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Evaluation and Optimization of Vehicle Cabin Ergonomics Using Virtual Reality

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***Abstract*—The article discusses the idea of developing a cabin design complex using virtual reality technology to optimize production, improve ergonomics and comfort of the vehicle. It is planned to create a modifiable "on-the-fly" hardware-software complex for cabin conceptualization, consisting of a set of real cabin elements, a virtual reality helmet for rendering the environment, road and cabin design for the test subject, as well as a special operator program for controlling the driver's condition and changing the configuration of the cabin. The creation of an on-the-fly modifiable hardware and software system will reduce the cost of recreating the model of each new cabin. Various methods of taking information from the human body, such as ECG and EEG, eye movement, level of sleepiness, international standards, and others are proposed. Reviewing and selecting the most relevant metrics will allow for a more accurate determination of driver fatigue levels, and therefore the selection of better vehicle ergonomics.**

Keywords*—*ergonomics, cabin, vehicle, design, ergonomics virtual reality, natural user interface

I. Introduction

In today's world, where vehicles have a key role in people's daily lives, ensuring their safety, comfort and efficiency becomes not just a priority, but a necessity. Vehicle cabin ergonomics is an area where human-machine interaction becomes particularly important, affecting not only usability but also driving safety. In this context, testing and validation of metrics for quantitative and qualitative assessments of ergonomics are of particular relevance, as they allow a scientifically reasonable approach to the design and optimization of vehicle cabins.

Ergonomics is crucial in almost all human activities, so the following basic conditions must be met when designing a driver's workplace:

- The driver should be provided with a working space sufficient to perform all necessary movements during driving and maintenance of the vehicle;
- Equipment and means of displaying information and controls shall be optimally placed in the cabin of the vehicle to ensure a comfortable position for the driver when working;
- The various controls, indicators and other equipment elements shall be easily accessible and clearly recognizable;
- The natural and artificial lighting required for both operational driving and maintenance tasks shall be provided;

The use of virtual reality within the control of other high-tech systems is not a novelty and keeps developing [1]. In the conditions of constant growth and changes in requirements to safety and comfort of vehicles (new technologies and materials) at the design stage of the cabin requires rapid adaptation of concepts of future models of vehicles. Therefore, the application of virtual reality with its opportunities becomes more relevant due to the rapid modification of computer graphics in relation to the production of the real cabin.

Also, an important aspect of developing new vehicle cabins is to test the concept for viability – whether the cabin is ergonomic, comfortable and safe for the average driver. For this purpose, it is important to have metrics to determine the above characteristics of the cabin.

II. Related Work

Vehicle design is an interdisciplinary field as it requires high knowledge of mechanical, electrical and aerodynamic design. Vehicle designs are constantly evolving with innovative and revolutionary technologies. One example of transportation technology is the design of morphing vehicles, in which vehicle interfaces can change their shape using actuators, sensors, and controllers to improve their performance as their environment changes.

The morphing vehicles allow to easily change components and their arrangement to adapt the cabin to the optimal conditions comfortable for the driver. A key factor in evaluating vehicle cabin ergonomics is the level of driver fatigue, as it directly affects driving safety and efficiency. Fatigue can reduce a driver's ability to concentrate, react to traffic situations, and their ability to control the vehicle, which increases the risk of crashes. An ergonomically designed cab should minimize physical and mental stress, thereby reducing

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fatigue and keeping the driver alert throughout the journey. Various methods can be used to assess such aspects, which help to determine how well the vehicle cab is adapted to long periods of driving without adversely affecting fatigue levels.

A. Overview of fatigue recognition techniques

Virtual Reality is one of the advanced tools that engineers are using to develop vehicle ergonomics. VR eliminates the need for designers to create a full-scale model for testing. Methods for solving design layout problems for driver workstation development through virtual reality technologies can significantly reduce the design time and cost of finalizing a passenger car to ergonomic requirements.

There are numerous techniques to determine driver fatigue based on physical, behavioral and technological methods. It is important, however, that the fatigue measurement devices themselves are not invasive, i.e., they do not disturb the driver and do not add to the risk of an accident on the road (restraining, distracting or annoying the driver).

At the moment it is worth mentioning 5 most relevant methods for determining driver fatigue, among which are: physiological methods, behavioral methods, driving analysis, subjective assessments, psychomotor tests.

Physiological methods include the use of ECG and EEG technologies. The study [2] states that an increase in the electromagnetic emission index of the human brain in the alpha frequency range (8-13 Hz) can indicate an increase in the subject's sleepiness. Another option is to track the heart rate using an electrocardiogram, since tired people have different heart rates [3].

