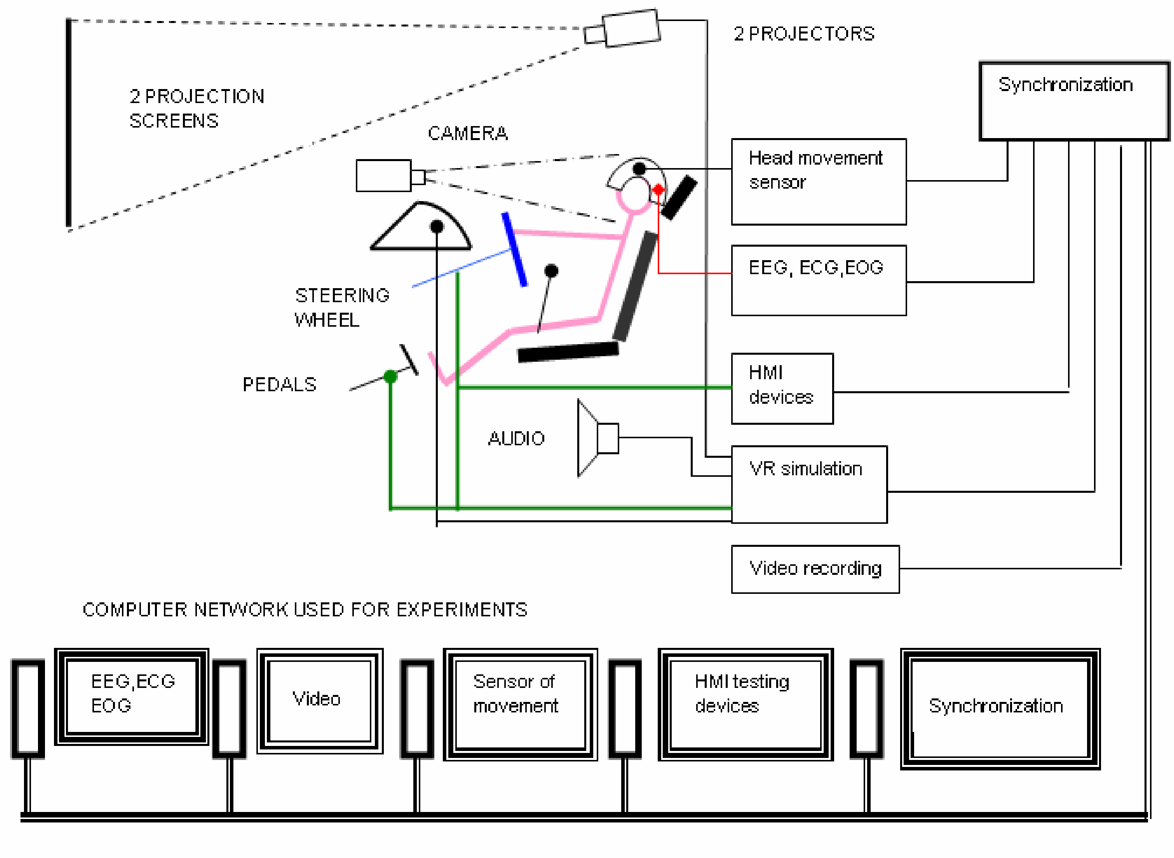


Fig. 6-1: Basic structure of the simulator laboratory

Unfortunately it is hard to predict all the needs and requirements of such experiments in advance. The methodology used evolves after evaluation of each particular experiment. From that point it is necessary to have a system adaptable enough, so that it can respect all required changes. Generally it is very hard to create a system robust enough, which can satisfy needs for several years. For that reason the effort invested in creating such a “perfect and technically clear” system will perhaps hardly pay off.

Our natural choice was for a modular system connected via unified connection. The heart of the measuring complex is a recorder of the EEG.

Unfortunately, since such devices are usually used in medicine practise, they are not ready to be incorporated into complex systems, usually they have one or two single purpose interconnections with surrounding. Only the reaction time module was able to substitute this function. We took advantage of the fact that most of the digital measuring devices use for its connection into PC an RS232 port [BOUP05/2].

The core of our modular system is a synchronization module which receives all the synchronization tags sent from all the modules. The only exception is an EEG recorder which cannot send anything. Every module records its data involving its local time and the time when a synchronization tag was sent. Transport delays are neglected since the human reactions are far from the millisecond precision. The next scheme describes an example of system setup (Fig. 6-2).

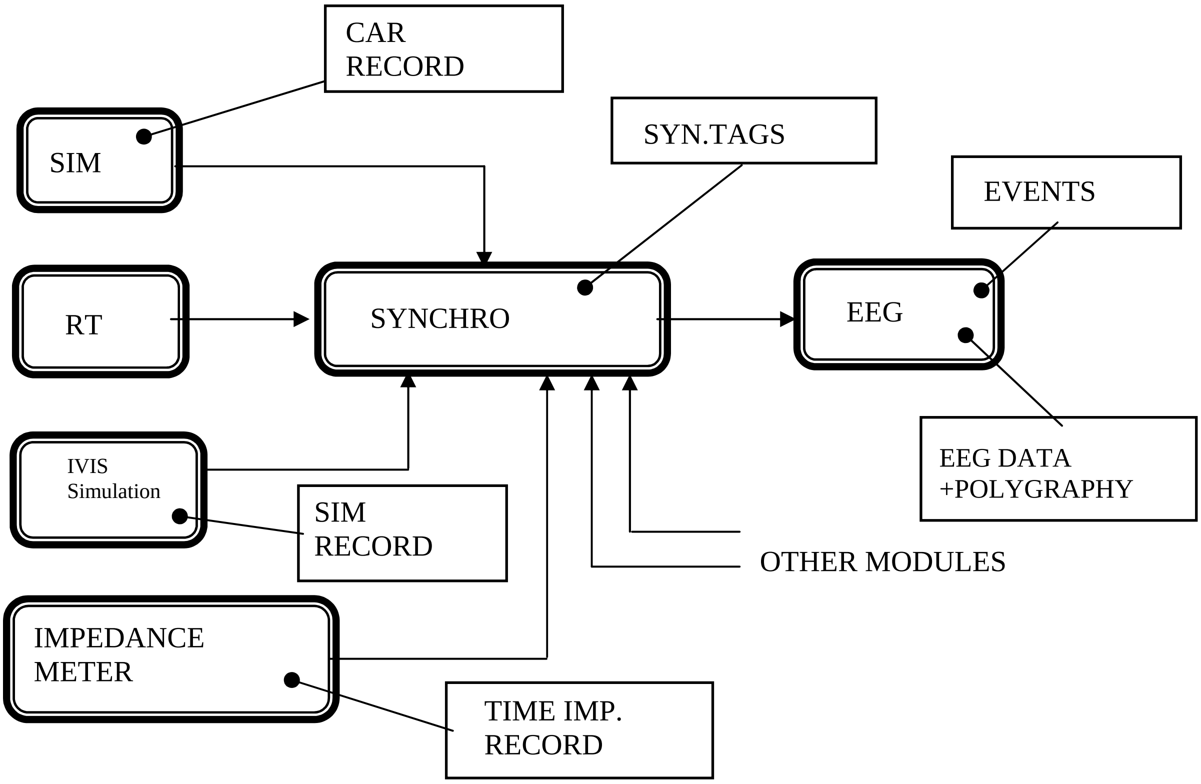


Fig 6.2: Modular architecture of measurement device

The output synchronization signals are then gathered and recorded in a SYNCHRO module. During the preprocessing phases all the records are incorporated into one big array (matrix) of all inputs with common time base (it off course requires re-sampling). Than the further analysis is very straightforward and can be considered complexly.

## *6.2 Collection of set of data from car simulators*

From the point of view of objectivity it is possible to subdivide measurement in to two parts objective measurement and subjective measurement. The situation is illustrated in a following picture (Fig. 6-2). Outputs from the simulator are included in set of objective measurement. It is possible to record mainly the speed of the car (simulator), the trajectory, deviation from proper lane (to border or to contra-flow-line).

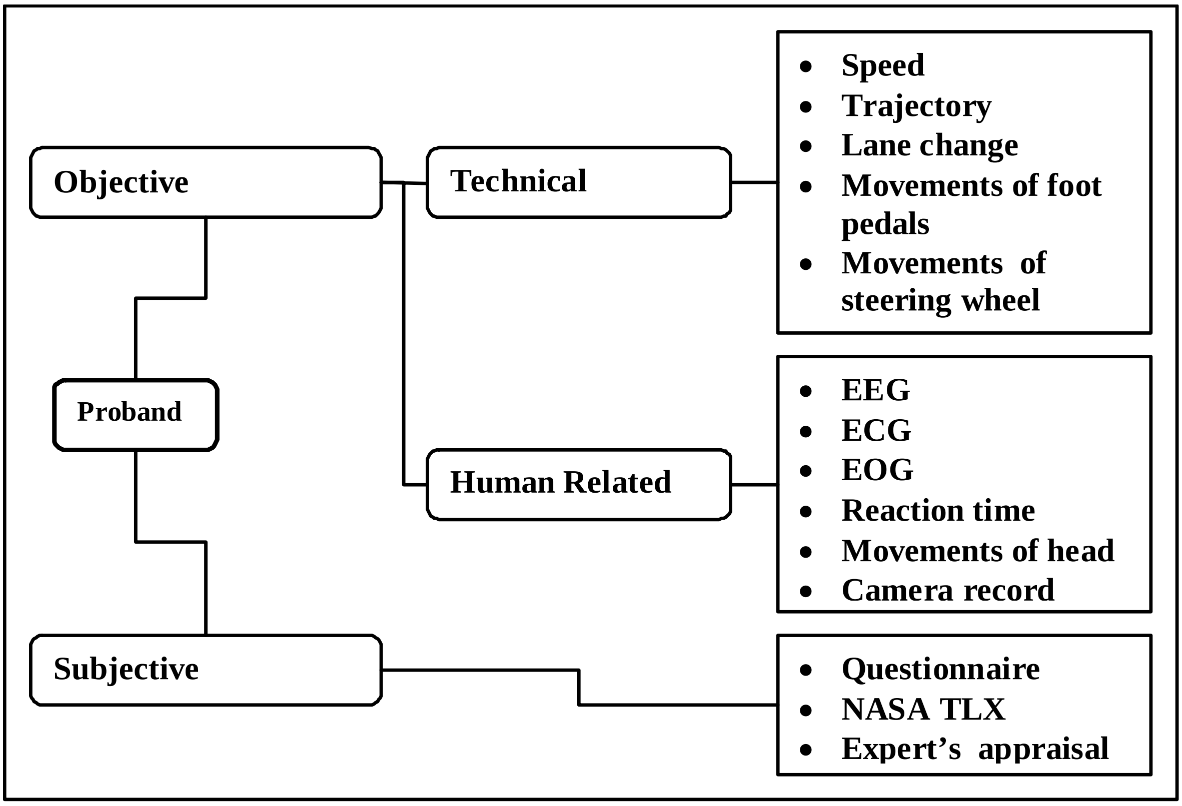


Fig. 6-3: Hierarchical structure of measurements

These three outputs, combined with reaction time, are basic outputs for analysis of the effect of different physical or mental strains during driving the car simulator. The simulator enables also to measure movements of pedals (throttle, brake) and movements of steering wheel. In addition to these simulator outputs, it is possible to place additional devices in the simulator or on experimental driver (proband). Outputs from these devices are also included in set of objective measurement. For example it is measurement of time of driver's reaction to different stimuli (RT), movements of head of the experimental driver or camera record. The outputs, which appear very important, are measurements of EEG signal or ECG signal.

Subjective measurements are represented for example by the analysis of subjective questionnaires, where the experimental driver describes own status before measurement, after measurement or during the process of driving the car / simulator. Also he/she subjectively evaluates different aspects of tested devices.

## *6.3 Driving performance data*

### 6.3.1 Speed analysis

One of the essential factors of a drivers' ability of safe and responsible driving is his/her attention [BOUP05/1]. Attention can be defined as driver's ability to react promptly and safely to standard and nonstandard situations. We made several different experiments on the car simulator. The attention of the experimental drivers is purposely decreased by means of the standard activities in the car. (Manipulating with car equipments, listening to the radio, phoning…). One of the factors, which could be easily monitored, is a speed of the car.

Probands are instructed to keep predefined speed. During driving the probands are asked to do certain activity (manipulating with some in-car devices). During this action the driver should split his/her attention between the task and the driving itself. Due to this fact he/she looses the correct control and we can find lots of correction actions in his/her behavior. One of them is correction of the appropriate speed (which is usually lost when performing the given task). From this we can derive that demanding task causes more variations in the car speed (comparing to the parts when the driver is not disturbed).

In the next pictures an example of a histogram of speed is shown. A graph (Fig. 6-4 left) represents spectra of speeds in time when the driver was not disturbed and could pay all his/her attention on driving. The driver was instructed to keep a speed of 50km/h. From the graph it is possible to see that he/she drove in between 43 and 48km/h without significant differences. The next graph (Fig. 6-4 right) shows the situation when the driver was asked to manipulate with a little complex device while driving (all the other requirements on driving were the same as in the previous case). At first sight it is possible to say that the speed varies significantly, speed oscillates in between 26 – 52km/h. It is mainly due to the fact that the driver cannot put his/her attention on driving and he/she does many corrections. We can also see that the average velocity drops to 40km/h.

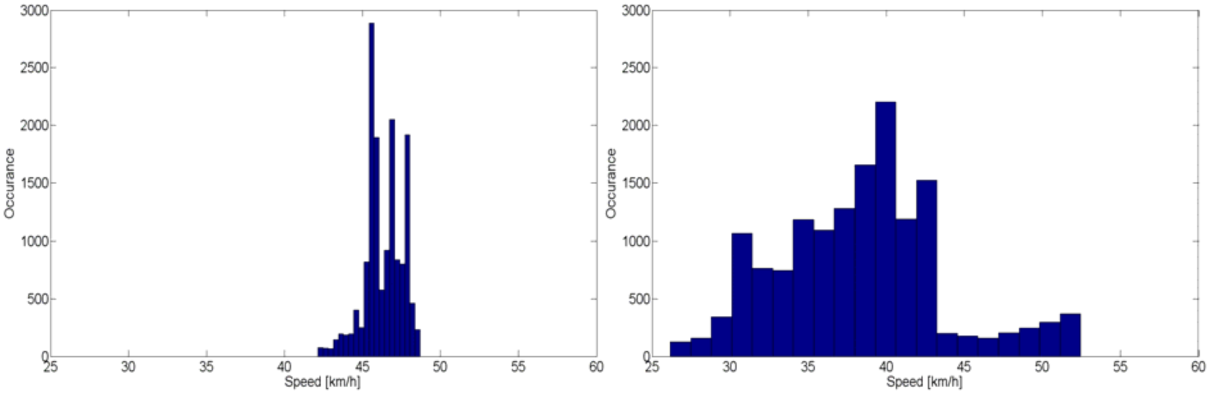


Fig. 6-4: Histogram of speed without disturbing (left) and with disturbing (right)

### 6.3.2 Trajectory analysis (car behavior on the road)

An analysis of a car trajectory seems to be a very promising and precise classification of driver’s behavior. We decided to base our classification on studying differences between the car trajectory and geometrically ideal path. The ideal path is a curve copying the middle of the road that experimenting person drives on. Discrete points of trajectory are interpolated so that they are of equidistant distribution. From these data a statistical analysis is derived.

The next graphs show exemplary histograms of differences of the trajectory of the driven virtual car and the geometrically ideal path. The left graph (Fig. 6-5 left) shows an analysis from the part of the measurement where the driver was not disturbed. The road width is 3.5 m and the reference curve is a middle of the road so the correct trajectory should be around 1.75m (i.e. in a center of right lane). The right graph (Fig. 6-5 right) shows the same proband driving on the same part of the track (road) but loaded with manipulation with some car assistance device. It is possible to see significant variations in distance from the ideal curve. Values near to 0 and over 3.5 mean that the car was out of its lane with at least 50% of its body.

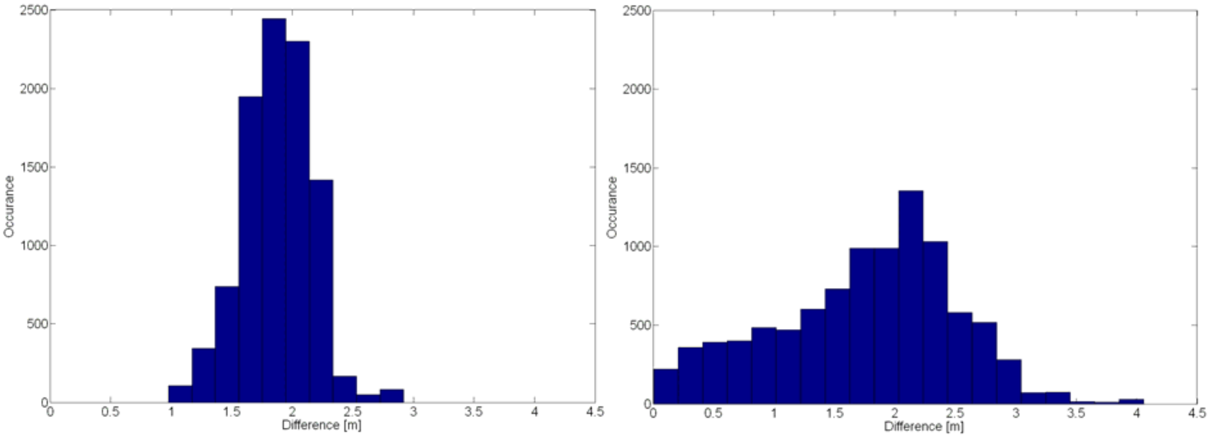


Fig. 6-5: Histogram of actual distances from the geometrically ideal path without disturbing (left) and with disturbing (right)

### 6.3.3 Driver's reactions

***Steering wheel***

The driver is permanently in contact with the steering wheel as it is only one control tool on which he/she keeps his/her hands in standard situation. Therefore the record of the driver is controlling movements of the steering wheel could serve as a basis of very good information of his/her driving abilities. Being stimulated by the initial activity of investigations started by Prof. P.Vysoky (for example [VYSP04]), we have made many measurements of such driver's reactions. The natural advantage of this attention marker is that such signals are practically continuous (in contrary of all other attention level indicators). Therefore we can take advantage form this fact and use methods for continuous signal analysis. Unfortunately such signals are also distorted by irregular incorrectness of a road surfaces transformed from a chassis onto the steering wheel in various manner depending on the type and quality of the particular power steering system. To reach more generally applicable results much more measurements have to be made.

***Pedal reaction***

The driver was instructed to stop as soon as he/she recognized the red signal on the semaphore (see [BOUP05/3] for more details). The semaphores are placed more or less equidistantly in straight segments, before curves. The red signal on the track is randomly generated when the car approaches the semaphore. The distance is randomly selected over the length of B (Fig. 6-5).

An earliest reaction should appear on a gas pedal which is released just before a driver's foot moves towards a brake pedal. The problem is that the gas pedal is pressed and released frequently during the drive - it is a natural way how the driver controls the defined speed of the car. We computed the time between the gas is released down to 25% of its original position and the moment the brakes is depressed (change from 0). When the measured values were plotted and interleaved with a regression line we get two categories of graphs. For the first category we can say that the difference is statistically steady, and the second where the difference rises linearly with time. For the category one, we could reliably use the reaction time on brake meanwhile the reaction time of the second type should be decreased with an appropriate value of linear deviation.