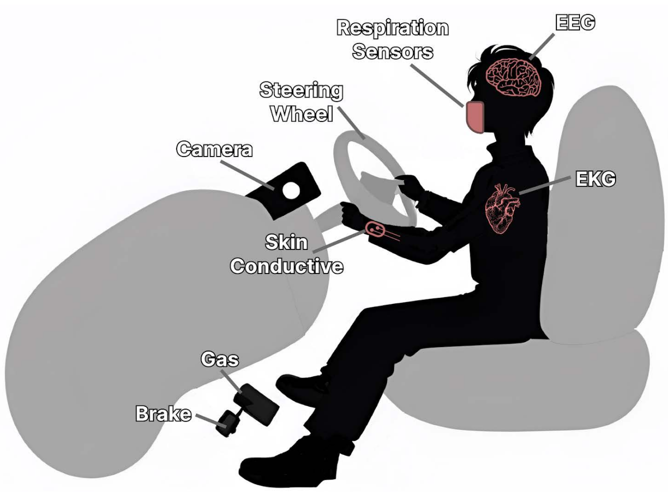

Fig. 1. Schematic representation of the connection of sensors for capturing indicators of the physiological state of the driver.

Studies [4, 5] show high efficiency of these techniques. At the same time, the high accuracy of these methods is accompanied by high invasiveness of these techniques. Consequently, during testing and condition monitoring, a set of sensors (Figure 1) must be attached to the driver to read physiological parameters, which may lead to stiffness of movement or annoyance [6].

Behavioral methods are based on less invasive methods to assess fatigue, such as by speech and voice. The rhythm and speed of speech, typical pauses, and clarity of the thought being presented can indicate confusion and slowed reaction time. Unfortunately, in practice, this methodology cannot provide a consistent assessment of the driver's condition, because in solitude the person will remain silent most of the time [7].

Another behavioral method is to track the driver's eye behavior. The most commonly used indicator related to driver eye condition is PERCLOS (Percentage of Eye Closure) [8, 9]. This parameter indicates the percentage of time that the driver's eyes remain closed during a defined period of time. Similar method is effectively used in the USA [10] and assumes that the driver, when the PERCLOS value reaches above 80%, is considered tired.

The great advantage of this method is that it is completely non-invasive as it utilizes a photo image of the driver. Also, this technique can be modified using machine vision to track other behavioral parameters of fatigue, such as yawning, typical nods when falling asleep, or facial expressions [11].

The manner in which the vehicle is driven is also one of the potential characteristics of driver mental clarity. This method involves analyzing the vehicle trajectory and assessing the success of keeping the vehicle within the roadway. In this case, the steering wheel may be a key tool for assessing driver fatigue. The steering wheel impacts can be divided into two types: macro corrections, representing road curvature or realignment maneuvers and associated with large wheel angles as well as micro corrections, represented as small corrective turns to keep the vehicle within the lane [12]. It is argued in [13] that the number of micro-corrections during awake state is much higher than in fatigue state, which will be the main parameter of driver's state.

Subjective assessment of fatigue level is usually performed by drivers using special self-assessment scales, the most common of which is the Karolinska Sleepiness Scale. This scale has a high correlation with driving quality and measures of brain activity. The advantage of subjective methods is that the driver knows his state best, but the problem with these methods is their inability to be used in real time driving. Subjective assessments often serve as the basis for other fatigue recognition methods and cannot be used as the only source of driver condition assessment due to human error and the possibility of error. In addition, tests that are too frequent may annoy or distract the driver during the actual trip.

Psychomotor tests measure a driver's ability to respond quickly and accurately to stimuli, which may decrease with increasing levels of fatigue. Reaction, coordination and memory tests help determine how well a driver is able to perform tasks that require psychomotor activity and attention. Unfortunately, these tests have too high a probability of error.

Thus, the most effective methods to detect driver fatigue (Table 1) [14], can be considered psychophysiological measures such as electroencephalography and pupillometry, due to their ability to accurately reflect the driver's cognitive states. These methods allow fatigue to be detected in early stages, providing the opportunity to take precautionary action to prevent accidents on the road.

TABLE I. EFFECTIVENESS OF DIFFERENT METHODS FOR EVALUATING DRIVER FATIGUE

Fatigue determination method	**Sleepiness indicator**	**Mental fatigue indicator**	**Efficiency**
EEG and ECG	Parameters related to spectral power based on alpha signal, heart rate		High
Eye movement	Blink-based parameters such as PERCLOS	Pupil and saccade-based parameters such as pupil diameter change and saccade velocity	High
Keeping the road trajectory	Basic statistics on vehicle position in the cross lane, such as average and standard deviation.		Low
Subjective definition of sleepiness	The Karolinska Sleepiness Scale, the Stanford Sleepiness Scale	Borg Perceived Load Rating Scale, Visual Analog Scale	Medium
Psychomotor tests	Tasks for psychomotor activity (alertness, oculomotor reactions, coordination of limbs and eyes)		Low

Of course, it is not efficient to limit the driver fatigue detection to a single method, as this may not take into account the many factors affecting the driver's condition. The combined collection of a wider range of non-invasive driver information, such as physiological, behavioral and other parameters, can significantly improve the accuracy of driver fatigue detection and prediction.