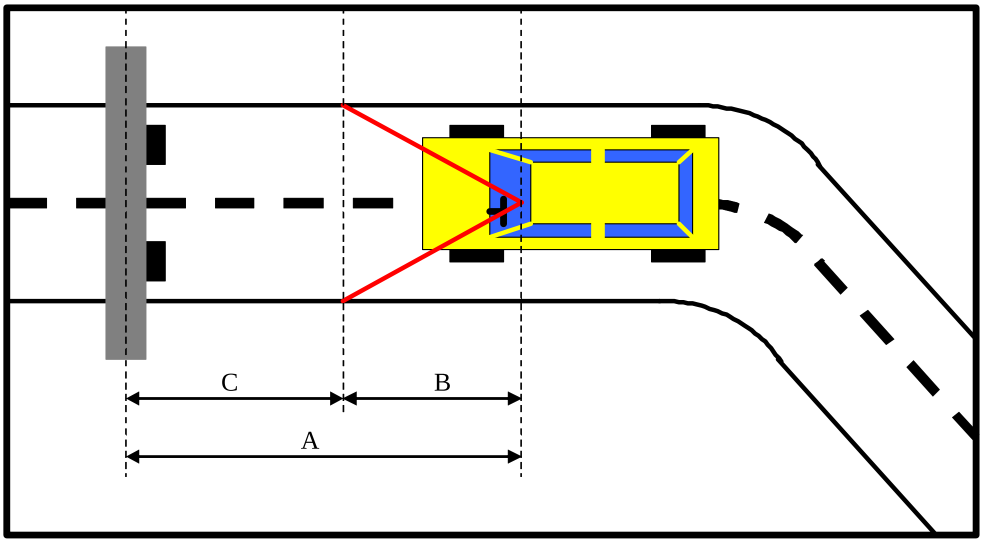


Fig.6-7: A - distance of good recognition, C - minimal safe stopping distance,
B – random difference

### 6.4 Subjective evaluation

Although we are mainly interested in the objective markers, the subjective measures are also very important. Their employment plays indisputable role within the range of experiments concerning assessments of different HMI devices used in cars (i.e. ergonomic issues, ease of use, positive/negative influence on driving safety, etc.). They are also successfully used for any kind of self assessments (self rating).The probands are for example instructed to report their actual state when asked by the operator during the experiment on the simulator. Usually they have the scale they use for self-rating just in front of them in their visual field, so that their answer is can be immediate and could give a valid result. Complex questionnaires frequently are used for investigations of the influence different driving scenarios after the experiments.

## 6.5 Psycho-physiological measures

To create a set of objective markers, it is necessary to take into account besides technical outputs also biological ones. For the experiments, which are focused on the detection of attention level, comfort (or discomfort) or influence of stressing factors, the psycho-physiological measures of non- invasive form are successfully used. Between the most popular ones it is possible to reckon mainly these following:

- EEG
- EOG (or movements of eyes)
- Skin impedance (or resistance, capacitance,etc)
- ECG (or heart beet frequency)

### 6.5.1 Encephalography

EEG signals arise from an activity of neurons of the thalamus and cortex. A normal EEG signal is quasi-periodic, but they are approximately of a sinusoidal shape (see [Faber]). The amplitude of the EEG signal is usually between 10 and 100, which varies with frequency. The frequency range is from 0 Hz to 80 Hz, the effective range is limited approximately to 30 Hz. It is measured on the scalp of the driver's head.

Several types of brain waves exist and they are classified into several categories. From our point of view, the most important are the following [2-ATNY05]:

- Delta - (0.5 - 4 Hz) - It can be found in a deep sleep. It is also typical for analytical thinking (Occurrence during adult's vigilance is pathological). The amplitude is usually between 10 and 200.
- Theta - (4 - 8 Hz) - It can be found together with delta activity in certain phases of sleep. Theta activity also increases during psycho-tests, even with open eyes.
- Alpha - (8 - 13 Hz) – It is most apparent with closed eyes. It is damped by an intellectual activity and opened eyes. Its amplitude is usually between 30 and 70.

- Beta - (13 - 30 Hz) - It is typical for uneasiness. The amplitude is up to 30. The maximum of beta activity is in the frontal part of the brain.

Each of the bands can give us certain information about that driver’s actual mental state. Unfortunately those markers are very individual ones and they are hard to be generalized. The topics to be investigated are mainly correlations between them and/or ratios among them. A non-linear analysis of EEG signals gives us a very interesting view (see for example [SVOP02]).

Similarly to the driving wheel signal analysis, when dealing with EEG signals as the fastest and most reliable attention indicators, much more measurements have to be done before the present knowledge could be generalized in a necessary wide scale and used for practical application.

# Chapter 7: Experiments

This chapter deals with experiments done in relation to my PhD. thesis on driving simulators in the LSR. The main focus of these experiments can be divided into three main directions:

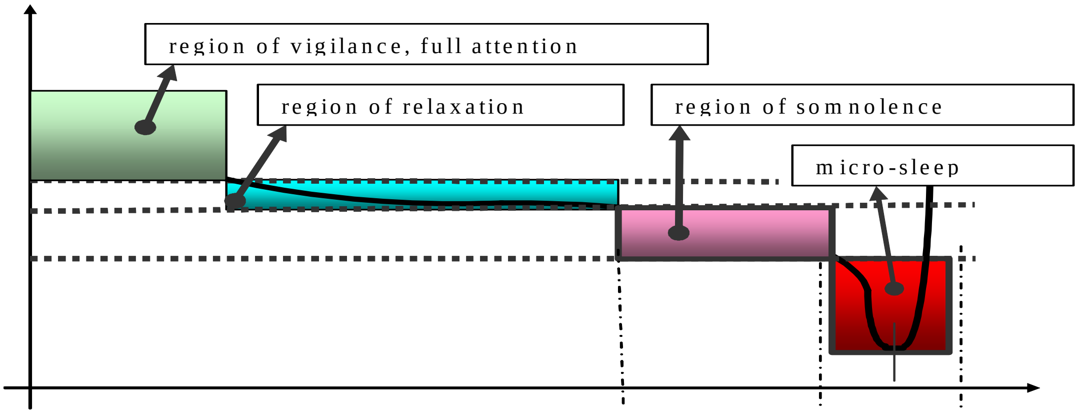
1. Fatigue related experiments
2. Assessments of influence of HMI devices (IVIS) on driving safety and comfort
3. Influence of environment on the driving safety

## *7.1 Problem of drivers' vigilance and fatigue*

The experiments being done in our laboratory are aimed to find patterns in brain waves that describe human vigilance (or fatigue) level [SVOP05]. Those patterns are promising candidates to be used as an input of automatic classifier of an actual driver's state (i.e. vigilance level). For us the most important are those sections preceding the incontestable micro-sleep. If these are correctly recognized, the driver can be warned in time. The procedure of getting asleep was divided into four stages [1]:

1. *vigilance*
2. *relaxation*
3. *somnolence*
4. *micro-sleep (for our purposes – otherwise we can talk about first stages of sleep)*

Micro-sleep development described by our neurologists (see e.g. [NOVM04]) is shown in Fig. 7-1.



.Fig. 7-1: Theoretical development of micro-sleep

There are several studies looking for patterns in brainwaves which describe the state of somnolence and sleep. Unfortunately there is no general consensus in this field which could reliably define the actual vigilance level in general. Some criteria suitable for practical classification were however presented in [FABJ02] e.g.

## *7.2 Problem of drivers' distraction*

### 7.2.1 Decreases of driver attention in the course of driving

A driver of the contemporary car is exposed to the almost continuous stream of various stimuli, affecting his/her senses. These stimuli (according to [NOVM06/2]) are:

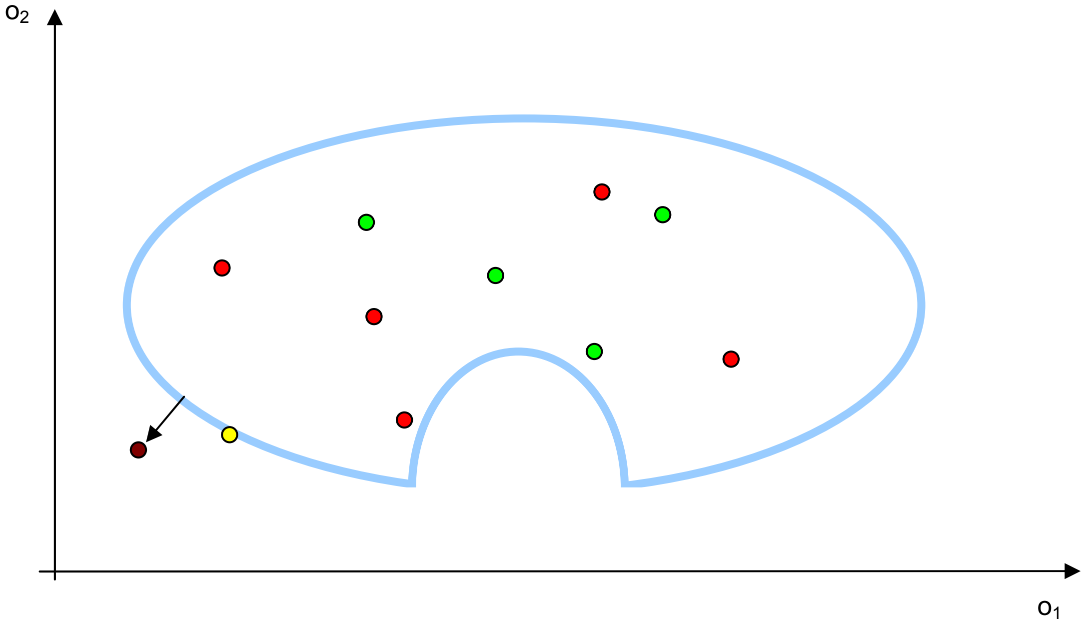
- Visual,
- Acoustic,
- Mechanical,
- Chemical,
- Humoral.

As concerns the driving activity reliability, the visual stimuli are of course the most important.

These come both from the inside and from the outside of the car cockpit. As for the external visual stimuli, they can appear in any place of the driver\s observation field, the idealized shape of which is sketched in Fig. 6-2.

If some stimulus appears outside the region $R_o$, the driver cannot see it and therefore is not able also to recognize it and react to it. In Fig. 6-2 such stimulus position represents the violet point ●.

However, if some stimulus appears very near to the boundary of $R_o$, the driver usually does not recognize it well (yellow point in Fig.6-2) – the boundaries of $R_o$ are more or less fuzzy. This causes that the driver recognizes that something interesting could happen in the appropriate part of his/her visibility field boundary, but because he/she cannot recognize it well, is forced to turn his/her head so, that the respective $R_o$ moves so that the considered stimulus position moves toward the center of $R_{o.}$ Such procedure can be called the centering of $R_o$ and is started by recognition of some stimulus near the boundaries of $R_o$. Of course, the procedure of $R_o$ centering with respect to some periphery (boundary) stimulus operates with another neural networks and requires muscular cooperation. This all needs some time. Therefore, the driver reaction time to periphery stimuli is significantly longer.



Coordinates $o_1$, $o_2$ of the observation field O

Fig.7-2: Rough sketch of the idealized visibility field, in which the external stimuli acting on drivers eyes can appear, if his/her head does not move. The hillock down middle corresponds to the part, in which the view of eyes is shadowed by nose. Small red and green dots represent here the individual observable visual stimuli. $o_1$ and $o_2$ are the coordinates of the observation plane

● _ stimulus on the boundary of $R_o$

● _ stimulus outside the region of observation $R_o$

The $R_o$ in certain manner corresponds to the region of acceptability, known in the theory of system reliability. Its actual shape and size varies with person, time and situation.

For the driver sitting in car cockpit one has also to consider the limitations of $R_o$ caused by the cockpit construction (front panel, wind shield, possibly glasses etc.). If some stimulus inside the $R_o$ is recognized by a driver, he/she starts to react to it. However, the parameters of such reaction procedure differ not only with the position, intensity, color and shape of the particular stimulus, but also with the stimulus duration and individuality of a driver. In literature one can find some information concerning results of respective tests, however as far as it is known not too much systematic research has been made in this area.

A special interest has therefore be given to investigation of reaction time values measured on drivers observing visual stimuli suddenly (unexpected) appearing in various places of the driver $R_o$. Such measurement is safely possible on advanced car-driver simulator only. The respective experimental stimuli are of various shapes (circular - simulating red, orange and red traffic signals, and also of silhouette forms, simulating the vehicles or figures, appearing in the road – especially those, representing the traffic on crossroads).

For such measurement the proper set of probands must be selected. Because of very high individuality of driver behavior, the influence of other disturbing factors, like the temperature, illumination level, dust, noise and the time of measurement has to me minimized as much as possible.

All probands have to be healthy people, with no tendency to be influenced by drugs, including alcohol and nicotine. They have also to be of an adequate motivation for the measurement. As concerns the sex, their set has to include about 65% of men and 35% of women – as corresponds to the average distribution of sex among contemporary driver population in central Europe.

Their age distribution should also approximate the age distribution among real drivers, i.e. about 60% should be of 18 – 55 and about 40% of the age above 55. The teenagers below 18 have to be excluded. All probands have to keep a valid driving license.

They have to start the experimental driving on simulator after short accommodation route about 20 minutes long. The measurement has to be about 60 minutes long. After the measurement run, each proband has to fill in a special anamnesis form.

All probands of the same series of measurement have to start equally tired, i.e. either almost immediately after their full night sleep or after almost equal work load.

Each measurement series has to involve 25 probands at least.

As concerns the attention indicators, in such measurements the reaction time seems to be the most important.

However, its correlation to other indirect attention level indicators, like the EEG and EOG signals is very important. Therefore also these indicators have to be carefully recorded. Besides this also the face grimaces (front and profile) and the record of observed scene are to be included in the set of recorded data. In such arrangement, the amount of data measured on one proband can reach about 20 GB. This causes a considerably high requirement on the disposable capacity of the storage field used for the appropriate database.

### 7.2.2 The process of attention decrease

Besides the investigation of fundamental data concerning the driver actual attention level, represented by the indicators mentioned above, the entire procedure of the attention decrease in the course of driving load of proband is also to be considered.

This procedure is very individual and it is influenced by very many factors as well. Some of them, which are of more or less of general nature, were already discussed in [NOVM01/1, NOVM01/2, NOVM03/1, NOVM03/2, FABJ02] e.g. In simplified idealized model, we can say that each driver, starting his/her driving activity in fresh condition, will subsequently go through the following 5 fundamental stages of his/her attention decrease:

1. stage of full vigilance
2. stage of relaxation
3. stage of somnolence
4. stage of micro-sleep
5. stage of awaking.

The first 4 are indicated by various colors in the Fig. 7-1. The fifth, the stage of awaking after possible micro-sleep, which is not shown in this figure, is also important, because under some circumstances, the driver can awake in panic form and react to awaking him/her stimulus quite un-adequate.

Each of these stages has its own characteristics and except the stage of full vigilance, each can lead to a dangerous situation on the road.

Depending on driver’s individuality, type and technical stage of the particular car, characteristics of the external traffic, environmental condition and quality of the road, the sequence of appearance of these stages and length of their duration changes. In some cases they can be very short so that their identification could be quite problematic. As schematically shown in Fig. 7-3, some of them (or possibly all) can be in the total course of driver driving activity repeated several-time.

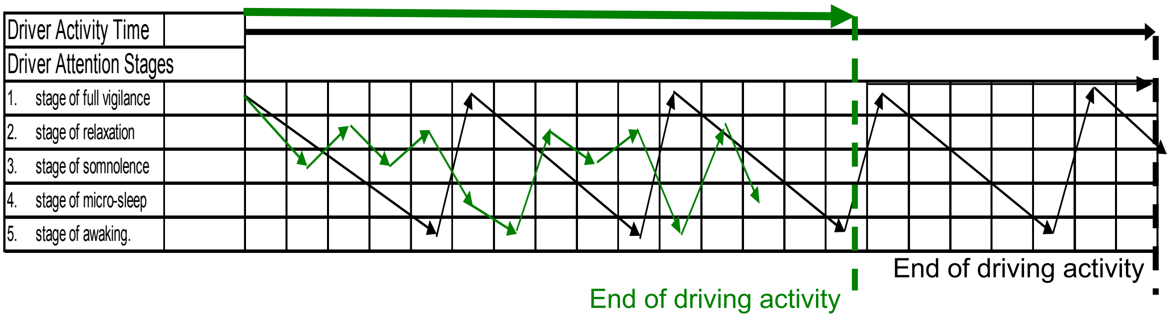


Fig.7-3: Sequence of attention stages in the course of driving activity. Black line: regular repeated transition through stages 1 – 5, Green line: irregular random transition through stages 1 – 5, with end of driving activity in the stage 3.

In real driving situations, at the end of driving activity the driver can never be in the stage 1 (except the very short driving followed by some quite different activity of particular person) and also not in the stage 4 (except the case when the driver continues from micro-sleep into the regular sleep and somebody else stops or controls the car without accident).

The stage 5 – awaking must not be considered as transition from micro-sleep to full vigilance – as is shown by black lines, but also as transition from stage 2, 3 or 4 to stage 1, 2 or 3. The transition from stage 4 to 3 or 2 and from 3 to 2 can be considered as partial awaking, which appears very often, especially in the course of long driving expositions. Also in such partial awaking the panicky reactions with high probability of wrong response to unexpected stimuli can appear.

### 7.2.3. Reliability Aspects of Driving Procedure

As it was already discussed in many other papers and reports (see [NOVM03/1, NOVM03/2] e.g.), the ability of a driver's reliable and safe driving can be represented by some point in the multi-dimensional space *{X}* of the N parameters $x_i$ representing the drivers attention level. In general various kinds of parameters $x_i$ can be taken into account. Such space represents actually the state-space of the heterogeneous system driver-car.

However, because the determination of these parameter values is very often loaded with considerably high level of uncertainty, the restriction of the number N to small values is recommendable [NOVM03/1].

For practical investigations, one deals therefore before all with two main parameters, representing the level of attention, i.e. the driver's reaction time RT and the probability $P_{corr}$ of his/her correct[1] response to certain external stimulus.

In the plane (RT, $P_{corr}$), the regions of acceptable attention are then restricted inside the gray shaded area, shown schematically in Fig. 6-4 (values of RF below 200 msec does not appear in practice, the RT above 1000 msec represent the fall into micro-sleep, or "hard" sleep ).

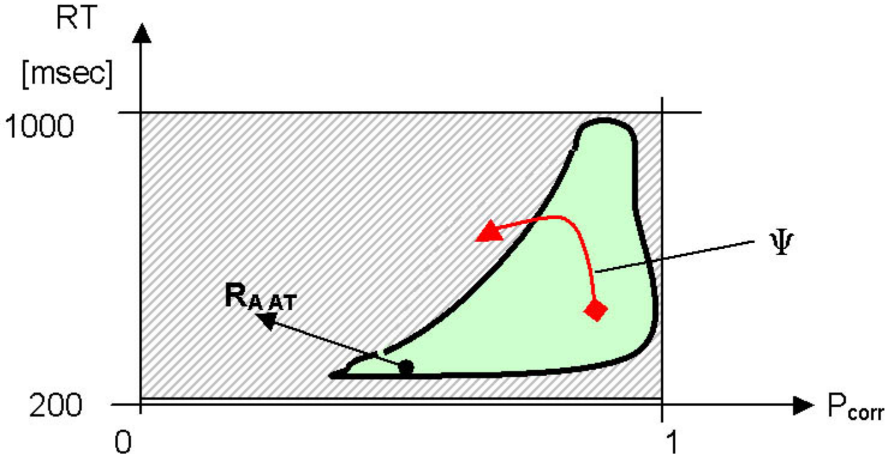


Fig. 7-4: The schematic representation of the region of acceptable drivers level of attention and the respective life curve $\Psi$.

However, as it was already mentioned here, the investigation of boundaries of $R_{AAT}$, even in such two-dimensional space represents a very laborious and complicated problem, especially because various types of car, road, driving situation and especially also the above mentioned driver's individuality has to be taken into account.

The factor of the probability of driver correct reaction $P_{corr}$ is however worth deeper discussion.

The fresh and skilled drivers, being in the state of full attention have the total reaction time, from the moment of the respective stimulus appearing to their reaction to proper actuator (driving wheel, brake, accelerator pedal) usually between 200 and 250 msec. The possibility to react in the time below 200 msec appears only rarely. In such state, the value of $P_{corr}$ is usually very high, approaching 1 (absolute safe for correct reaction is of course nobody). When the particular driver attention decreases, the values of his/her RT prolong. Together with this increase of RT, the respective

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[1] Alternatively his/her wrong response (1-$P_{corr}$)

values of $P_{corr}$ decrease. The sleeping driver does not react at all and therefore his/her $P_{corr}$ approaches zero.

Therefore, one could expect the simple indirect dependence between RT and $P_{corr}$, like it is schematic shown in Fig.7-5.