B. Ergonomics of cabs

The seating posture of the driver is also an important criterion for the ergonomics of the vehicle. There are general principles governing the correct seating position of the driver in a vehicle. These principles apply to all drivers, regardless of their anthropometry. In [15], the ergonomics of vehicle cabs is discussed and the optimization of interaction between disabled drivers and vehicles is addressed. The article [15] discusses methods for evaluating suitable driver cabin configurations, including seating and control access approaches that support driver independence and comfort. Ergonomic factors affecting driver cabin configurations are presented as a versatile framework including the driver, the external environment, and legal requirements affecting driving safety and comfort.

In [16, 17] the issues of vehicle modification based on individualized assessment of driver's health, including support with rehabilitation measures, are raised.

C. Standardized assessments of cabin ergonomics

In addition, the Russian state standards, the international ISO standard [18] or local standards of car manufacturers offer some verified dependencies between the location of different cabin elements. Summarizing these normative documents allows us to identify the following qualitative and quantitative metrics:

Speed of access to controls and ease of reaching them. Measured by touch time using a stopwatch.

Subjective perception of seat comfort and available leg and headroom. Measured on a subjective perception scale using a driver self-report questionnaire.

Visibility and location of controls in the driver's field of view. Measured in degrees of viewing angle or on a scale of subjective perception using a driver questionnaire. Also included in this item is the level of illumination, measured in lux.

Evaluation of the intuitiveness and usability of control buttons and displays. Measured on a subjective perception scale using a driver questionnaire.

Size and distance of individual cabin elements to the driver. Measured in millimeters and reflects the available space in the cabin.

To effectively evaluate qualitative metrics, it is important to carefully analyze the data obtained, taking into account the diversity of personal preferences and feelings of the participants. These metrics can help in evaluating cabin ergonomics and improving the overall vehicle experience.

D. Virtual reality for design refinement

In [19], the issues of natural interfaces in virtual reality (VR) and ways to evaluate immersion are raised. These approaches are in direct relation to the validity of the metrics used to evaluate car cabin ergonomics. A position from the article: "One possible way to make VR tangible is to use real-world physical props that are paired with virtual objects." The user can interact with virtual objects by interacting with real-world props. In order to develop predictable systems, it is necessary to be aware of the impact of this mismatch on the user's behavior in VR and their perception of the virtual object [19].

For the detailed development of the vehicle cabin equipment, many car manufacturers actively use immersive approaches that allow to change the characteristics of the cabin design in runtime, testing various hypotheses of ergonomics [20]. Such a hardware complex should include, in addition to the stationary unchanging base of the cabin (see Fig. 2), a virtual reality headset, a set of cameras and sensors for tracking the driver's state, and in addition a set of motion capture devices with the ability to track the driver's limbs and posture using marker-based motion capture technology (Motion Capture). In this case, the motion capture technology will allow any movement of the driver to be transmitted to the virtual environment.

To reduce the cost of development and implementation of hardware and software complex for vehicle cabin conceptualization using virtual reality, it is recommended to optimize the choice of hardware and software, focusing on the modularity and scalability of the system. This will not only reduce the initial investment, but also provide flexibility in further development and adaptation to new requirements.

Fig. 2. Example appearance of the hardware complex [20].

This complex will be equipped with high-precision sensors capable of recognizing the smallest movements, providing an accurate reproduction of the driver's actions in real time. Such systems must be highly adaptive and can be calibrated for different body types and sizes, which will ensure full coverage and accuracy. The system should include advanced software algorithms for processing the data obtained during motion tracking and interpreting it to understand the driver's behavioral patterns and ergonomics.

An example of using virtual technologies for driver research is a special virtual cabin for drivers, the National Advanced Driving Simulator (NADS), developed by engineers at the University of Iowa [21]. Inside it is a car with many sensors that transmit all the data about the driver's actions. The cabin is designed to simulate virtual situations with a 360° angle. This project is being implemented to study problems related to the human factor, including drug use, traffic violations, distracted driving, etc.