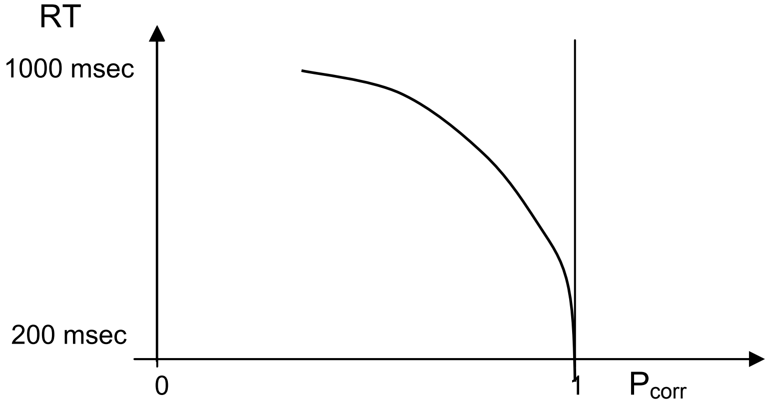


Fig. 7-5: The principal inverse dependence between RT and $P_{corr}$

However, the probability of correct reaction of drivers in relaxation and also in somnolence state is influenced also by a set of other factors, like the intensity of observed stimuli, their position in visual field, color and shape and – of course – by their duration. Also the physical and psychical state of a particular driver has to be considered. The drivers starting their driving activity after preceding other long lasting tiring activity have lower values of the probability, that they will select as the response to certain stimulus the correct answer. This concerns especially the cases, when the tested person has more than 2 possibilities for answer, e.g. he/she can react to stimulus representing the barrier on road in front of car either by braking, or by turning the driving wheel to the side or by strong acceleration and making the turning maneuver. In such cases the particular values of $P_{corr}$ can spread in certain interval, as it is shown in Fig.7-6.

More over, the boundaries of $R_{A\ AT}$ or some their parts have often more or less fuzzy character.

In the course of driving, the point X = {RT,$P_{corr}$}, representing the actual level of particular driver attention moves inside the space {RT, $P_{corr}$}. It follows some curve, which in analogy to the technical system reliability theory can be called the “life curve”$\Psi$ . This can be scaled by the values of various independent variables, namely by time. If the curve $\Psi$ remains inside $R_{AAT}$ the driver is able to drive considerably reliably and safely. If it approaches the boundaries of $R_{AAT}$ or if it crosses it, the situation becomes dangerous.

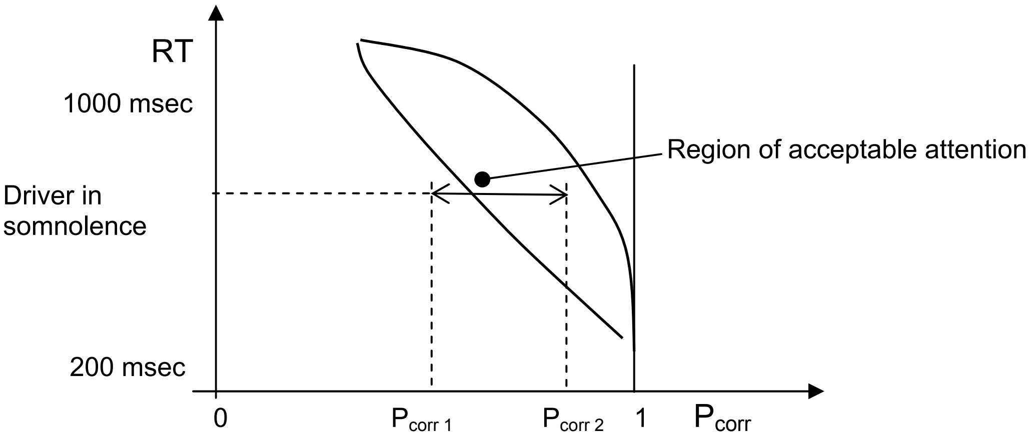


Fig. 7-6: The spread of $P_{corr}$ values corresponding to certain RT

The practical investigation of the $R_{AAT}$ is possible only on advanced adaptive driver-car simulators, where the process of driver attention decrease can be performed till the crossing of particular $R_{AAT}$ boundaries. This is impossible on the road, of course. Nevertheless, such investigation is still very laborious, especially because the direct measurement of driver's reaction time RT is even of the invasive nature. The recognition of some presented stimulus, which the driver has to react to, leads in any case to changing his/her actual level of attention and the next measurement must therefore be done after some delay – usually 1-2 minutes. More over, to determine the value of the probability $P_{corr}$ of correct reaction (at least approximately), several measurements with the same stimulus and the same proband attention level have to be done. This all prolongs very significantly the length of measurement, which sometimes must be divided into several sessions because the tested person gets too tired.

Nevertheless, the estimation of the $R_{AAT}$ size and shape – at least approximate - represents the fundamental knowledge without which neither further investigations of driving reliability, nor the development of warning systems for attention decreases can be done.

## *7.3 Experiments focused on assessments of driver drowsiness – Response time based*

### 7.3.1 The testing cohort

The experiments were done in two stages.

The first one – the preliminary testing – are used mainly for necessary methodology design. There were 7 people tested in the first stage and 10 people in the second stage (in fact there were only 9 people used because the 10th did not finish the experiment correctly and therefore these results were discarded). The testing cohort consisted of drivers of 21 to 31 year of age, of mixed sex (70 % males). They all were passenger-car drivers with average driving experience, but not the professional drivers. The basic condition for their acceptance into this cohort was to have a normal EEG record.

The next picture (Fig. 7-7) shows one of the tested drivers equipped with the EEG cap and heart beat recording.

a)

b)

Fig. 7-7: The tested driver equipped with EEG cap and heart beat recording sensors (the Compact simulator type I – a),   Light simulator type I version 2005– b)).

### 7.3.2. The testing procedure for drowsy drivers

The experiments with the proband category representing the drowsy drivers were done in the following way; at the beginning of the measurement the driver passes the initial (reference) test and adaptation rounds on the simulator. After the driver gets deeper into the "on-simulator" driving (i.e. immerses into the virtual reality) he/she becomes accommodated to these measurements and more relaxed.

This situation appears to be significantly different from doing other kind of HMI experiments with fresh drivers, where much longer initial adaptation and much more introductory rounds are necessary.

Here we set up following general requirements:

1. *The probands were required to be after 24 or 36 hour sleep deprivation*
2. *The probands did not have consumed any drugs (alcohol, medicines…, coffee, strong tee of other exciting agents).*
3. *The length of the drive varied between 2 and 2.5 hours, depending on development of his/her condition.*
4. *Before and after the testing drive the probands passed the standard neurological tests. Those tests served mainly to recognize if the proband brain was not affected by some possible illnesses.*

The measurement was divided into two parts; in the first one the probands were after the sleep deprivation and consequently their level of vigilance was lowered but without knowledge how seriously.

The second part was performed in different time (day) when the driver was supposed to be in the fresh state.

### 7.3.3 The simulator sickness problem

The simulator sickness seems to be one of the most common problems of the experiments made on driving simulators.

In our experiments the probands fill out before and after the measurement complex anamnesis questioner telling us the set of necessary information about the actual psychophysical state of a particular person.

Till now from almost 500 provided measurements, we fortunately experienced very low number of serious simulator sickness occurrences (<2%).

We explain this effect before all by the fact that we use relatively small FOV (up to $100^{O}$ horizontally) and that we performed carefully the preparatory oral discussion about motion sickness eventually appearance with each of participating probands.

### 7.3.4 The testing scenarios

From the real situations reported by drivers (mainly professional ones) the micro-sleep usually comes when the driver goes on a calm highway. Critical moments are mainly those when the traffic is very low, the driver is not forced to solve more complex problems. The driving then becomes automated and the driver loses control over the car. We took this experience into account when designing the testing track and proposed following requirements on it:

1. *Simplicity. The track should be very simple to drive, so that the drive could use as few mental forces as possible.*
2. *Boring scenery. Variety of the objects on the scene always excites the driver.*
3. *Limited visibility. The main problems with drivers' fatigue occur during the night rides. We chose dusk like scenery appearance.*
4. *Limited traffic. It could be very exciting for drowsy driver to solve any kind of traffic problems.*

The driver should keep the speed 90km/h for all the way. From the driver's point of view the most of the ride seems to be almost straight. A very light curvature was chosen so that the drivers need all the time to pay his attention to steering. If not, they go out of their lane. The track is equipped with parking lot with "slalom" proving ground.

The next figures show the top view on the reconstructed testing track (Fig. 7-8). The original old track was used for initial set of experiment but the analysis exhibited difficulties mainly thanks to the curvy part which brought problems with classification of trajectory and forced the drivers to refresh themselves. The new track contains traffic lights in distances of approximately 200 m in such an arrangement that they are always one or more successive in driver's view.

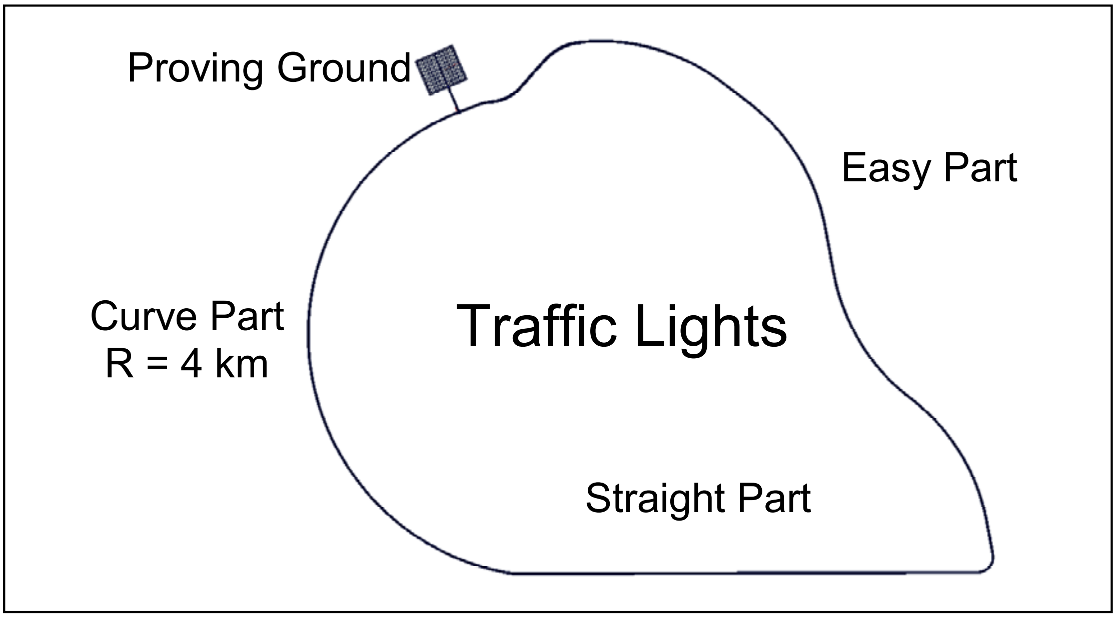


Fig. 7-8: Testing track used for drowsiness experiments

To be fair we should consider issues of visibility and in the ability of the driver to recognize correctly a lights status change. In fact, including above the factors above into the analysis could lead to a big degree of uncertainty. We bypassed this problem by creating multiplied semaphore plates with only two color lights (red-green). The semaphore state change comes if and only if the lights are really well recognizable and simultaneously if the driver can safely stop before passing through the lights stand. In advance the tested driver was instructed to keep an eye on the lights during the whole course of driving.

There is (till now) no other traffic (only parked cars around), no crossroads and no additional driving situations needed to be solved installed in our simulation scenarios.

The tasks which the driver solves are as follows:

1. *Keeping the lane*
2. *Keeping the speed*
3. *Watching the traffic lights*
4. *Reacting to red signal with immediate pushing on the brake pedal*

Such an arrangement makes the tested proband solve only a primary driving task and so we can rely that *his/her reaction time to red signal is not influenced by other factors* and that it can be believed that the measured values testify reliably the level of his/her vigilance. The possible improper fulfillment of any one of above listed tasks gives evidence of poor driver’s attention, which is caused (in our experiment) by fatigue.

The following pictures (Fig. 7-9) represent screenshots from the testing track equipped with traffic lights. Note the dusk light conditions which should help to simulate naturally “sleepy” environment.

On the left hand side there is common type of road semaphore used in Central European countries, which was used in our original virtual simulation scenarios. The right picture shows a modified version equipped with multiple lights and orange–lightless.

Fig. 7-9: Real semaphores (left) and semaphoers satisfying needs of our experiments

### 7.3.5 The data acquisition

The next figure (Fig. 7-10) shows outputs which we reached by our measurements and recorded during the experiment.

The data which we used for the analysis of driver’s state are highlighted red.

The right hand part of the picture shows an example of the snapshot from the video record supplemented with EEG record of the proband just-in time of micro-sleep and the relevant actual state of the road in front of him/her.

About 50 such long time measurements were made. The results of them are stored in the respective part of the LSR neuroinformatic databases, created in the range of the project ME 701 of the Czech Ministry of Education.

Fig. 7-10: The standard form of our driver’s video record completed with EEG record (right bottom) in time of driver’s micro-sleep

### 7.3.6 The measurements

During both parts of the measurements (testing of drowsy driver after sleep deprivation and reference tests of fresh drivers), all the data discussed above were measured respecting the same protocol.

The objects of these measurements were:

***Response time (RT)***

The response time to the stimuli (reaction time) is one of the basic measures which testify driver’s vigilance. The results of these measurements seem to be satisfactory reliable and as the most objective parameters, which all other indicator values can be correlated with. The reaction time was measured at about **70-times** per one full measurement session, so that allows the statistical evaluation which overcomes the problems specified above. In the reference measurements the RT was measured only **15-times**.

There were certain problems with definition of what is “late” (or prolonged) reaction and what is considered as a “sufficiently” long time spent out of the proper lane.

Sometimes it happened that the driver was simply thinking about other things not relevant to driving and did not pay enough attention to tasks important for driving, without any specific reason. Because of that we set our measures simply and unambiguously.

### *Self rating (SR)*

The probands were instructed to report their actual state when being acoustically asked by our measurement operators.

Usually they were asked every time after stopping on red signal. They were instructed to answer only on demand, so that they should not keep in mind any more information than the driving itself and/or keeping an eye on the semaphores.

Such a concept gave us a possibility of more precise correlation of reaction time and other measured parameters with self reported state of drowsiness.

The proband actual state was classified according to driver's capabilities of safe driving and subjective feeling of drowsiness.

The table with the scale was also placed on a steering wheel. We proposed to give the driver 5 degrees scale of self evaluation:

1. *I feel fine/fresh & driving does not make me any problems.*
2. *I feel drowsy & driving does not make me any problems.*
3. *I feel drowsy & I notice some problems.*
4. *I feel very drowsy & I need excessively concentrate on driving correctly.*
5. *I experienced 'blackouts' & losing control over the car.*

### *Lane variability (LV)*

In the research of a driver's drowsiness on simulators the trajectory-lane keeping and weaving are frequently analyzed. The lane departures are very useful when finding serious driver's state but they are not suitable for statistical analysis which is the topic of this thesis. We looked therefore mainly for overall variance. From the contemporary level of our knowledge it is also possible to say that the movement of car within the lane borders (originated in steering wheel movements) could be a very promising attention level indicator (marker) [VYSP04].

### ***Heart-beat rate response (HRR)***

The heart beat rate variability is widely used for detection of sleep stages [YAMY04, WATD01]. The heart beat rate was measured during both parts of our experiments but not it was analyzed continuously.

We discovered a very interesting behavior of this marker:

- when the driver was drowsy, his/her heart rate has increased significantly after each red signal approach.
- This increase was not so evident when the driver was fresh.

Probably, similar effect can be expected as concerning the skin impedance, however, here one has to take into account, that – in contrary to heart beat, for this indicator with a very long delay between stimulus appearance and indicator change is typical. The first approach to this kind of attention classification we have published in [BOUP05/3] and [PIER06].

### ***EEG analysis***

In a general it is possible to say, that all the stages of driver's vigilance and attention level (i.e. *full vigilance, relaxation, somnolence, micro-sleep*) have their specific images in the EEG signals. These attention stages are recognizable immediately it the time-space, but much better they can be indicated in the respective frequency space.

Similar well recognizable patterns can be achieved also from the records measured on probands getting asleep in quiet, sitting in an armchair, relaxing, with closed eyes and without any disturbance.

A set of EEG signals is usually recorded from standard 10/20 montage of the head electrodes (see [FABJ05]e.g.).

The electrodes which we used for analysis were those, which are least affected by eye blink or other muscular artifacts. It seems that those can be the occipital electrodes (O) and the central electrodes (Cz).

The respective EEG signal power spectra which usually are computed using standard FFT were in our case for better reproducibility (with respect to their principal quasi-periodical and quasi-stationary character) determined by the use of band-pass Gabor filtration by polynomial transfer function of the 50th order.

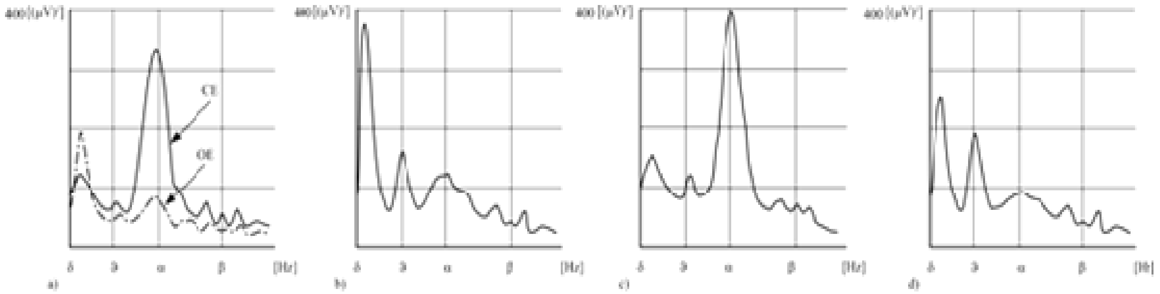


Fig. 7-11: The EEG spectra for a) vigilance (Closed Eyes and Open Eyes) b) thinking (Rav.) c) relaxation (Rex.) d) Sleep (Sp).

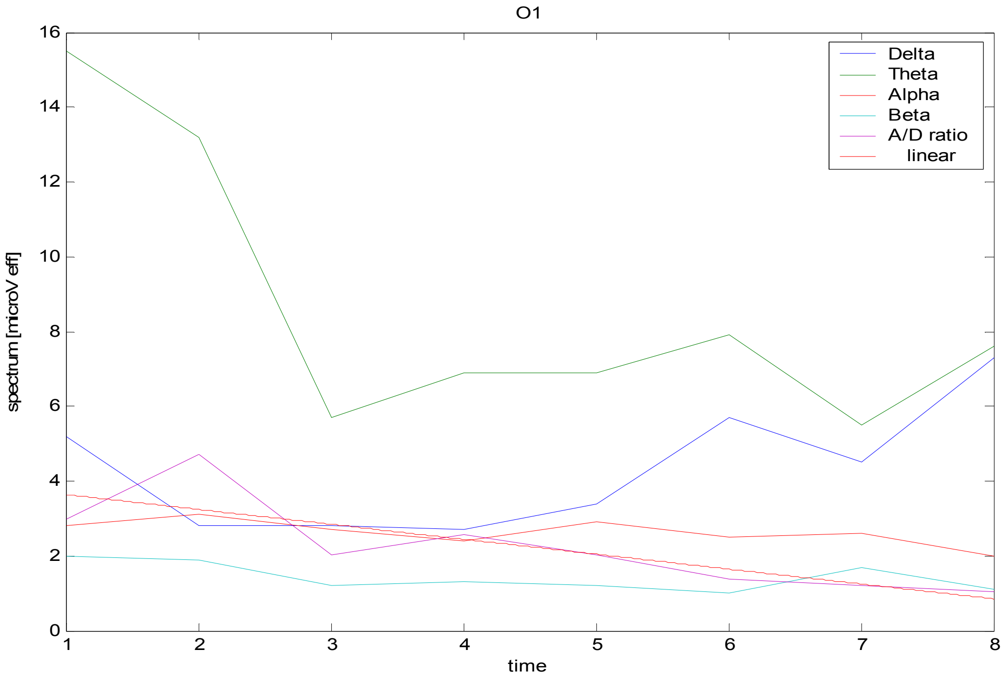
All the analyzed samples were of a length 3 sec. in the time just preceding the appearance of red light signal during the simulated drive

Unfortunately the brain waves recordable on the head surface are of a very low magnitude (several tents of $\mu V$ ) and any muscular activity on the head or neck and facial areas destroys the EEG signal, so that the classification in unfeasible. Any faster motions, grimaces or any “refreshment” movements are causing problems for further analysis. For that reason there is a big portion of garbage within measured EEG data, so that some proband results need to be discarded from the set suitable for further EEG analysis.

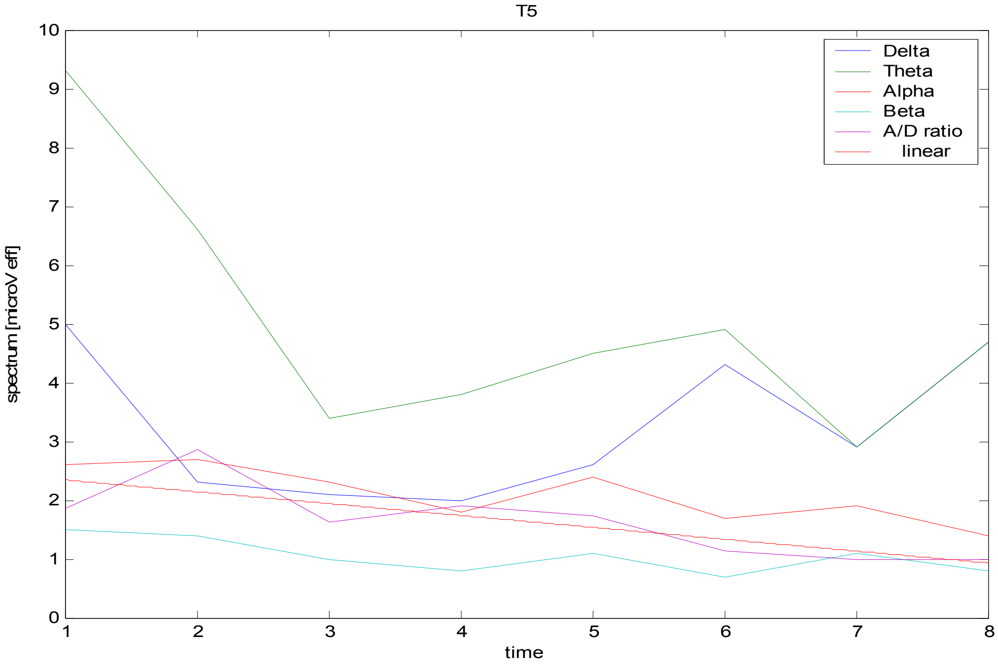
Works in the LSR were made on different ways of analysis of the EEG - starting from classical frequency analysis, with advanced fuzzy classification [FABJ05], nonlinear methods like LLE (Largest Lyapunov exponent), chaotic attractors [FABJ03, SVOP02] or classification using neural networks [TATV03].

These classification methods are still hard to be used reliably in an automatic way and even more they are tested on probands not loaded with any demanding task. They are however very important for laboratory calibration of other attention indicators. Because of that fact thinking of practical applications, we should rely on simple method like a frequency analysis is.

The next picture (Fig. 7-12) shows such an analysis for the driver just before accident caused by the micro-sleep backtracked 40 seconds before driver waked up from the sleep. There is an apparent *alpha/delta* decrease in this micro-sleep episode.



a)



b)

Fig. 7-12: EEG frequency analysis of 8 sec. long record just before the accident a) - O1 electrode, b) - T5 electrode

As it is now considerably well known, the values of the single average amplitudes of the power spectra in the standard EEG spectra regions (delta, theta, alpha and beta) itself are not good for representation of particular proband attention level, though in many recent works these were used for such purpose. Therefore, since the very beginning of the investigations made in LSR in this area (practically since 1997), a considerably large attention was given to finding of some more sophisticated combination of values, derivable from the calculated EEG spectra, which are more representative for attention level determination.

As the first approximation in this respect, the ratio of the mean amplitude of signal power in the alpha and in the delta region of the EEG signal (in Fig. 7-12 mentioned as A/D ratio) was found (see [NOVM05] e.g.). In simple cases, such indicator seems to be useful, at least for preliminary classification.

However, the further investigations made on higher number of probands have shown, that the single A/D ratio cannot allow the reliable distinguishing of real attention decrease and situation, when the proband mind is concentrated on other kinds of mental activities. Therefore, in [NOVM05], the further, more complicated combination of about 8 rules for determination of attention level from the particular proband EEG spectra, were proposed. Though their validity were tested on the introductory set of about 25 probands with quite good result, nevertheless because of the well known extremely high individuality of human brain structure and function, this is not satisfactory. Much more serious measurements on much higher number of various probands will be necessary before one can generalize the validity of such rules. This of course requires much more time and probably the high level of cooperation of several laboratories.

This is the main reason (neglecting the above mentioned difficulties with artifacts disturbing), why in this thesis there was not possible to apply such indicator in more general manner.

### 7.3.7 Correlation analysis

We chose a very simplified experiment scenario which allows neglecting unwanted input signals influencing their reaction time. Reaction time is stated to be the most reliable measure available and it is correlated with others measured quantities.

We wanted to investigate which of other measures are also reliable. The main problem of reaction time as a continuous attention level indicator is that it cannot be reached for continuous classification because of affecting the proband attention level by invasive nature of any direct RT measurement. Some complex correlations were already tested however using statistical tool like GUHA [3], but the reached results cannot be generalized yet.

### *RT-SR*

We observed a very interesting correlation between the reaction time and the self rating. In those parts where the self rating is of rising trend, the correlation was good.

This can be explained with the hypotheses that drivers can reliably evaluate their attention level only until the culminating point till which they are vigilant enough.

This could lead to conclusion that the decrease of the attention can be detected by the driver him/her-self (and this is what experience of many drivers tells us in real life).

The next table (Tab. 7-1) shows the values of correlation coefficients between the driver's response (RT) and his self evaluation (SR) "drowsy" part. The correlation increases when extremely long responses are lowered, even more when only the part where SR is increasing to its culmination point was investigated.

| **Proband number** | **correlation coefficient** | **correlation coefficient (after lowering of extremely high values)** | **correlation coefficient (in the time when the SR was of rising trend)** | **average growth in drowsy stage[ms]** |
|---|---|---|---|---|
| 180001 | 0.327609411 ** | 0.379581509 ** | 0.425348895 * | 919 |
| 180002 | 0.354050845 ** | 0.437522942 * | 0.498732498 * | 1917 |
| 180003 | 0.555872108 * | 0.587254750 * | 0.678420680 * | 1257 |
| 180004 | 0.475883596 * | 0.569450897 * | 0.635272799 * | 1862 |
| 180005 | 0.522006659 * | 0.552847165 * | 0.608840413 * | 1599 |
| 180006 | 0.421839507 * | 0.596272761 * | 0.630388376 * | 875 |
| 180007 | 0.404269564 * | 0.506757236 * | 0.630450058 * | 1529 |
| 180008 | 0.349610644 ** | 0.404777172 * | 0.353874476 * | 1143 |
| 180009 | 0.421534164 * | 0.451781240 * | 0.495957579 * | 852 |
| 180010 | 0.199595318 | 0.316442184 *** | 0.326939926 ** | 976 |
| * significant at the p<0.001 level ** significant at the p<0.01 level *** significant at the p<0.05 level | | | | |

Tab. 7-1 Linear correlation between Reaction Time and Self Rating during "drowsy" part

### *RT-HRR and SR-HRR*

We correlated this phenomena with the self rating (SR) and with reaction time (RT). However, the measurements of only 4 of 9 probands provided clear ECG data suitable for the analysis from both parts of the experiment.

We have measured HR at the moment of red signal approach and *10 seconds* after it. For drowsy drivers there was an average increase of HR 3-10%, for fresh drivers from decrease 2% to increase 1.5%.

We can say that heart rate slightly increased with both SR and RT, the correlation coefficient was between 0.16 and 0.32.

The following tables describe correlations with self rating (Table 7-2) and reaction time (Table 7-3) to the red signal. Fresh drivers are not correlated with self rating since a level ‘1’ is expected during the whole “fresh” part (Table 7-4).

We suppose that a better way should be used for getting data from heart rate curve. Correlation coefficients and its p-values are not all statistically significant although when observing heart rate curve, we can see a big increase in a heart rate after red signal approach.

After elimination of about 5% values considered as outliers the correlation with SR for all four probands was greater than 0.3 while p-value less than 1%.

| **Proband #** | **Correlation with SR** | **p-value** | **Mean After/before red signal approach ratio** |
|---|---|---|---|
| 180001 | 0.3122 | 0.0135 | 1.088011 |
| 180003 | 0.2057 | 0.0875 | 1.029453 |
| 180004 | 0.2650 | 0.0343 | 1.085213 |
| 180009 | 0.1991 | 0.0959 | 1.102619 |

Tab. 7-2: Drowsy drivers – correlated with self rating

| **Proband #** | **Correlation with SR** | **p-value** | **Mean After/before red signal approach ratio** |
|---|---|---|---|
| 180001 | 0.2122 | 0.0978 | 1.088011 |
| 180003 | 0.1560 | 0.1973 | 1.029453 |
| 180004 | 0.2051 | 0.0839 | 1.085213 |
| 180009 | 0.2472 | 0.0363 | 1.102619 |

Tab. 7-3: Fresh drivers – correlated with reaction time

| **Proband #** | **Mean After/before red signal approach ratio** |
|---|---|
| 180001 | 0.985757 |
| 180003 | 1.002014 |
| 180004 | 0.994511 |
| 180009 | 0.982811 |

Tab. 7-4: Fresh drivers

### 7.3.8 Pair-wise comparison analysis

This section describes an analysis which was done on the base of the comparison of pair wise measurements.

All the tested drivers in the second part of measurements also had to pass additional reference measurement when they were incontrovertibly fresh.

So that we could do a classification if there is significant difference in our monitored factors. In other words the fresh state is stated to be of known level but the fatigue appears in general in unknown and fluctuating level. We wanted to validate our monitored factors to be reliable markers of significant difference.

The second trial was performed in a different day only if the probands felt really fresh. The length of the measurement was about ¼ of normal one, since we did not expect development of fatigue in this case.

Longer measurements could bring more aspects of upcoming drowsiness and could make the reference data unusable. To investigate the significance of difference a *T-test* for confidential level 0.05 (and/or 0.01) was used.

***RT comparison***

The response time was validated to be significantly increased during the "drowsy" part of experiment.

| experimentee | 180001 | | 180002 | | 180003 | | 180004 | | 180005 | |
|---|---|---|---|---|---|---|---|---|---|---|
| Sloha | 0.05 | 0.01 | 0.05 | 0.01 | 0.05 | 0.01 | 0.05 | 0.01 | 0.05 | 0.01 |
| Hypothesis | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Significance | 3,1956e-006 | 3,1956e-006 | 9,5506e-005 | 9,5506e-005 | 0,0033927 | 0,0033927 | 3,7983e-008 | 3,7983e-008 | 0,00095439 | 0,00095439 |
| Confidence interval | 132,75 | 104,38 | 436,16 | 302,01 | 158,37 | 58,569 | 464,24 | 390,99 | 328,6 | 180,46 |
| | 306,33 | 334,71 | 1263,3 | 1397,4 | 772,36 | 872,16 | 913,09 | 986,35 | 1240,3 | 1388,5 |

| experimentee | 180006 | | 180007 | | 180008 | | 180009 | |
|---|---|---|---|---|---|---|---|---|
| Sloha | 0.05 | 0.01 | 0.05 | 0.01 | 0.05 | 0.01 | 0.05 | 0.01 |
| Hypothesis | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 0 |
| Significance | 0,11476 | 0,11476 | 0,0016219 | 0,0016219 | 0,00058427 | 0,00058427 | 0,03385 | 0,03385 |
| Confidence interval | -66,1 | -174,19 | 293,34 | 143,83 | 197,23 | 116,81 | 12,126 | -34,514 |
| | 600,81 | 708,91 | 1211,6 | 1361,1 | 691,12 | 771,53 | 296,65 | 343,29 |

Tab. 7-5: RT appears to be significantly different for drowsy vs. fresh drivers

### *HRR comparison*

If we take more detailed view of its evolution, it is possible to see evident differences in the look of sections where the self-rating is good and where it is bad. If the state is ”more drowsy” we can observe much more steep and bigger ascent than during state reported within “less drowsy” values. The next two graphs show such a comparison (Fig. 7-13).

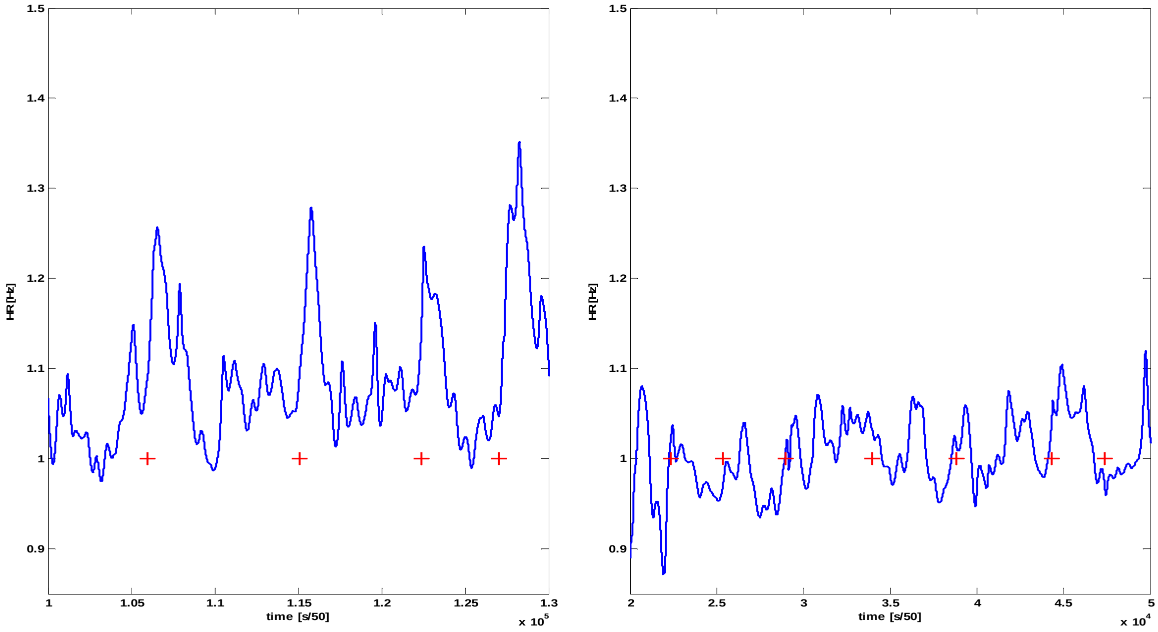


Fig. 7-13: The difference of HRR: Left - very drowsy driver, Right - reference (fresh). The red crosses indicate the time of stimuli appearances.

### *LV comparison*

In this computation we wanted to prove that the ability of a smooth and correct driving in drowsy state is worse than in fresh state, i.e. drivers cannot keep the ideal path and weave. We investigated the difference in variance of absolute distance form geometrically ideal curve in the middle of the lane. From the following table (Tab. 7-6) it is possible to see that all the probands show significant rise of variance when driving drowsy. Even more, 7 from 9 have this difference in order of magnitude. The mean value does not give any evident result, but it was expected.

| experimentee | 180001 | | 180002 | | 180003 | | 180004 | | 180005 | |
|---|---|---|---|---|---|---|---|---|---|---|
| Experiment part | Drowsy | Fresh | Drowsy | Fresh | Drowsy | Fresh | Drowsy | Fresh | Drowsy | Fresh |
| Mean of LV | 0,42699 | 0,2145 | 0,075899 | 0,28103 | -0,13634 | -0,076315 | 0,36381 | 0,26481 | 0,31383 | 0,25641 |
| Variance of LV | 0,22854 | 0,17962 | 6,187 | 0,08549 | 0,17493 | 0,092522 | 4,3202 | 0,088299 | 1,8323 | 0,10973 |

| experimentee | 180006 | | 180007 | | 180008 | | 180009 | |
|---|---|---|---|---|---|---|---|---|
| Experiment part | Drowsy | Fresh | Drowsy | Fresh | Drowsy | Fresh | Drowsy | Fresh |
| Mean of LV | 0,23247 | 0,15039 | 0,077151 | 0,12072 | 0,42699 | 0,39014 | -0,014709 | 0,10983 |
| Variance of LV | 1,4504 | 0,11037 | 2,339 | 0,095493 | 0,22854 | 0,1489 | 0,21363 | 0,14082 |

Tab. 7-6: Comparison of "weaving" in drowsy and fresh parts of experiment

### *EEG comparison*

We tried to investigate the differences in *alpha, theta and alpha/delta EEG signal ratio* between “drowsy” and “fresh” driving. The first results which we received were however quite uncertain.

One of the reasons could be that many of samples of our disposable signals were discarded due to the artifacts in EEG signal and it did not give enough representatives for good statistical analysis.

The used method of picking of the samples of EEG signals in time just before the stimulus appearance perhaps suffers from significant aliasing.

The following tables (Table 7-7) show significant difference between “fresh” and ”drowsy” driving classification reached on Cz and O1 electrode. For statistical evaluation again a *T-test* was used.

We can see that 4 exhibits increase in all variables, 3 exhibits a decrease in alpha and theta and majority of probands no significant difference was proven. Only 7 of 9 probands could be used for the analysis because the EEG of the other two was however distorted too much.

| Cz | 180001 | 180003 | 180004 | 180006 | 180007 | 180008 | 180009 |
|---|---|---|---|---|---|---|---|
| $\theta$ | - | + | x | x | + | + | x |
| $\alpha$ | - | + | x | x | x | + | x |
| $\alpha/\delta$ | x | + | x | x | x | + | x |

| O1 | 180001 | 180003 | 180004 | 180006 | 180007 | 180008 | 180009 |
|---|---|---|---|---|---|---|---|
| $\theta$ | - | + | x | - | x | + | x |
| $\alpha$ | - | + | x | - | x | + | x |
| $\alpha/\delta$ | x | + | x | x | x | + | x |

Tab. 7-7: Significant increase (+), decrease (-) and no significant difference (x) on the electrode Cz (upper)

### 7.3.9 Observations about micro-sleeps

Almost all the drivers, when forced to drive when they are drowsy try to focus their attention on the most necessary tasks.

Unfortunately, they are not usually capable of putting the attention on multiple targets at once.

The drowsy driver can, for example, keep driving in his dedicated lane but he/she in the same time loses the control over the speed (which he is instructed to keep) or cannot correctly react to sudden event. From the observation (with respect to our simple experiment setup) we deduced measures of such low vigilance states:

- *If the driver reacts to the red signal and lately or not at all.*
- *If the driver crosses the lane border and does not do a correction immediately*
- *If the car suddenly increases or drops its speed without any clear reason*

### 7.3.10 General observation concerning the chapter 7.3

Although we did more than a hundred measurements with drowsy drivers performed on the driving simulator, only the last set of our measurements can be used for the analysis which was introduced in this chapter. The methodology of the experiment has been maturating for a long time and not all of previously performed experiments can be used now in all studied factors. Our final approach to classification of the actual driver's state (*vigilance*) should be based on the brain waves analysis and all secondary should serve mainly to support finding cogent pattern of degraded vigilance. We plan to use all the earlier measurements mainly to approve and adjust the algorithms of EEG classification correlated with video recording.

We described our approach to the measurement of several traditional markers of driver's *vigilance* level (as is response time, EEG, heart beat rate…) and one which seems to be innovative in described sense (HRR on sudden stimuli).

We confirmed the RT in our experiments to be an objective measure which can be correlated with other ones. We tried to find significant differences between drowsy driving (of unknown level of fatigue) and fresh driving. It was successfully done in lane keeping distortion and self rating (in the beginning periods). The most direct method of fatigue detection should be EEG analysis but we should apply much more sophisticated methods than simple frequency analysis (e.g. [SVOP05]).

## 7.4 Experiments focused on assessments of driver drowsiness – long time analysis without disturbance

Comparing to another type of drowsiness experiment, which was aimed to obtain driver's reaction times testifying of driver's vigilance level [BOUP06/1] which was conducted on our 'light' simulator, here we preferred giving the driver most realistic feelings from the car interior (this include also sound damping properties of the car cabin) and no distortion during the simulated driving.

### 7.4.1. Data collection

During all the measurements of the experiment the technical and psycho-physiological data were being collected [BOUP04/1]. All the data needed to be synchronized in a sufficient manner so that it could be possible to do a correlation analysis over them. The synchronization is realized via central logging application which gathers all the time long trigging signals from all the measurement devices including the simulator all connected with RS232 links. This appears to be sufficiently precise [BOUP04/1].

The following data were used for further analysis:

- Technical data:
    - Trajectory and geometrically ideal path
    - Speed in sense of car heading
    - Steering wheel absolute angular position
    - Video record and its expert analysis

- Biological data:
    - EEG
    - EOG
    - Heart beats
- Questionnaires

The next picture (Fig. 6-14) shows the tested driver equipped with the EEG cap, EOG electrodes and heart beat recording.