III. Conceptualization of the Vehicle Cabin Using Virtual Environment

It is proposed to use an easily modifiable framework of the cabin to design the vehicle cabins, the equipment of which will be completed when immersed in virtual reality according to a pre-prepared project (template) by a team of designers and engineers, which is responsible for the ergonomics of the cabin. Among the identified criteria to be met by this hardware-software complex are:

- Setting up a template of the driver's workplace in a realistic three-dimensional model, repeating all the elements in the vehicle, their appearance with precise indication of texture and its light reflection characteristics, as well as setting up all lighting sources;
- Simulation of the tested workplace of the vehicle by changing the template - changing the position of individual elements of the template or replacing the elements of the template;
- Physical modification of the system according to the settings for the workplace under test;
- Testing of the system by means of immersion in virtual reality;
- Evaluation of ergonomics of the tested driver's workplace;
- Logging of all testing stages.

A. Technical realization

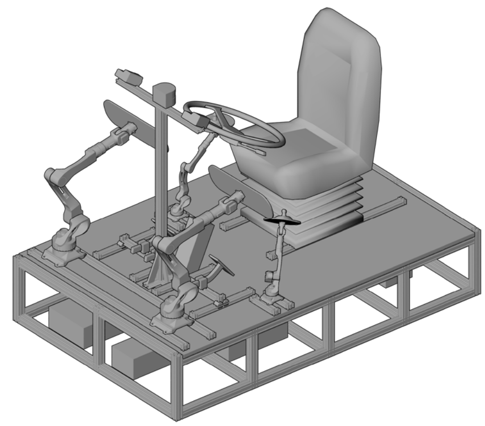

Fig. 3. Schematic representation of the physical model of the Stand.

This VR-conceptualization system will allow to select the appropriate dimensions and position of individual components of the car interior for further design. The development of the software and hardware complex is divided into two parts:

1) The hardware part consists of several separate elements:

a) a physical model or Stand (see Fig. 3), simulating the workplace of the driver-operator of the vehicle - with a set of physical structures and devices, providing an opportunity to regulate the position of all its individual components and equipped with sensors to transmit information about all changes made to the workstation with the possibility of changing the position of individual components of the Stand. All changes shall be recorded and information about the changes shall be transmitted to the System's program complex;

b) virtual reality headset;

c) a set of devices for capturing driver's movements (Motion Capture);

d) a set of sensors, detectors and cameras for tracking the driver's condition.

2) The software system shall be implemented as a set of three-dimensional elements and user interface elements forming a virtual scene of the driver-operator's workplace in real time. The software system shall have the ability to *transmit changes in the position of components of the hardware complex. The system shall be implemented for two user roles: operator and tester. Each of the roles is not limited to a single user:*

a) for the role of the tester only the virtual reality mode shall be used;

b) for the role of the operator only the PC control mode is used.

IV. System Limitations

When selecting metrics to evaluate vehicle cabin ergonomics, such as physiological measures or subjective tests, it is critical to make sure that they are relevant to the actual cabin environment. This means that the analysis must take into account the actual operating conditions of the vehicle. Doing a comparison analysis of data obtained while driving on a real road and in a simulated environment can reveal key differences in driving behavior and response, allowing adjustments to be made to the evaluation methods. In this way, a higher level of accuracy in ergonomics evaluation can be achieved and the quality of driver interaction with vehicle controls can be improved, ultimately contributing to improved driving safety and comfort.

Among the disadvantages of this approach is the lack of possibility to assess other important characteristics of the cabin for the driver:

The ability of the cabin to keep optimal temperature conditions. Measured in degrees Celsius using a thermometer or on a scale of subjective perception using a driver questionnaire.

Assessment of cabin sound insulation level. Measured in decibels using a sound meter at various conditions.

Vehicle safety during accidents, which depends on the materials used and the exterior shape of the cabin.

V. Conclusion

The current study confirms the significant potential of using virtual reality to evaluate and optimize vehicle cabin ergonomics. This approach not only opens new horizons in design and usability, but also makes a significant contribution to improving driving safety and efficiency. By combining virtual reality with advanced analytics, including artificial intelligence, the driver's interaction with the cabin can be analyzed in detail and improved, anticipating the needs of future generations.

The need for an interdisciplinary approach in the design and evaluation of cabin ergonomics is becoming apparent. Effectively combining knowledge from design, engineering, psychology and information technology is key to creating cabs that are not only comfortable and intuitive for the user, but also contribute to reducing fatigue and crash risk.

The research and development conducted emphasizes the strategic importance of integrating innovative technologies into the vehicle design process. Investments in improving cabin ergonomics not only improve the user experience, but also make a significant contribution to public safety on the road. The automotive industry is facing new challenges and development opportunities that require a constant search for innovative solutions and improvements.

In consideration of these findings, we emphasize the need for further research in this area. Continuous technological development and changing safety and comfort requirements require an adaptive approach to design and ergonomics evaluation. An approach that combines virtual reality technology with a deep understanding of user needs opens up new perspectives for creating safer, more comfortable and more efficient vehicles of the future.

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