Fig. 7-14: The tested driver equipped with heart beat recording, EOG electrodes and the EEG cap

The measurement devices were developed by Alien technologies, Ltd. [ALI]. EEG signals were managed in standard 10/20 setup, heart beat electrodes were placed on both driver's wrists. The biological outputs were recorded with sampling rate of 128 or 256 Hz. The record from simulator is 100 Hz but for analysis it was reduced.

### 7.4.2 Testing cohort for this set of measurements

The experiment was done in two stages. First one – the preliminary testing – used mainly for necessary methodology design. There were 39 person tested. The testing cohort consisted of drivers in between 20 and 39 years of mixed sex (82 % males). The average age is 23.3 years and the variance is 9.3 years. They are the common passenger car drivers with average driving experience but not professional drivers. They had to have normal EEG record and no apparent sleep related diseases. (Not all the drivers could be involved into EEG analysis because of artifacts appearing in their record.)

All the probands have to pass preliminary tests. Except for adaptation laps on the simulator they had to pass anamnesis questioners and standard neurological test (equipped with EEG cap). Requirements on testing drivers can be summarized as follows:

1. *The probands were after at least 24 hour sleep deprivation*
2. *Experiment was realized in the morning hours starting at 9 or 10 o'clock*
3. *They did not have consumed any drugs (alcohol, medicines…), coffee of other exciting agents.*
4. *The length of the drive varies between 2 and 2.5 hours, depending on development of his/her condition.*
5. *Before and after the testing drive the probands passed standard neurological tests including 3 types of mental load. Those serve mainly to recognize if the probands brain is of "standard type" and to discover possible illnesses.*
6. *Before measurement they are asked to fill up detailed questionnaire concerning  their sleep habits*
7. *Before and after the measurement they are asked to fill up testifying about their actual state*

### 7.4.3 Testing track

One of the most important factors which influences the usability of data obtained from experiments performed on a driving simulator is a design of testing tracks [BOUP04/1, BOUP05/4]. Our approach follows standard setup of boring highway scenario with minimum or no interactive traffic. Such a setup should assure that all possible outer factors influencing the driver performance are diminished and all the driver's errors can be consequently considered to be caused by his/her inattention. This inattentiveness could be of several different origins but in the case of our experiment it's assumed that it is caused predominantly by drowsiness and/or micro-sleep occurrences. The tasks which the driver normally copes with are reduced to ***speed-keeping and lane-keeping.*** From that reason the track consists of mainly almost straight parts and curvy parts which radius is minimally 1500m. Following table describes structural design of the whole testing track (Tab. 7-8) and following picture shows top view on the track (Fig. 7-15).

| Type of part | Length [Km] | [%] | Radius[m] |
|---|---|---|---|
| Straight | 105,0 | 33,8 | 0 |
| Left curve (light) | 38,5 | 12,4 | 6500 |
| Left  curve (easy) | 42,3 | 13,6 | 1500 |
| Right  curve (light) | 66,5 | 21,4 | 6500 |
| Right  curve ( easy) | 58,2 | 18,7 | 1500 |
| Total | 310,5 | 100,0 | x |

Tab. 7-8: Types of part and their lengths

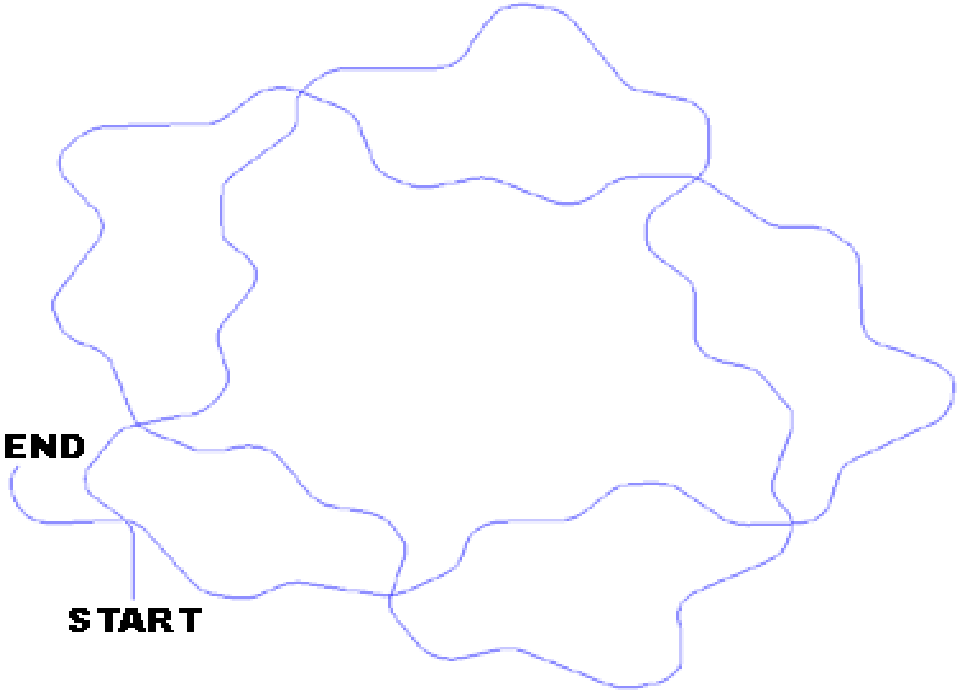


Fig.7-15: Picture of testing track

### 7.4.4 Analysis

The above data were analyzed after an election process, where poor quality data, incomplete data and/or data being unfeasible to be classified using each particular method were excluded. All the probands' EEG records and anamneses were assessed by neurologists. Unlike in other type of experiments in which we put reaction time (measured on brake) as a measure to which other measures were correlated [BOUP06/1], in the experiment being described here, we do not rely on any direct measure of response time.

***Expert video analysis of drivers and behavior***

The offline expert analysis of a driver's face and hands video record had seemed very promising to us (see Fig. 7-16 till Fig. 7-18 e.g.). Unfortunately, such an evaluation is very subjective either from the side of an expert or from the side of a subject. Because of this fact the expert evaluation serves mainly for finding specific patterns, which are further used in the EEG analysis. From the experience we decided to watch three significant patterns:

a) man

b) girl

Fig. 7-16a,b: Pictures of probands, who are indisputably yet fresh (in high vigilance level - usually at the beginning of an experiment)

Fig 7-17: Picture of proband, who is going to be drowsy . The proband has still at least partially open his eyes

Fig.7-18: A “nod” off – when the driver gets into very short sleep and he/she is immediately woken up - usually drop of his/her head.

Fig. 7-19:: Sleeping proband, who has close eyes (right picture). Going out of the road due to the long microsleep, proband has closed eyes (left picture)

Fig. 7-20: Serious lost of control. This state comes when the driver is so drowsy that he/she is unable to fight against upcoming sleep. Such a situation often ends by an accident

### *Unintentional lane changes accidents*

We performed several tens of measurements. Every record from simulation engine contains actual car position in each simulation step. We computed instantaneous differences from geometrically ideal path (reference curve) and found the regions where the driver unintentionally deviated from his lane into contra lane or shoulders. Those events were then correlated with video record (facial expression). The parts where the drivers deviated intentionally were rejected from further analysis.

### *EEG activity*

Similarly as in the experiment mentioned in chapter 7.3 we tried to look for differences in alpha, theta and alpha/delta ratio between “drowsy” and “fresh driving”. The results were again uncertain probably became of the same reasons.

For statistical evaluation a T-test was used again. The following tables (Tab. 7-9) shows same examples of finding, in some cases there is a significant of difference between “fresh” and ”drowsy” driving on O1, O2, T5 and T6 electrode (10/20 system). It is possible to conclude preliminarily, that some of drivers show increasing power of alpha bands which is accompanied by decrement of ration alpha/delta band. Unfortunately there is no statistically approvable difference which is static over the whole measurement. Note that sampling of analyzed samples was done for all the micro-sleep occurrences derived either from video record or trajectory analysis. Only those which were affected with artifacts were excluded from analysis.

| O1 | **8011** | **8056** | **8106** | **8403** |
|---|---|---|---|---|
| $\theta$ | x | x | x | + |
| $\alpha$ | x | + | x | + |
| $\alpha/\delta$ | - | x | x | x |

| O2 | **8011** | **8056** | **8106** | **8403** |
|---|---|---|---|---|
| $\theta$ | x | x | x | + |
| $\alpha$ | x | + | x | + |
| $\alpha/\delta$ | - | x | x | x |

| T5 | **8011** | **8056** | **8106** | **8403** |
|---|---|---|---|---|
| $\theta$ | x | x | x | + |
| $\alpha$ | x | x | x | + |
| $\alpha/\delta$ | x | x | x | x |

| T6 | **8011** | **8056** | **8106** | **8403** |
|---|---|---|---|---|
| $\theta$ | x | x | x | x |
| $\alpha$ | x | x | x | + |
| $\alpha/\delta$ | - | x | x | x |

Tab. 7-9: Significant increase (+), decrease (-) and no significant difference (x) on electrode O1, O2, T5, T6, columns mark proband evidence number

### 7.4.5 Trends of certain variables over the whole experiment

Because of the fact that the driver was not distracted by any stimuli, it is possible to classify trends in his/her behavior.

The measurement of each one member of the proband crew was pretty long. It took about 2 to 3 hours per proband. In real life, when the necessity of driving for a considerably long time (3 and more hours) occurs, it is recommended to make a break, off course in normal state of vigilance (i.e. without any attention deprivation). From that point it is possible to consider this experiment as leaving the proband in the same conditions as the maximum recommended driving period in reality.

***Average speed trends***

As one of the measures which could testify the time development of driver's actual vigilance level and consequently about his/her ability of safe driving we can consider the proband ability to keep the required car speed. For such experiment, the probands were instructed to keep the speed of 130km/h with some reasonable tolerance. Moreover, they are periodically (approximately each 700m of the road length) evoked by standard traffic sign of speed limitation on 130km/h. In such a way, over the whole testing track there were displaced approximately 450 of such traffic signs.

Unlike the real-life situation the probands had no reason to deviate intently form predefined speed. More over, we excluded any situation requiring speed changes from the used simulation scenario (no other traffic, no obstructions, no sharper curves, just all the time  the "free to drive" highway scenario and consequently no objective reason for speed fluctuation except of driver's inattention).

Even this, in all the tested probands driving records the slight fluctuation of the speed appeared as a general trend.

In the results obtained after deeper analysis, we can distinguish 4 groups of drivers behavior:

- Continuous increase (Fig. 7-21)
- Steady behavior or decrease (Fig.7-22)
- Driver cannot keep the speed in 'reasonable' limit / goes much faster than required (Fig. 7-33)
- Experiment was interrupted – excluded from analysis (Fig. 7-24).

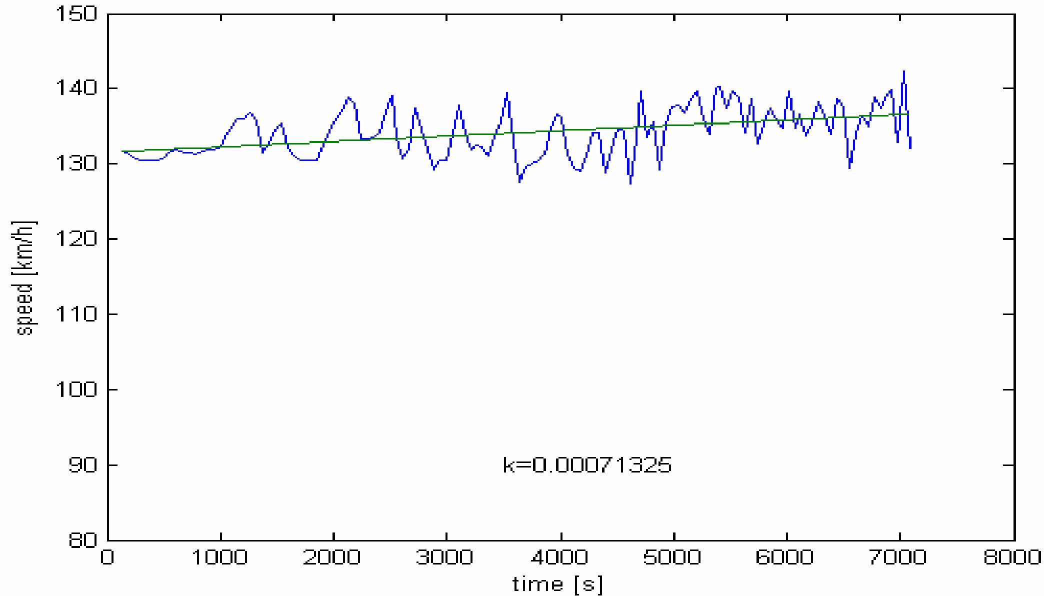


Fig. 7-21: Continuous increase of average speed of proband driving with almost constant (after starting time interval of about 1000 s) amplitude of speed variations

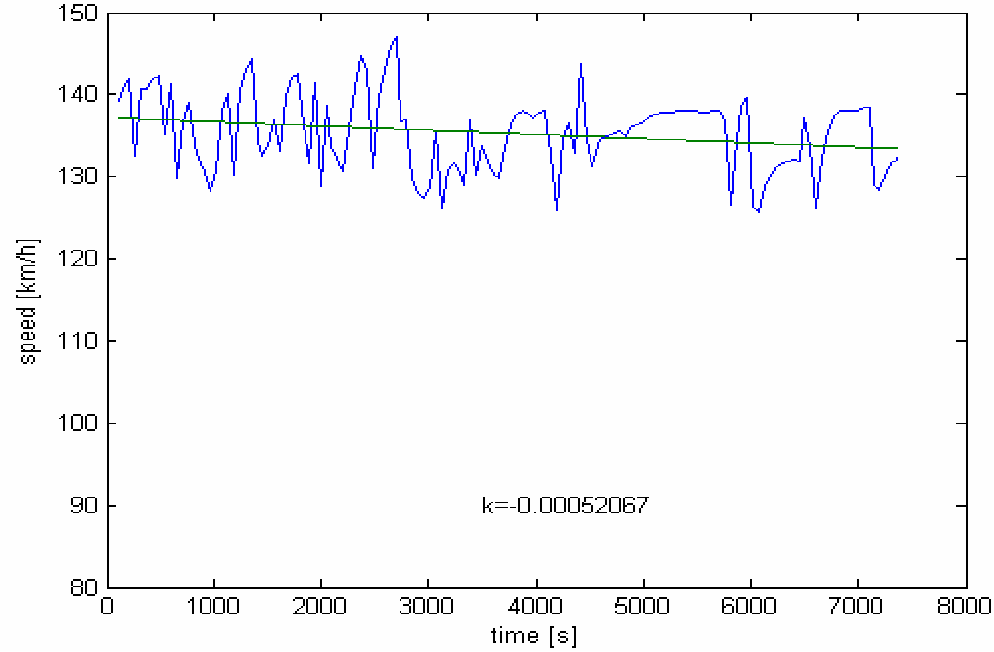


Fig. 7-22: Continuous decrease of average speed of proband driving with almost constant amplitude of speed variation

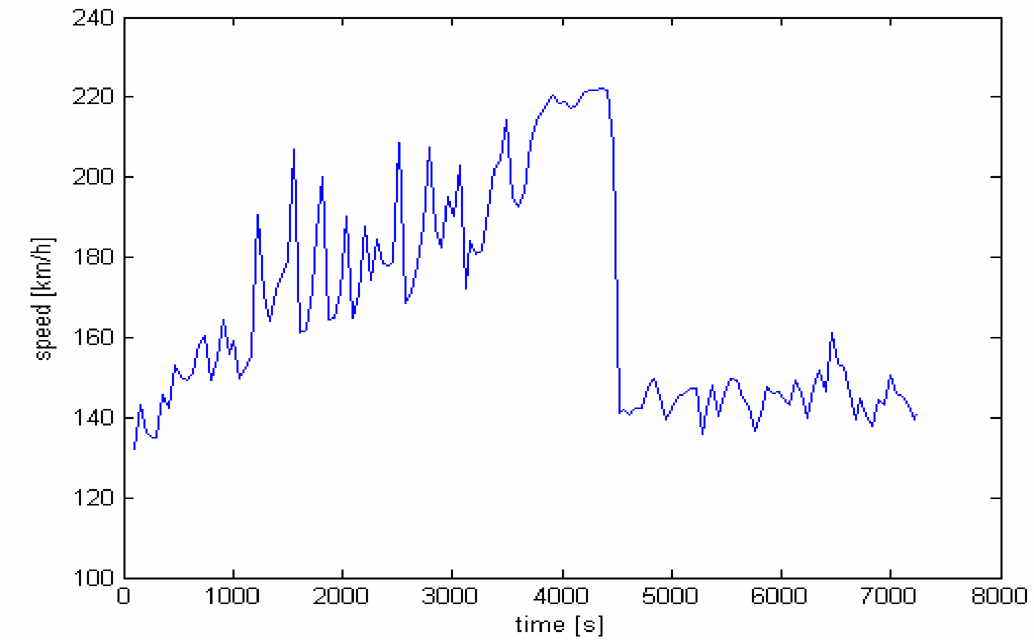


Fig. 7-23: Un-ability of following the required speed value

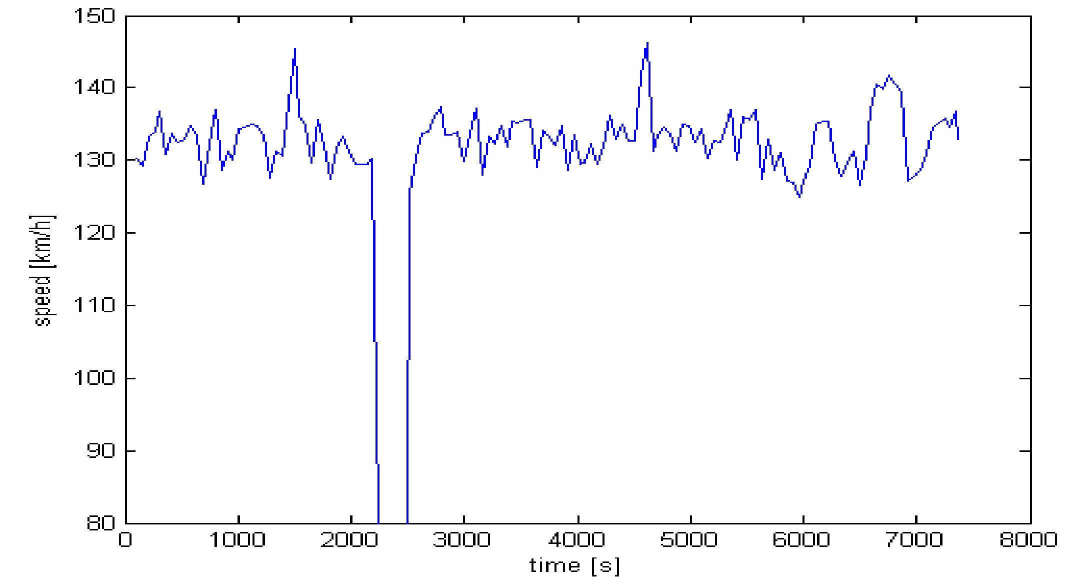


Fig. 7-24: Experiment was interrupted – excluded from statistical analysis

The following table (Tab. 7-10) proves that there is a general increasing trend in average speed for majority of tested probands. The particular experiments, which had been interrupted during the measurement (due to any reasons) were excluded from final evaluation.

| Continuous increase | Steady behavior or decrease | Driver cannot keep the speed in 'reasonable' boarder / goes much faster than required |
|---|---|---|
| 60,87% | 17,39% | 21,74% |

Tab. 7-10: Percent occurrence of particular groups

### *Steering wheel correction movements*

The number of correction movements done by driver on the steering wheel was counted with respect to time. The following graphs (Fig. 7-25) shows a percentage of the fast corrections (bigger than modus of all corrections) related to all instant corrections. From a linear regression analysis it is possible to derive that *81,48% of tested probands showed the increasing trend in this measure meanwhile only few probands (18,52%) showed the decreasing trend*.

This corresponds to the hypothesis that the correction movements are more apparent and faster when driver drowsiness appears (expected to be getting worse during experiment) [VYSP04].

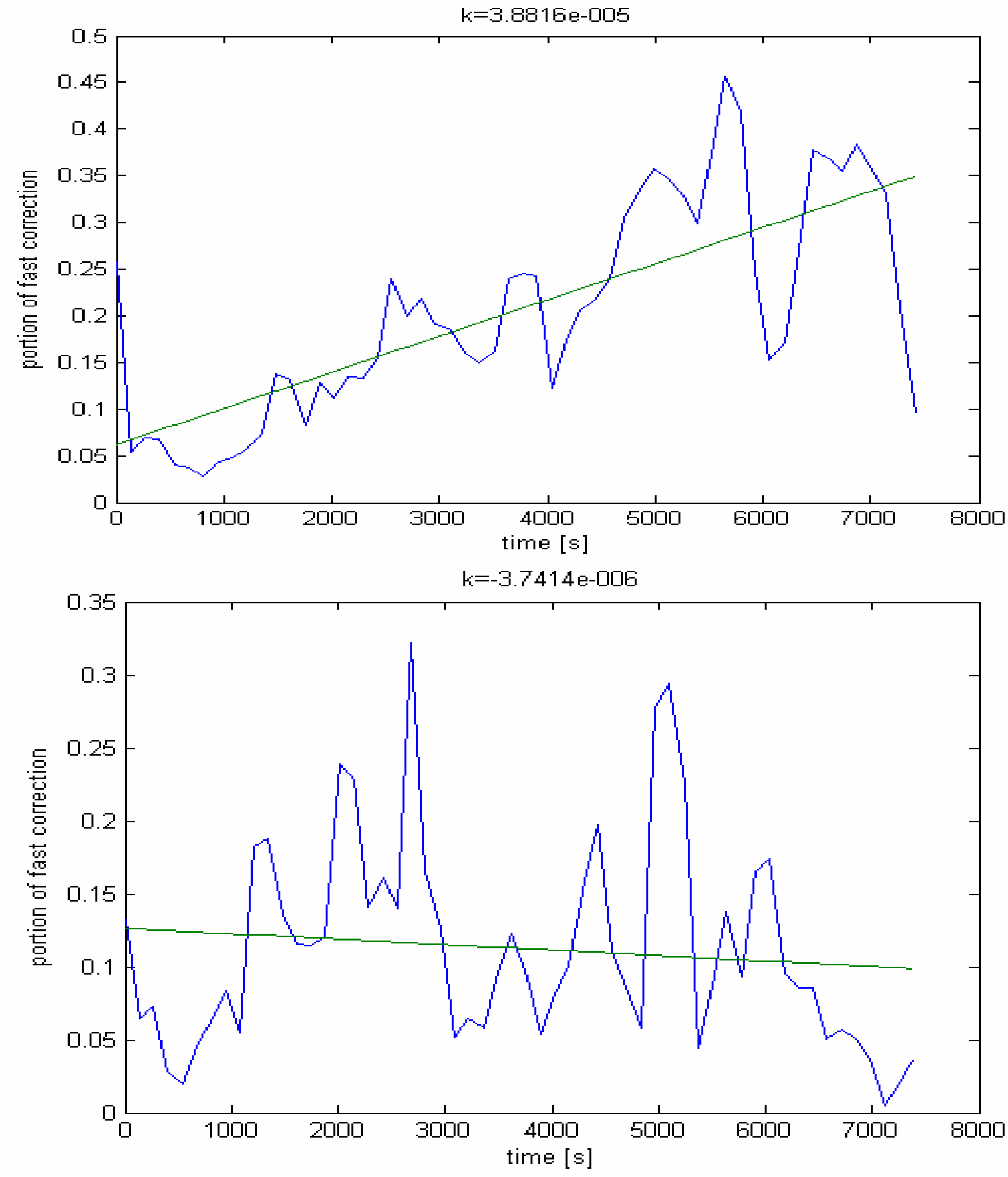


Fig. 7-25: Examples of the ratio of fast and slow steering corrections (increasing –up) and non-increasing - bottom) trend during the whole measurement

### ***The trajectory to lane center position***

In the research of driver drowsiness on simulators the trajectory of line-keeping and weaving are frequently analyzed. The lane departure analysis is very useful when finding serious driver's state but not suitable for statistical analysis.

First of all we looked mainly for the overall variance. From the contemporary research it is also possible to say that the movement of a car within the lane borders (originated in steering wheel movements) could become a promising attention level indicator [VYSP04].

It is also possible to conclude from the results of our experiments that the *majority of tested probands showed the increase in "weaving"* around geometrically ideal trajectory, corresponding with increase in their drowsiness. *These values were up to 3 times higher in amplitude comparing with non-drowsy ones*. The very drowsy drivers demonstrate much higher amplitude of necessary steering corrections by the end of measurement than relatively fresh ones at the beginning of measurement.

The following graph (Fig. 7-26) shows an example of such trajectory fluctuations around geometrically ideal path (the so called 'weaving') during the time of whole experiment.

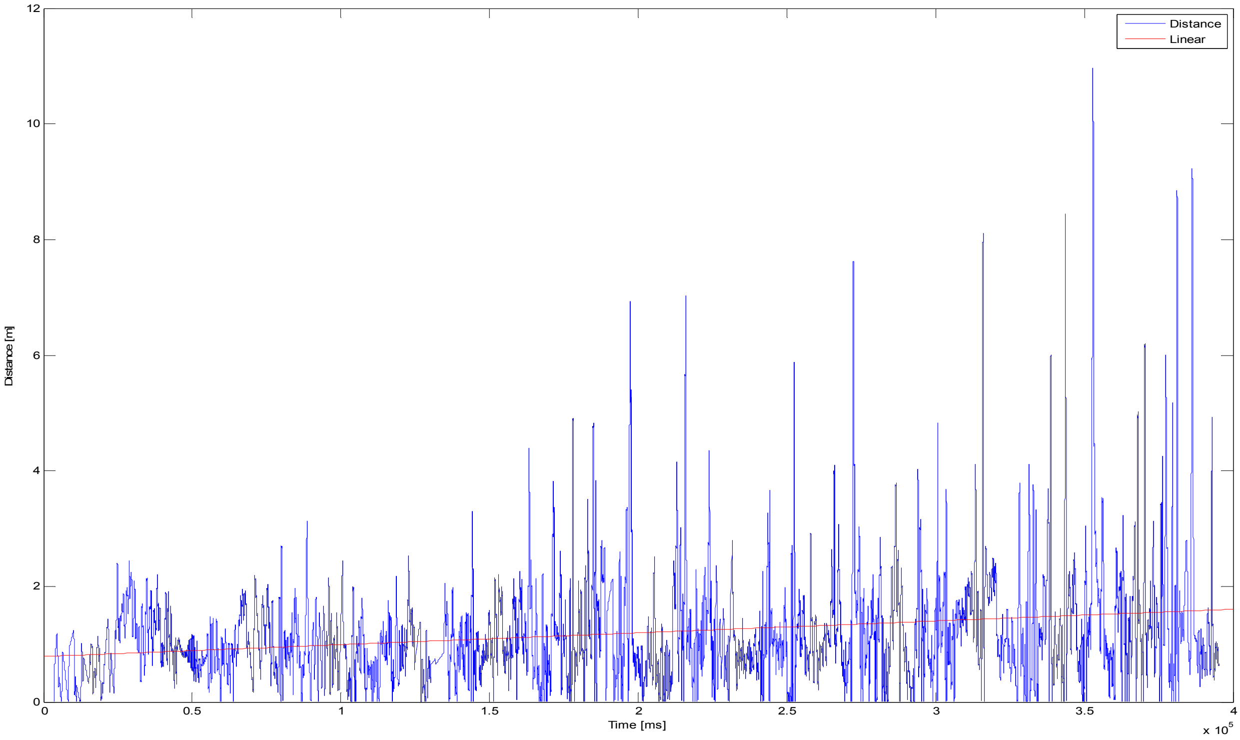


Fig. 7-26: The deviation of a car trajectory from geometrically ideal path during the whole experiment.
Blue curve – instant deflection in absolute value;
Red curve– linear regression.

### 7.4.6 Discussion and conclusion

As the result of the above discussed experiments one can formulate the following observations that are almost general.

The expert analysis of face video record gives us an very good and objective results. Unfortunately people behave very differently and have generally diverse behavioral patterns from one to another, especially when drowsy. Even more these aspects are different in the time for the same people.

Also the other values, which averagely change with time spent with driving ('trends'), such as we can see for example in average car speed, can also give us interesting results as long as we know that they are not influenced by some outer factors. Of course, this can be at least partially ensured in laboratory simulators, but it is hard to be applied in real cars on road.

The EEG shows different features in assessment of drowsiness levels when experiments are done without a mental load and when performed on driving simulator. However, it proves much faster dynamics in this case. This leads to notion that the simple criteria based on replacements of basic EEG rhythms applied from neurology are hardly applicable here and much sophisticated criteria need to be found.

Concerning the testing the virtual track, the proposed experiment design almost generally meets the needs quite well.

One problem is coupled with long and totally streight track parts, where the simulated car can drive correctly without any driver's effort. This serves well for experiments with traffic light stimuli [BOUP06/1] but in such case we can hardly detect the level of driver inattention. Therefore for further measurements those long straight stages are not suitable, until the road model could provide dynamics of real car driving.

## *7.5 Experiments focused on HMI devices (IVIS)*

In this paragraph the results of the research made on interactions between the driver and the In-Vehicle Information Systems (IVIS) are presented. Besides an influence of the attention decreases on the course of driving still increasing driver fatigue, these influences play also a very important role. These are mainly the interaction with:

- Navigation systems
- Mobile phones
- Car radio sets
- Controlling of assistance and comfort systems

### 7.5.1 Testing track

One of the most important factors which influences the usability of data obtained from experiments performed on a driving simulator is a design of testing tracks.

The testing track is divided into two parts; easy and demanding one.

The driver should keep the speed 90 km/h for easy track and 50km/h for demanding one. From the point of driver the easy track seems to be almost straight. The radii of curve for such easy part were chosen about 2000m and for demanding track it was decreased up to 300m.

The next figure (Fig 7-27 and 7-28) describes the situation.

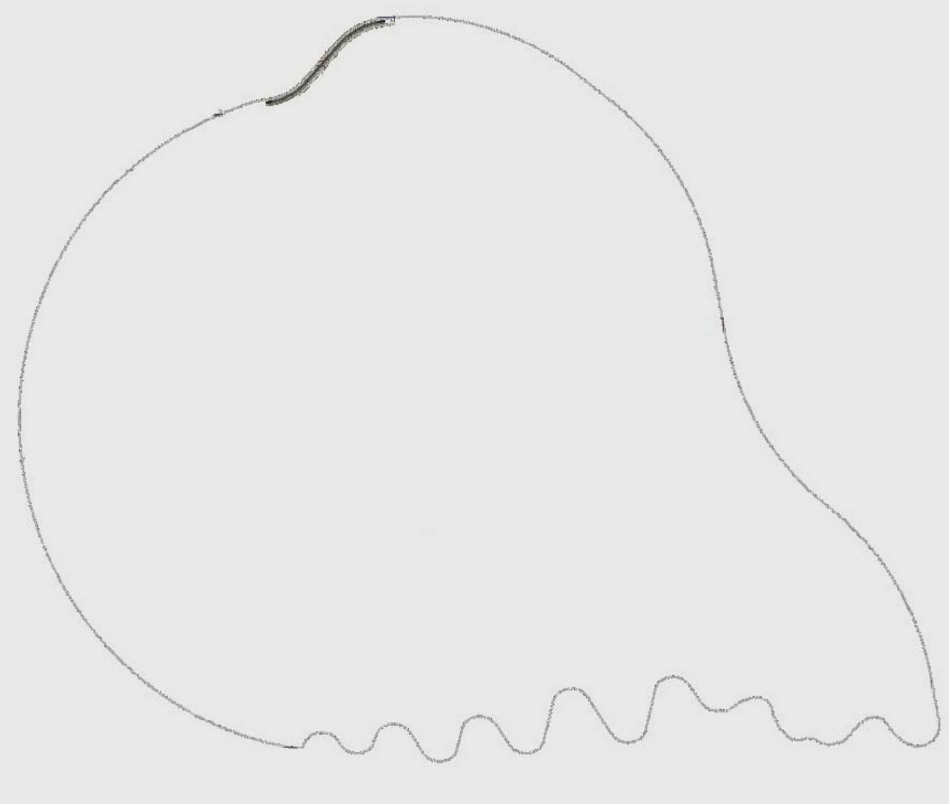


Fig. 7-27: Top view on the testing track.

Fig. 7-28: The screenshot from a virtual scene

### 7.5.2 The tested devices[2]

The navigation systems are one of the most used IVIS devices in contemporary cars. The majority of mid- and high-class cars contain those devices in the standard package.

The use of the navigation systems(and any other IVIS systems as well) consists of two activities; entering the information and obtaining the information. From the point of view of navigation systems obtaining of information is usually either

- the watching the map or
- listening to the audio guidance.

These activities can of course distract the driver from primary driving tasks especially if a screen is placed improperly (out of driver's common field of view) or the voice instructions are too fast, improperly timed or ambiguous. On the other hand it usually does not require too much effort from the side of the driver himself. Entering the information (in a case of navigation systems input of targets) makes incomparable higher load on driver if doing it while driving. Sometimes it requires so

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[2] From the reason of commercial nature of the research, only a rough description can be sketched

much time demands that the driver can completely lose a track about a situation on the road.

The aim of our investigation was to detect (and compare if possible) the influence of such devices on comfort and safety of driving. Following table shows basic features of particular setups (Tab. 7-11).

| **Device** | **Input placement** | **Input type** | **Screen placement** | **Voice feedback** |
|---|---|---|---|---|
| 05 – Common system | next to screen | Knob – roll | Right-Middle | No |
| 06 – Alternative system | middle tunnel | Knob – roll | Right-Low | Yes |
| 08 – Alternative system | on screen | Virtual keyboard | Right-High | No |
| 09 – Alternative system | middle tunnel | Knob – roll | Right-Low | No |
| 12 – Alternative system | on screen | Virtual keyboard | Right-High | Yes |
| 13 – Common system | next to screen | Knob – roll | Right-Middle | Yes |
| 14 – Alternative system | by the hand | Roller | Right-Middle | No |
| 15 – Alternative system | by the hand | Roller | Right-Middle | Yes |

Tab. 7-11: Description of testing devices

### 7.5.3 The procedure

The main task which the testing drivers had to complete was to insert the name of the target city into navigation system.

Of course, they were also asked to drive safely and to respect all the traffic rules.

From this point of view their task consisted of three mean subtasks:

- Keeping appropriate position within their lane
- Keeping the speed defined by traffic signs
- Inserting of given target city name into the navigation system correctly and as fast as possible

The relevant experiments were made under the following procedure:

- Training of proband drivers in the simulator use, so that they feel to be experienced enough with simulated driving

- Familiarization with particular car assistance device, trial of inputting the targets city names (different from those which were later on used for the measurement)
- Filling out of questionnaires asking the probands about their psycho-physiological conditions and skills
- Neurological examination (if the EEG signals were measured)
- Performing of the reference drives, where the probands were asked to drive as well as possible, without any disturbance
- Using the tested assistance device while staying (input names of target cities into the navigation system on demand)
- Using the tested assistance device while driving (input of target city names into the navigation system on demand)
- Reference drives, where the probands had to drive as well as possible, without any disturbance
- Filling out of questionnaires for subjective evaluation of each particular device

### 7.5.4 The testing cohort

We performed 9 different experiments with 9 different assistance devices (or different setups), even with 24 probands participating in each experiment. It was required that in each measurement there should be 30% of older people and 30% of women. All of them were non-professional but skilled and active drivers, all of them had to be healthy and fresh during the experiment. The next table (Tab. 7-12) shows the statistics of tested probands for all such measurements. The highlighted columns represent the experiments on which the *ideal path deviation* analysis was applied.

| The | **Series 05** | **Series 13** | **Series 09** | **Series 06** | **Series 08** | **Series 12** | **Series 14** | **Series 15** |
|---|---|---|---|---|---|---|---|---|
| **Average age** | *37.4* | *38.0* | *36.1* | *36.8* | *34.0* | *38.2* | *35.7* | *35.8* |
| **MAX age** | *66* | *75* | *66* | *65* | *68* | *75* | *66* | *72* |
| **MIN age** | *21* | *21* | *21* | *21* | *21* | *24* | *20* | *19* |
| **Number** | *25* | *24* | *24* | *24* | *24* | *24* | *24* | *24* |
| **Female** | *7* | *7* | *7* | *7* | *7* | *9* | *8* | *7* |
| **Male** | *18* | *17* | *17* | *17* | *17* | *15* | *16* | *17* |

Tab. 7-12: Statistics of drivers in each experiment

### 7.5.5 The measured data

During the measurements the technical and psycho-physiological data were being collected (see Tab. 7-13). All the data needs to be synchronized in a sufficient manner so that it is possible to make the correlation analysis over them.

| **Technical data** | **Biological data** | **Subjective** |
|---|---|---|
| Trajectory and geometrically ideal path | EEG | Questionnaires |
| Speed in sense of car heading | EOG | TLX |
| Steering wheel absolute angular position | ECG | |
| Video recording | | |

Tab. 7-13: The data measured during experiments

### 7.5.6 Analysis

Although the complex sets of outputs were measured, the analysis was focused mainly on the technical outputs. This was mainly because of the fact that these data can be more objective and their analysis is much more straightforward.

The analysis was done in two ways:

- Comparison of parts of the measurement where the driver was loaded with secondary task and the “reference” parts (only driving). It was expected, that the there would be a significant difference in behavior between these two states.
- The simple subjective evaluation analysis was also done, so that there would be a subjective reference.

***Ideal path***

A rate of deviation from the geometrically ideal path was chosen as the most important measure in this respect. In fact it is possible to say:

*The greater driving deviations the more dangerous situation in a real traffic.*

As concerns the computation of the deviations from the reference curve one follows the later mentioned procedure:

- Computation of an actual deviation which is measured as a distance of the rigid point (we chose a middle point in between front wheels) from the correct path.

- A virtual road is constructed from polygons which approximate real curvature of the testing track [BOUP06/1].
- A driver controls his/her car depending on expectation of direction, shape and sharpness of the upcoming curve. All those corrections are continuous as the road is expected to be continuous.
- Unfortunately the shape of the virtual road is in fact composed of many straight parts which a drivers brain percepts continuously.
- We used the *spline* interpolation to create the appropriate “ideal path”.

### *The analysis of differences*

In the course of analysis one compares the parts where the driver was forced to fulfill secondary tasks with those parts where he/she was driving without any distraction.

Following graphs (Fig.7-29) show the examples of normalized histograms where the difference between sections with disturbance and without any is easy to be seen. It is apparent that such histograms are significantly flatter and cover bigger range in case of driver attention disturbances.

This observation approves that the respective drive had problems with keeping the straight and proper path.

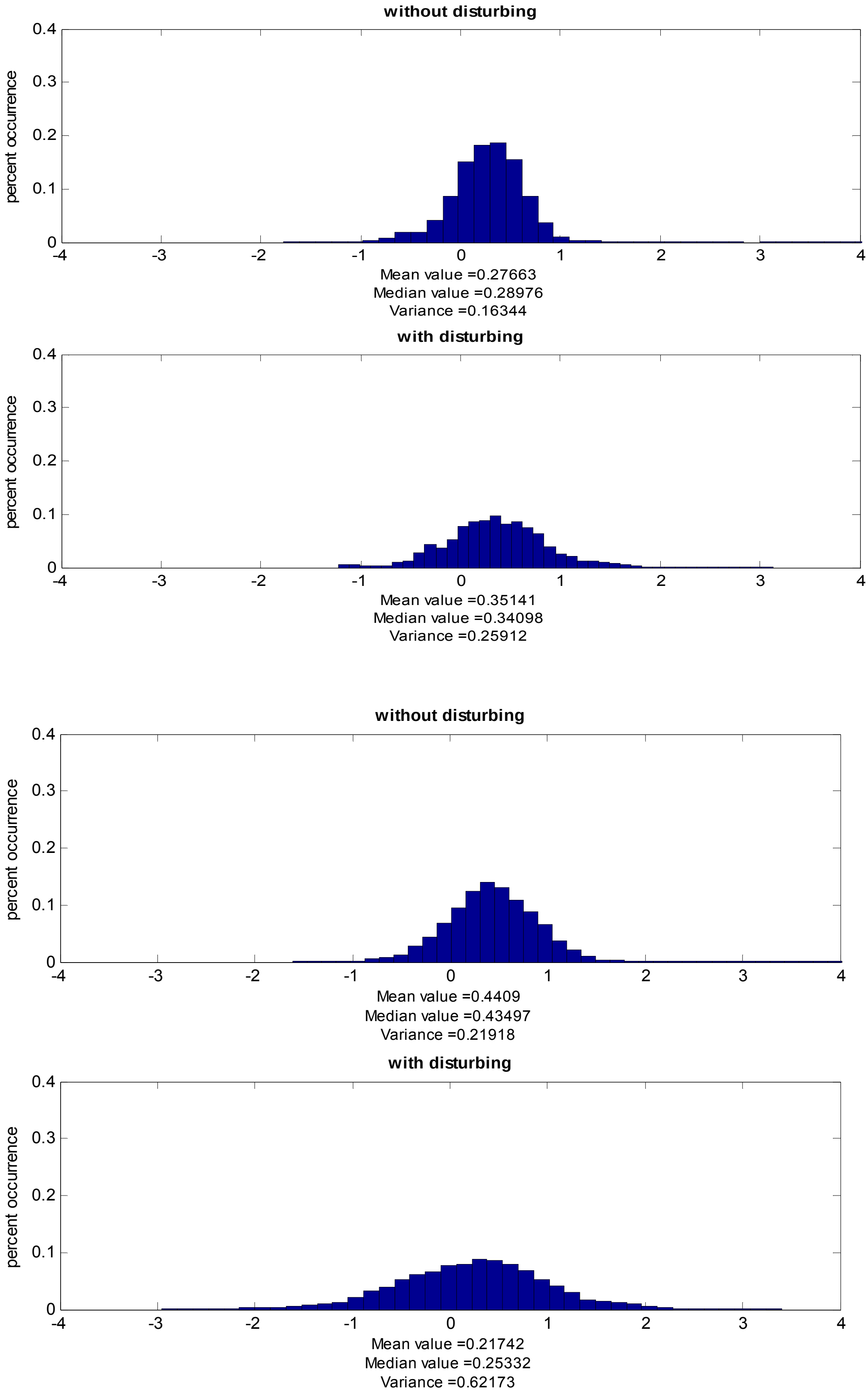
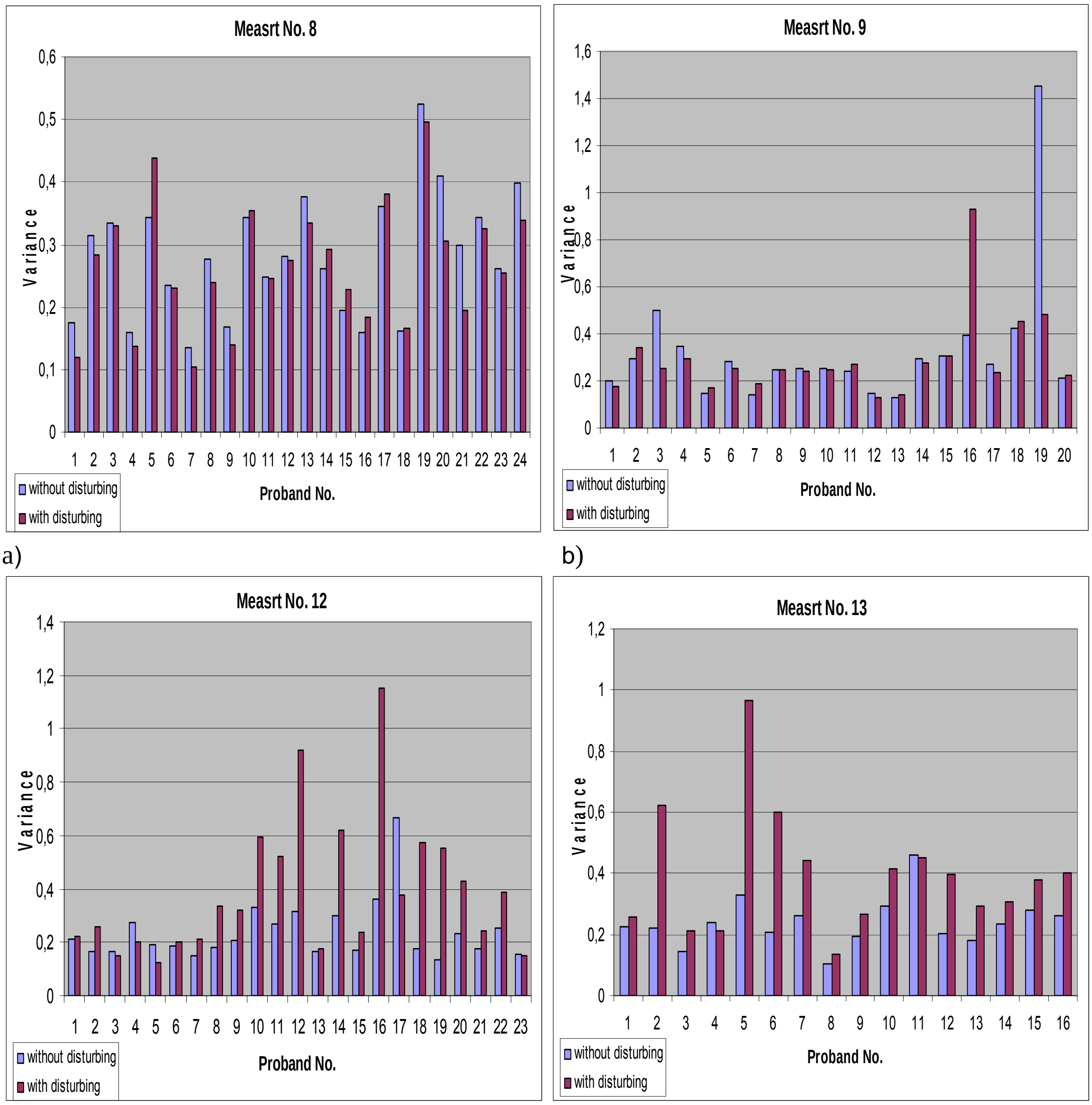


Fig. 7-29: Normalized histograms of path deviations of two different probands (upper: without disturbing, lower: with disturbing**)**

The next set of graphs (Fig. 7-30) shows the measured differences between variances of deviations from ideal path. Two adjacent pairs of bars (each probad) show variance computed in the time when the driver was loaded with the additional task and the time when driving without any load.



a) b)

c) d)

Fig. 7-30: Variances of deviations for 4 different experiments – comparison with/without disturbance

The next table (Tab. 7-14) shows variances of deviations from ideal path with and without load. Fields highlighted gray indicate the pairs of variances when the loaded driver exhibited greater variance when loaded.

| | Measrt No. 8 | | Measrt No. 9 | | Measrt No. 12 | | Measrt No. 13 | | Measrt No. 14 | | Measrt No. 15 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | without disturbing | with disturbing | without disturbing | with disturbing | without disturbing | with disturbing | without disturbing | with disturbing | without disturbing | with disturbing | without disturbing | with disturbing |
| Variance | 0,1759 | 0,12007 | 0,19826 | 0,17846 | 0,2103 | 0,22292 | 0,22632 | 0,25812 | 0,22979 | 0,28558 | 0,14571 | 0,29525 |
| | 0,31469 | 0,28405 | 0,29344 | 0,34063 | 0,16344 | 0,25912 | 0,21918 | 0,62173 | 0,26757 | 0,97003 | 0,16558 | 0,13673 |
| | 0,33437 | 0,33061 | 0,49887 | 0,25283 | 0,16303 | 0,15151 | 0,14558 | 0,21138 | 0,16187 | 0,20554 | 0,11832 | 0,15265 |
| | 0,16021 | 0,13688 | 0,34427 | 0,29689 | 0,2747 | 0,20283 | 0,23827 | 0,21279 | 0,20605 | 0,45215 | 0,18464 | 0,27817 |
| | 0,34344 | 0,43922 | 0,14977 | 0,16889 | 0,18868 | 0,12263 | 0,3299 | 0,9649 | 0,15042 | 0,19768 | 0,21383 | 0,32264 |
| | 0,2353 | 0,22982 | 0,28258 | 0,25317 | 0,18588 | 0,19911 | 0,20839 | 0,5982 | 0,13879 | 0,28593 | 0,15411 | 0,20066 |
| | 0,13481 | 0,10398 | 0,14349 | 0,18543 | 0,14887 | 0,21258 | 0,26147 | 0,44054 | 0,25698 | 0,33375 | 0,28835 | 0,41354 |
| | 0,27692 | 0,23808 | 0,24863 | 0,24851 | 0,18015 | 0,33605 | 0,10463 | 0,1347 | 0,1786 | 0,33536 | 0,26711 | 0,31397 |
| | 0,16746 | 0,14038 | 0,25104 | 0,23976 | 0,20408 | 0,31991 | 0,19571 | 0,26601 | 0,20228 | 0,4927 | 0,34878 | 0,57404 |
| | 0,34358 | 0,35407 | 0,25469 | 0,2494 | 0,32954 | 0,59195 | 0,29167 | 0,41642 | 0,16891 | 0,249 | 0,3538 | 1,0629 |
| | 0,24903 | 0,24612 | 0,23924 | 0,27301 | 0,27029 | 0,5216 | 0,46143 | 0,45039 | 0,21294 | 0,37456 | 0,19573 | 0,23264 |
| | 0,28143 | 0,27399 | 0,14917 | 0,131 | 0,31655 | 0,91998 | 0,20275 | 0,39874 | 0,29585 | 0,34976 | 0,12752 | 0,17529 |
| | 0,37613 | 0,33389 | 0,12846 | 0,14159 | 0,16332 | 0,17617 | 0,17963 | 0,29518 | 0,16898 | 0,20723 | | |
| | 0,26188 | 0,29287 | 0,2966 | 0,27705 | 0,30141 | 0,61962 | 0,23379 | 0,3057 | 0,302 | 0,31544 | | |
| | 0,19541 | 0,2286 | 0,30691 | 0,30825 | 0,16836 | 0,24014 | 0,27824 | 0,3788 | 0,2481 | 0,37962 | | |
| | 0,15874 | 0,18342 | 0,39696 | 0,92907 | 0,35976 | 1,1499 | 0,26351 | 0,40237 | 0,18835 | 0,24786 | | |
| | 0,3608 | 0,38098 | 0,27059 | 0,23497 | 0,66428 | 0,37698 | | | 0,15618 | 0,22586 | | |
| | 0,16163 | 0,16601 | 0,42271 | 0,45312 | 0,17347 | 0,57272 | | | 0,27192 | 0,3787 | | |
| | 0,52502 | 0,49681 | 1,4544 | 0,48337 | 0,13634 | 0,55128 | | | 0,22879 | 0,17546 | | |
| | 0,41033 | 0,30476 | 0,21207 | 0,22059 | 0,23486 | 0,43018 | | | | | | |
| | 0,29896 | 0,19502 | | | 0,17361 | 0,24403 | | | | | | |
| | 0,34249 | 0,32479 | | | 0,25374 | 0,3875 | | | | | | |
| | 0,26056 | 0,2552 | | | 0,15626 | 0,14935 | | | | | | |
| | 0,39948 | 0,33919 | | | | | | | | | | |

Tab. 7-14: Table of resulting variances of deviations for 6 different experiments

### *Speed fluctuation*

Some traffic experts have expected that the natural fluctuations would of the driving speed will be more apparent when the driver is tired. Being not sure of this effect, we decide to verify it. For this analysis a different approach from the “ideal path measure” was used.

The whole experimental tracks where the driver was distracted were compared with the rounds where the driver was free of any additional load. The reason for such an arrangement was that corrections of the speed should appear during loading but also after the task (when the driver again fully concentrates himself on driving). It required additional standardizing rounds to be performed. Because of that fact, much fewer measurements were analyzed using this method.

The following graphs (Fig. 7-31) show the exemplary case of different driver ability to speed keep the constant speed.

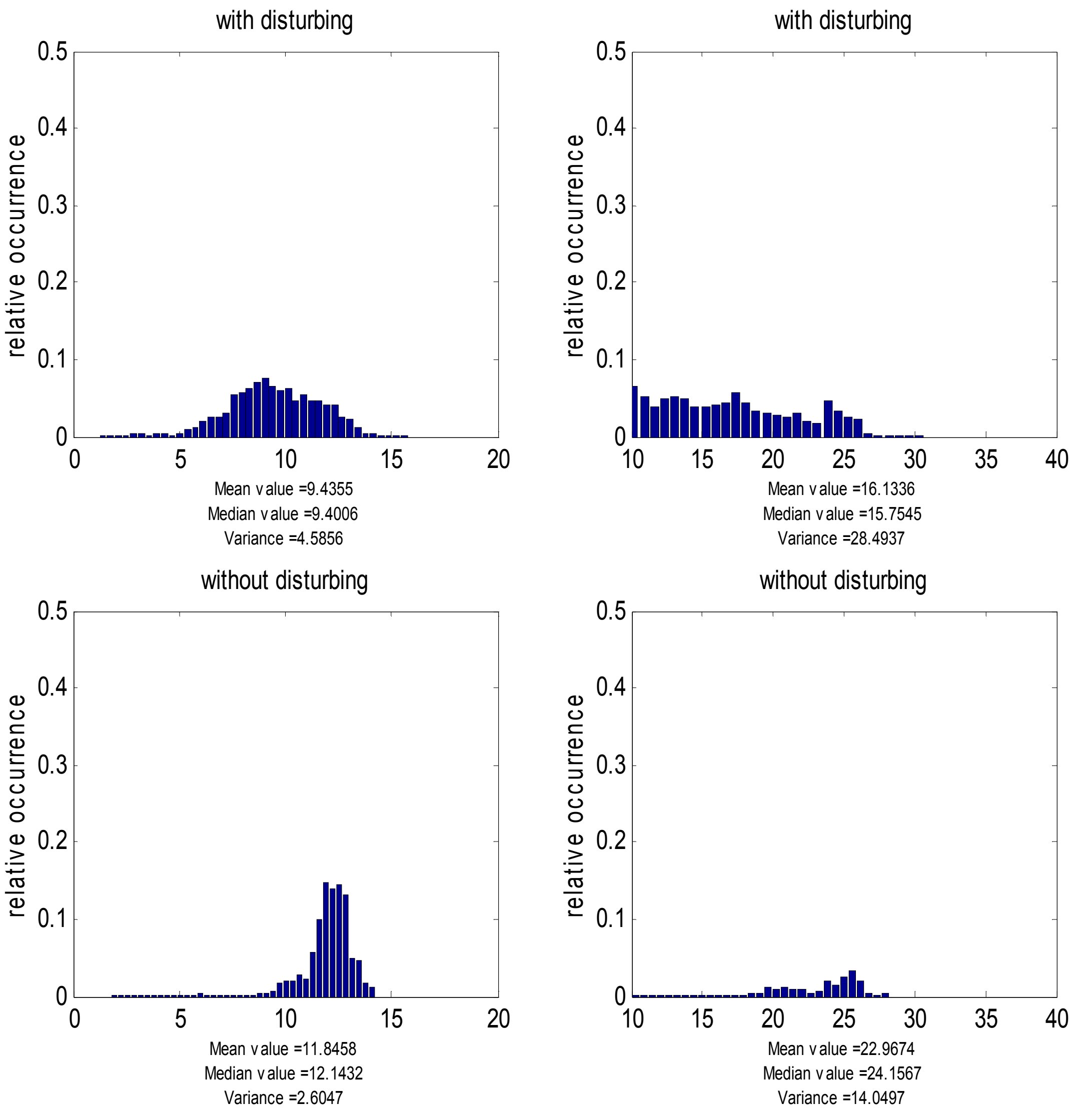
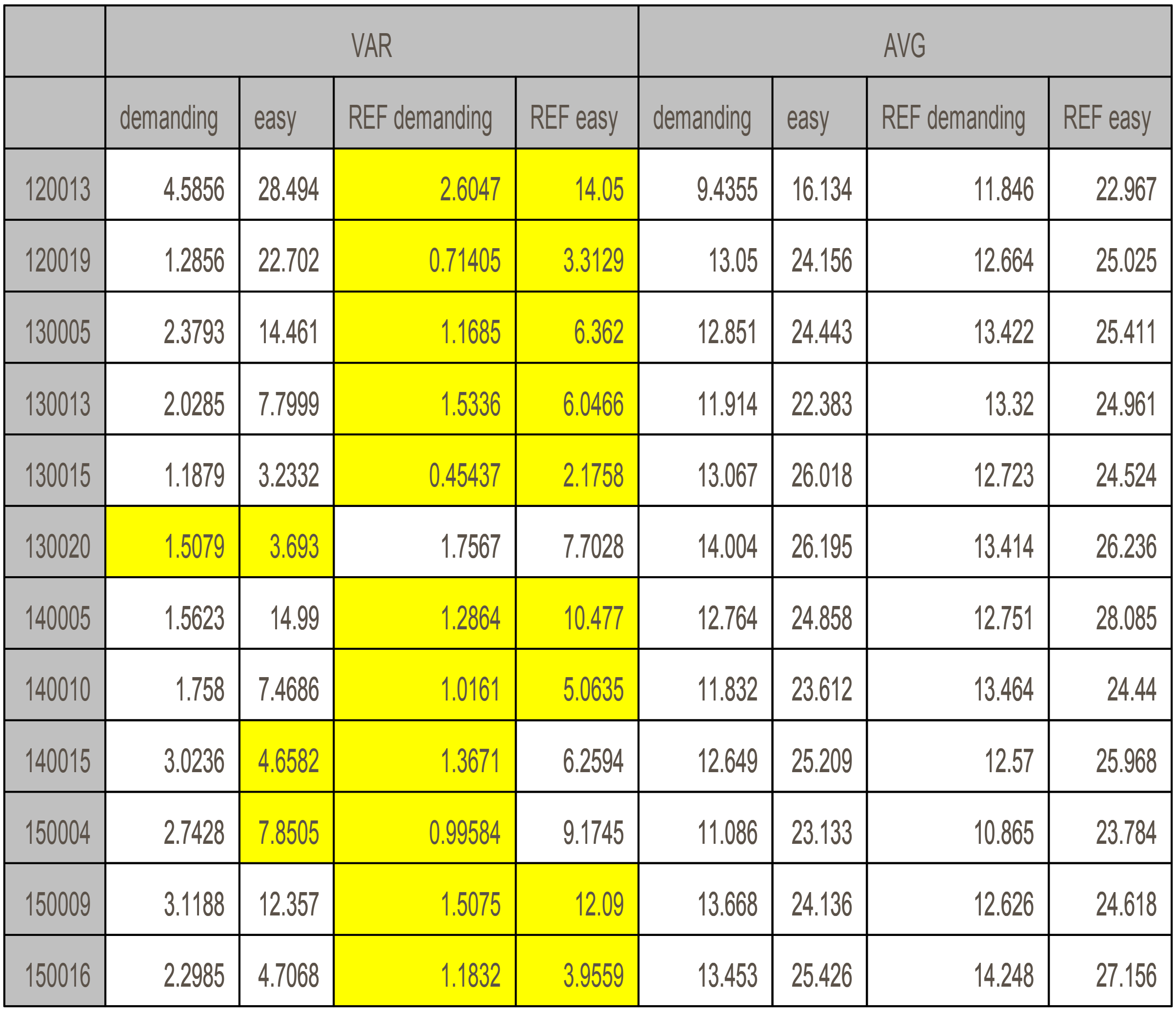


Fig: 7-31: Normalized histograms of speed fluctuation of different two probands (upper: with disturbing, lower: without disturbing)

The next complex table (Tab. 7-15) describes the variance and average values of a car velocity measured for various drivers driving on simulator. It was also necessary to treat demanding (50km/h) and easy (90km/h) part of the testing track separately. First two columns in the variation (VAR) table show values measured when the driver was distracted and those next two from the reference rounds. The same holds for mean value (AVG). The highlighted fields indicate the pairs of variances when the loaded driver exhibited greater variance if loaded.

No evident change was found within average velocities analysis.



| | VAR | | | | AVG | | | |
|---|---|---|---|---|---|---|---|---|
| | demanding | easy | REF demanding | REF easy | demanding | easy | REF demanding | REF easy |
| 120013 | 4.5856 | 28.494 | 2.6047 | 14.05 | 9.4355 | 16.134 | 11.846 | 22.967 |
| 120019 | 1.2856 | 22.702 | 0.71405 | 3.3129 | 13.05 | 24.156 | 12.664 | 25.025 |
| 130005 | 2.3793 | 14.461 | 1.1685 | 6.362 | 12.851 | 24.443 | 13.422 | 25.411 |
| 130013 | 2.0285 | 7.7999 | 1.5336 | 6.0466 | 11.914 | 22.383 | 13.32 | 24.961 |
| 130015 | 1.1879 | 3.2332 | 0.45437 | 2.1758 | 13.067 | 26.018 | 12.723 | 24.524 |
| 130020 | 1.5079 | 3.693 | 1.7567 | 7.7028 | 14.004 | 26.195 | 13.414 | 26.236 |
| 140005 | 1.5623 | 14.99 | 1.2864 | 10.477 | 12.764 | 24.858 | 12.751 | 28.085 |
| 140010 | 1.758 | 7.4686 | 1.0161 | 5.0635 | 11.832 | 23.612 | 13.464 | 24.44 |
| 140015 | 3.0236 | 4.6582 | 1.3671 | 6.2594 | 12.649 | 25.209 | 12.57 | 25.968 |
| 150004 | 2.7428 | 7.8505 | 0.99584 | 9.1745 | 11.086 | 23.133 | 10.865 | 23.784 |
| 150009 | 3.1188 | 12.357 | 1.5075 | 12.09 | 13.668 | 24.136 | 12.626 | 24.618 |
| 150016 | 2.2985 | 4.7068 | 1.1832 | 3.9559 | 13.453 | 25.426 | 14.248 | 27.156 |

Tab. 7-15: Velocity fluctuation for four different experiments (in m/s)

The next set of graphs (Fig. 7-32) illustrates more intuitively the above presented table. The differences in speed variations are evident in both – demanding and easy - parts of the testing track. The differences in average velocities are – as I have already mentioned -negligible.

A similar fact is evident also from Fig. 7-32.

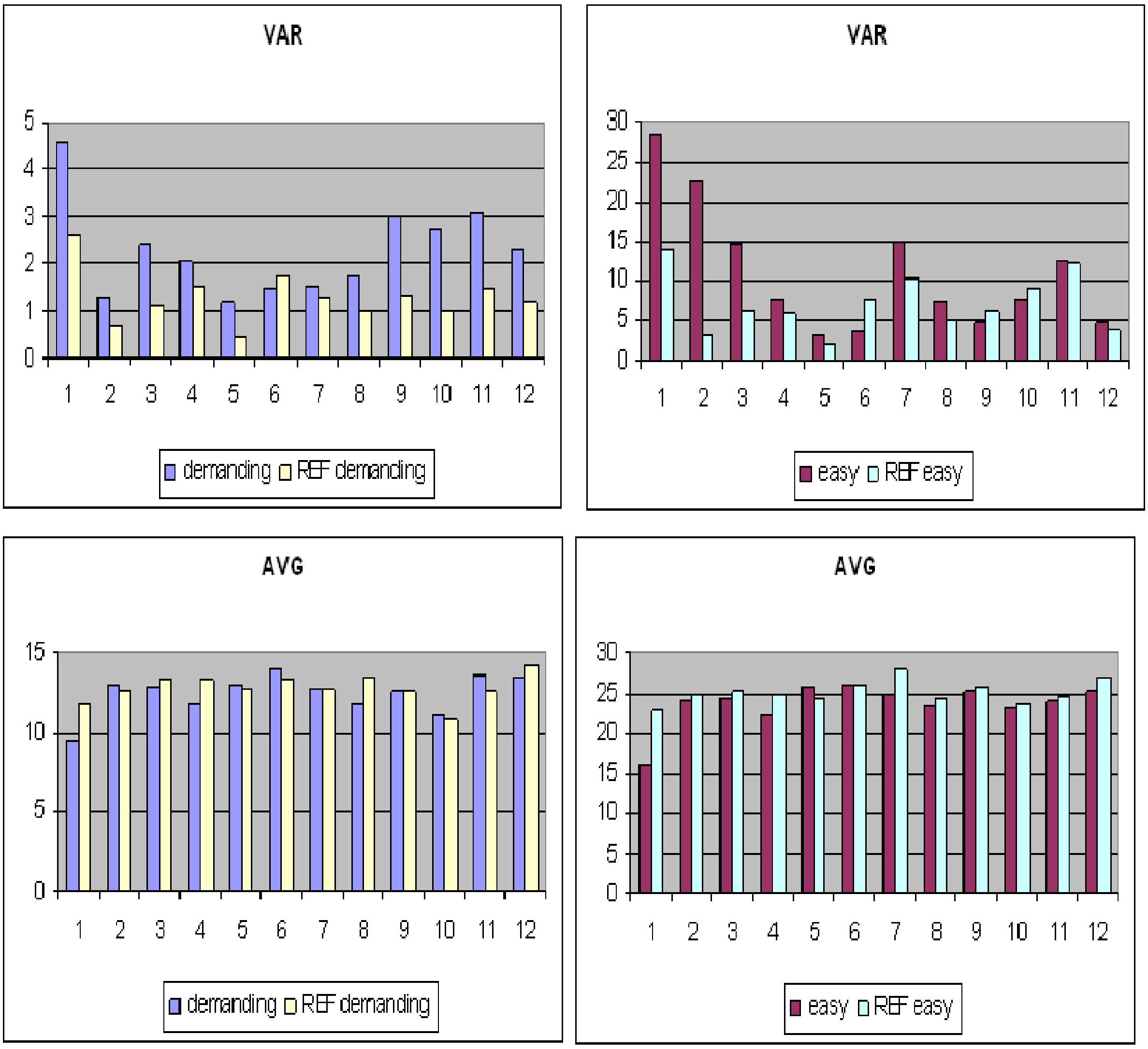


Fig. 7-32: The speed fluctuations in four different experiments – comparison of results when driving was with/without disturbance

### 7.5.7 Subjective evaluation (questionnaires)

All the probands, which we have tested had to complete a complex questionnaires asking for specific features of each device (placement of input, output interface, legibility of particular visual output, etc.), which cannot be applied for overall evaluation.

For comparison of methods which we have used, only a final evaluation question is discussed here. This is: “*Would you recommend the tested setup for usage in real cars?*”

For that purpose, the five degree scale was used with neutral opinion in the middle. The results are summarized in the table Tab. 7-16).

The respective rating was done by simple weighting of negative or positive evaluation.

*Rating = (2 x Very suitable + 1 x Suitable + 0 x Neutral) – (1 x Not suitable + 2 x Very unsuitable)*……………………………………………………………………….…(7.1)

| Is the tested device suitable for usage in a real car? | Very suitable | Suitable | Neutral | Not suitable | Very unsuitable | Rating |
|---|---|---|---|---|---|---|
| Serie 05 | 0 | 3 | 4 | 6 | 14 | -31 |
| Serie 06 | 2 | 10 | 5 | 5 | 2 | 5 |
| Serie 08 | 2 | 7 | 2 | 9 | 5 | -8 |
| Serie 09 | 4 | 5 | 1 | 9 | 4 | -4 |
| Serie 12 | 1 | 7 | 4 | 5 | 4 | -4 |
| Serie 13 | 1 | 8 | 1 | 4 | 2 | 2 |
| Serie 14 | 4 | 10 | 1 | 7 | 2 | 7 |
| Serie 15 | 4 | 4 | 6 | 5 | 3 | 1 |

Tab. 7-16: Overall subjective evaluation

### 7.5.8 The discussion and conclusion

The analysis of deviation variance proved our expectations and it a considerable increase of variances of *deviations from the ideal path* was noticed especially in those parts of the drive where the proband was inserting the targets into navigation system. Although such behavior was apparent in majority of cases, using devices labeled 8 and 9 had no evident influence on driving style.

On the contrary to our expectations, some devices with voice feedback had worse results than the same devices without any voice feedback. It testifies in favour of the fact that voice feedback is sometimes more annoying than helpful.

The analysis of velocity fluctuation in our case showed certain difference in its variance in majority of tests but the average velocity was not affected too much. Finally there was a significant difference between the subjective ratings (8 and 9 were evaluated as very unsuitable) and “ideal path measurement” (8 and 9 were the best).

Unfortunately we were not able to create scale and order the tested devices depending on their impact on safe driving using one of above described objective methods.

To create really objective evaluation with possibility to order and decide which of the devices influences the drivers more, it is necessary to take into account the use of combination of more different methods.

## *7.6 Influence of outer environment – Experiments with road tunnels.*

Next type of experiments, which we dealt with, was measurement of the impact of outer influences on a driving safety and comfort. It is generally known that driving through the road tunnels is much more risky and loading. It could also present an insurmountable problem for certain percentage of driver population. The accident which happens inside the tunnel or just by the tunnel may have incomparable more serious consequences than any similar accident on an open road. It is caused mainly by following intrinsic properties of tunnel constructions:

- Difficult escape of people and vehicles
- Difficult access of emergency
- Chimney effect in case of fire
- Nonstandard (panic) behavior of accident participants

### 7.6.1 Experiment requirements

Since the simulator was used for this study, we should take into account that there is certain difference between car in real environment and the virtual environment of the simulator. It was necessary to reconstruct the influence of the tunnel environment as close to reality as possible. From those principal features which can impact the driver perception we emphasized most the following ones:

- Light conditions
- Frequent light changes
- Environment (walls) tightly surrounding the driver

The first two requirements can be successfully simulated with standard means computer graphics (the light reflected from the projecting screens influence the driver enough) but the last point requires a specific construction solution. Suitable design for such an experiment could be a fully surrounding projection [NOVM06/1] (either cylindrical or flat-shaped). Unfortunately even if the driver is fully surrounded by the tunnel environment, his/her perception does not include a feel of depth (in other words, the distance from sidewalls). Better way of meeting this requirement is the so called ”Depth projection”. For simplicity we chose flat frontal projection, with the so called “Sutter Glasses” technology (see chapter 5.1.2).This allowed the proband to feel realistically driving through the virtual tunnel scenery, while keeping the perception of full color spectra and freedom of head movements.

Following data were collected for further analysis:

- Trajectory (the actual position compared to the geometrically ideal middle of the lane)
- Car velocity
- Steering wheel and pedals movements
- Subjective evaluation

### 7.6.2 Testing cohort

Since this experiment was a part of pilot measurements in the scope of Optun project and had to replenish measurements in plan air, the amount of tested drives was limited. The testing cohort comprised 13 people.

### 7.6.3 Testing track

Testing track is about 43km long and comes from layout of the real highway tunnel “Panenska” belonging to the highway D8. It consists of three parts which are identical from the top layout (Fig. 7-33). Such a design allows fair comparing of driver’s behavior in and out of the tunnel.

Fig. 7-33: The top profile of the testing track

### 7.6.4 Experiment procedure

Before the driving on the simulator the probands had to fill in the obligatory anamnesis questionnaire enhanced with topics probing his/her visual, mainly stereo, perception. The driver wore shutter glasses and accommodated to the use of training scenario, then he/she passed the three consecutive rounds of the testing scenario.

### 7.6.5 Analysis

***Differences***

The recorded trajectory of the car is compared with a geometrically ideal path in the middle of the appropriate lane. The analysis was done from the values of actual distances from the ideal curve (differences) in an each particular segment of open air road and inside tunnel.

***Variances***

This analysis was based on the above described data, resampled on 100ms base. The statistical variance analysis was applied on the data set of differences again for particular segments.

***Subjective evaluation***

Each proband had to fill in the questionnaire dealing with:

- Health anamnesis
- Driving skills
- Experience with tunnel using and driving
- His/her current state and self assessment
- Subjective evaluation of simulated tunnel

Some interesting results can be derived from this subjective analysis. Those most interesting are:

- 80% of drivers drive under normal conditions slower in the tunnel than in the open air environment ( or they strictly respects the rules)
- Majority of the tested drivers subjectively feels that they should control the car with more effort inside the tunnel than outside of it

- On the other hand, the analyses of variances says that the drivers went through the tunnel in a much straighter way

### 7.6.6 Discussion on a tunnel behavior

The results of above described analyses can be seen in the following table (Tab. 7-17). We can derive the differences in average deviations and variations in between the segments of the track.

| **Mean value is bigger after leaving the tunnel** | **Lower variance in the tunnel than in both open air parts** | **Higher variance after leaving the tunnel** | **Special case Fig. 7-33** | **Lower mean value in the tunnel than in both open air parts** | **Lower mean value in the tunnel before OR after the tunnel** |
|---|---|---|---|---|---|
| 73,08% | 51,30% | 69,20% | 32,05% | 44,87% | 75,64% |

Tab. 7-17: A percentual occurrence of behavioral patterns

From the above table it is possible to derive patterns which the drivers follow when entering to the tunnel, when riding inside the tunnel and when leaving the tunnel.. The most significant patterns are illustrated in the picture Fig. 7-34.

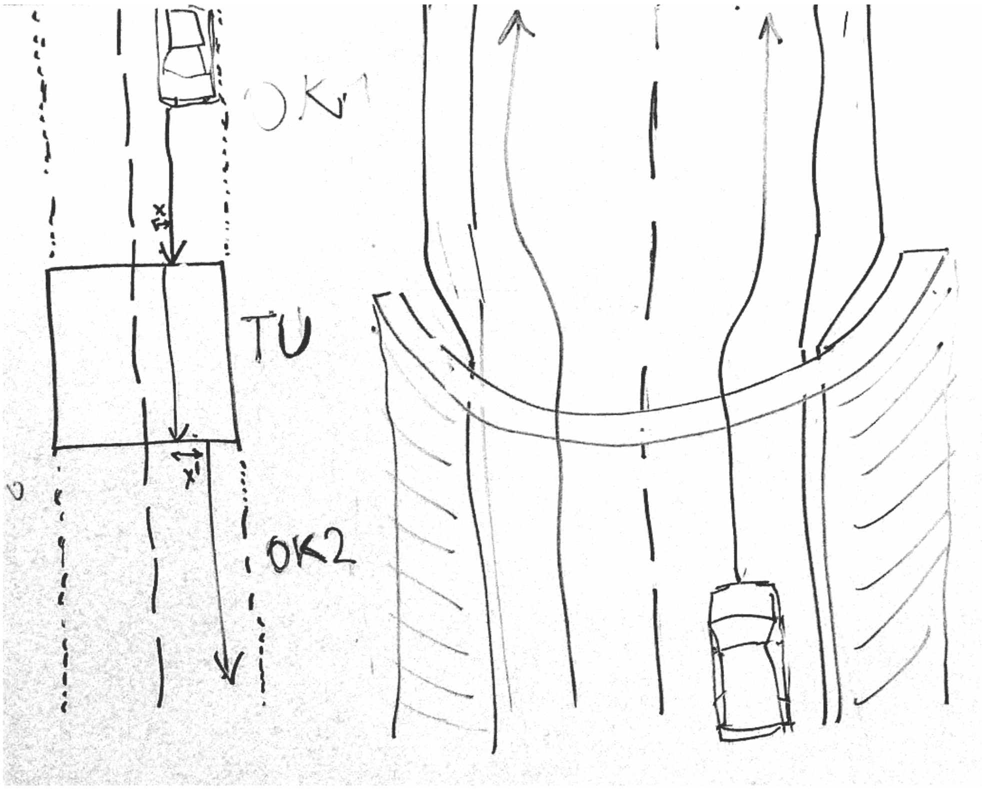


Fig. 7-34: Sketch of possible driver behavior when the riding through the tunnel (left picture) and leaving the tunnel portal (right picture)

The driver controls the vehicle in the era in front of the tunnel closer to the side part of the route, in the tunnel he/she is getting closer to the middle and after leaving the tunnel he / she is getting back to the side. What happened in most cases was that the driver got to the side only when leaving of the tunnel. This observation is in effect for both cases of driving either in the left lane or in the right lane.

The experiments concerning the tunnel driving have been performed during last three years within research works in the scope of grant *Optun.* Several similar measurements were performed in a real traffic and the some of the results from these real rides gave very comparable results. For more information on this topic see research reports [NOVM04/2, BOUP05/5, NOVM06/3].

# Chapter 8: Conclusion

This PhD thesis summarizes some results of my research activities in the field of Human-Machine Interaction made in LSR during last four years. These were focused mainly on the problems related to the possibilities of minimizing the tremendous loses caused by driver attention decreases, which, as far as I know, represent in the EU the amount of about 100 billion EUR per year (and the decreases are the reason for about 10.000 killed people on the road). Such research was focused on the following main approaches which seems to be promising for reaching the goal, announced now by the EU representatives – to diminish these loses in a next 3-4 years down to about 1/2:

- To improve our knowledge about the procedure of how a driver falls asleep
- To optimize the car cockpit with respect to minimization of negative influences on driver attention and comfort
- To develop the warning systems against the fatal decreases of driver attention
- To develop the advanced methods of driver's training with respect to significant improvement of his/her resistance to attention decreases and splitting

For all the above mentioned approaches the disposability of very advanced tools, which are the adaptive driving simulators equipped with very compact scenarios in virtual reality are necessary. It is also necessary to have the skills and knowledge how to use effectively and reliably such equipment for real measurements.

Therefore in my work I focused mainly on development and improvement of such tools. I hope that some of my results - although they are not (and actually cannot be) complete – will be useful for such research and also for practical applications in car industry and traffic control. I only have described the problems concerning the attention decreases mechanisms and selection of appropriate attention level indicators if it was necessary for designing and measuring the described experiments.

In my PhD thesis I focused mainly on description of my contribution to FIDS development, design, construction and applications for various measurements dealing with driver attention decreases. Some of the reached results I have presented at several domestic and abroad scientific conferences and published in several proceedings and articles. I hope that in the future I will be able to prepare a more compact publication concerning the Fully Interactive Driving Simulators.

I hope that in the range of my expected further work in existing research projects of the Czech State Grant Agency, Czech Ministry of Education and Czech Ministry of Transportation I can contribute to improvement of our knowledge in this important area.  Tit can be expected that some of the present results and the future research will be successfully projected onto the activity of the International Neuro-informatic Coordination Facility of Global Science Forum OECD.

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## List of abbreviations

| **Abbreviation** | **Full Name** |
|---|---|
| 2D | Two Dimensional |
| 3D | Three Dimensional |
| ABS | Antiblockiersystem (Anti-lock braking system) |
| AI | Artificial Intelligence |
| AVG | Mean value (Average) |
| CAD | Computer Aided Design |
| CAN | Controller Area Network |
| CG | Computer Graphics |
| CRT | Cathode Ray Tube |
| CS | Compact Simulator |
| CTU | Czech Technical University in Prague |
| DCT | Discrete Cosine Transform |
| DLP | Digital Light Processing |
| DSRG | Driving Simulation Research Group |
| ECG | Electrocardiography |
| EEG | Electroencephalography |
| EMG | Electromyography |
| EOG | Electrooculography |
| ESP | Elektronisches Stabilitätsprogramm (Electronic Stability Control) |
| FFT | Fast Fourier Transform |
| FIDS | Fully Interactive Driving Simulator |
| FOV | Field of View |
| GIS | Geographical Information System |
| GPS | Global Positioning System |
| GSF OECD | Globa Science Forum of OECD |
| GUI | Graphic User Interface |
| HBF | Heart-beat Frequency |
| HCI | Human-Computer Interaction (Intarface) |
| HF | Human Factors |
| HMD | Head Mounted Desplays |
| HMI | Human-Machine Interaction (Intarface) |
| HR | Heart Rate (=HBF) |
| HRR | Heart-beat Rate Response |
| HW | Hardware |
| INCF | International Neuro–Informatic Coordination Facility |
| ISO | International Organization for Standardization |
| ITS | Intelligent Transportation Systems |
| IVIS | In-Vehicle Inforamtion System |
| Kph | Kilometers per Hour |
| KSS | Karolinska Sleepiness Scale |
| LCD | Liquid Crystal Display |
| LIN | Local Interconnect Network |
| LLE | Largest Lyapunov exponent |
| LOD | Level of Detail |
| LS | Light Simulator |

| | |
|---|---|
| LSR | Laboratory of Systems Reliability |
| LV | Lane Variability |
| MD CR | Ministry of Transportation of Czech Republic |
| MS | Motion Sickness |
| MSMT | Czech Ministry of Education |
| MSQ | Motion Sickness Questionnaire |
| NN | Neural Networks |
| OA | Oculi Aperti (Opened eyes) |
| OC | Oculi Ceraity (Closed eyes) |
| OECD | Organization for Economic and Cultural Development |
| PIARC (AIPCR) | World Road Association |
| RGB | Red, Green, Blue |
| RPM | Revolutions per Minute |
| RT | Response Time / Reaction Time |
| SA | Systemic Analysis |
| SAE | Society of Automotive Engineers |
| SR | Self Rating |
| SS | Simulator Sickness |
| SSQ | Simulator Sickness Questionnaire |
| SW | Software |
| TLX | NASA Task Load Index |
| Var | Statistical Variance |
| VR | Virtual Reality |

# List of figures

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# Appendix – DVD

The enclosed DVD contains movies illustrating the design and use of driving simulators developed and operated within the Laboratory of System Reliability.