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Virtual Reality as a Training Tool for Utility Vehicle Operators in Smart Cities

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ABSTRACT: The increasing complexity of urban mobility and infrastructure maintenance in smart cities necessitates the development of enhanced training methodologies for utility vehicle operators. This paper analyzes contemporary simulation techniques used in operator training, emphasizing the role of virtual reality (VR) in improving design evaluation, ergonomics assessment, and operator performance. We introduce a framework for integrating VR into the design evaluation process for next-generation utility vehicles within an immersive simulation environment. The presented approach incorporates objective metrics such as head and hand tracking and motion analysis, with subjective questionnaire-based feedback.

KEYWORDS: design evaluation, ergonomics, utility vehicle operator, virtual reality, immersive environment

1. INTRODUCTION

The increasing complexity of smart cities demands skilled utility vehicle operators, yet traditional training methods fail to replicate real-world challenges. Current training relies on classroom instruction and physical simulators, which lack real-time adaptability and engagement. Smart city operations require adaptive learning techniques for situational awareness, rapid decision-making, and smart infrastructure interaction (Stefan, Mortimer, & Horan, 2023). Without scenario-based training, operators risk longer reaction times and higher accident rates.

Traditional training overlooks ergonomic challenges, leading to fatigue and inefficiencies, pointing out the need for user-centered approaches to ergonomic design instead of machine-centered approaches (Grandi, Peruzzini, Campanella, & Pellicciari, 2020). Devine et al. emphasize ergonomic hand tracking to reduce strain and improve interaction accuracy (Devine, Nicholson, Rafferty, & Herdman, 2017). VR can integrate motion tracking, hand-eye coordination analysis, and physiological monitoring to optimize training effectiveness. VR has emerged as a powerful tool for simulation-based training, offering a safe, immersive, and cost-effective environment for skill development (Vincenzi, Mouloua, Hancock, Pharmer, & Ferraro, 2023). It has been widely adopted in industries such as aviation, defense, and healthcare, demonstrating its effectiveness in reducing learning curves, minimizing risk exposure, and improving operator performance (Stefan, Mortimer, & Horan, 2023; Morse, Mokhlespour Esfahani, & Krishnan, 2024). The ability to integrate real-world scenarios, motion tracking, and biometric feedback makes VR an ideal solution for training utility vehicle operators.

Given these challenges, this study focuses on developing a VR-based framework for training and design evaluation in smart city utility vehicles.

2. OVERVIEW OF TOOLS AND APPROACHES

2.1 Simulators, Visualization, and Sensors

Vehicle simulators can be categorized based on various criteria, depending on the context. However, the most used evaluation parameter is the level of fidelity of the overall experience (Wynne, Beanland, & Salmon, 2019; de Winter, et al., 2009). The immersion cube is a 3D model developed by Pfeffer et al. that classifies different levels of immersion in VR simulations, particularly for ergonomic assessment, by defining immersion across three sensory dimensions: visual, auditory, and haptic (Pfeffer, et al., 2024). Each dimension varies in its level of virtuality or reality, ranging from fully virtual to fully real interactions. The authors further point out the limitations of simulating real loads and recommend hand tracking instead of controllers. The same classification approach was chosen for the purposes of this article but focused directly on vehicle simulators. It is useful to classify simulators according to their use of VR in the context of the depiction of the vehicle's cabin and surroundings. (Morra, Lamberti, Pratticó, La Rosa, & Montuschi, 2019)

A full simulator replicates the entire vehicle cabin, including physical controls (steering wheel, pedals, buttons) and large surrounding displays that create an immersive urban environment.

A mixed-reality simulator combines real cabin controls with augmented reality (AR). The driver interacts with physical buttons and a steering wheel while an AR headset overlays a virtual cityscape, reducing the need for large projection screens.

A VR-based simulator with haptic elements provides an immersive experience where the entire scene is rendered in VR. The user wears a VR headset, but key physical components, such as the steering wheel, pedals, and control buttons, remain tangible. This ensures that while the visual world is entirely digital, the operator can still feel and manipulate real-world objects, improving training effectiveness. The combination of VR immersion and physical touchpoints helps develop realistic responses and enhances muscle memory for real-world operations (Eswaran, Eswaran, Eswaran, & La Rosa, 2023). The VR-based simulator approach has further benefits, such as the possibility of easily switching between different simulated vehicles and compact dimensions that are more suitable for deployment at different training locations.

In terms of immersion of the trained machine operator, AR- or VR-based approaches are generally better because, unlike flat displays, they allow for the perception of scene depth, which is critical for some types of tasks. (Morana, 2024)

In terms of the range of measured data, all types of simulation are practically equal (Li, et al., 2024), because their range is determined by additional measuring devices around the driver – typically recording the states of the simulated vehicle, the position of the controls, eye tracking, sensing the position of the head, hands and the whole body.

2.2 Common Tasks and Scenes

VR-based training environments commonly mimic real-world tasks to simulate operator posture, control layout, and workflow efficiency. In industrial settings, simulations often involve human-machine interface (HMI) interactions, such as controlling heavy machinery, assessing visibility constraints, or navigating machines in specific areas. For example, studies have explored the integration of a heads-up display (HUD) in an excavator cabin, comparing its ergonomic impact with traditional HMIs. These simulations help researchers understand how visual interfaces, control layouts, and spatial constraints influence user performance and fatigue. (Akyeampong, Nevins, Udoka, & Carolina, 2013; Zhang, Chen, Sun, & Carolina, 2023)

To assess cognitive load and physical strain, VR scenarios frequently incorporate decision-making and motor tasks. Users may be required to choose between different head motion trajectories to complete a visual task or press virtual controls under time constraints. These tasks measure reaction time, accuracy, and muscle workload, providing insights into ergonomic risks such as neck strain or repetitive motion fatigue. By forecasting potential discomfort based on target head positions, VR-based assessments serve as a quantitative tool for optimizing interface design and reducing operator fatigue in immersive environments. (Devine, Nicholson, Rafferty, & Herdman, 2017; Grandi, Peruzzini, Zanni, Campanella, & Pellicciari, 2018)

2.3 Evaluation Metrics

To evaluate control accessibility and ergonomic efficiency, other studies have been using virtual hands based on wireless controls, which are part of the VR headsets (Topcuoğlu, 2018), or experimental technologies like wearable motion capture sensors (Anacleto Filho, Colim, Cristiano, Lopes, & Carneireo, 2024). To make VR scene interaction more immersive, hand tracking was used to provide a realistic model of the hands. This technology required an additional tracking sensor for the VR headset (Grandi, Peruzzini, Campanella, & Pellicciari, 2020; Devine, Nicholson, Rafferty, & Herdman, 2017), which was limiting tracking reliability. In our study, we used a Meta Quest 3 headset with integrated tracking of the point fingers, providing a sufficient overview of movement and interaction within the VR scene.

The field of view within the VR cabin was evaluated using digital human modeling (DHM) (Akyeampong, Nevins, Udoka, & Carolina, 2013; Grandi, Peruzzini, Zanni, Campanella, & Pellicciari, 2018; da Silva, Mendes Gomes, & Winkler, 2022). The tracking head rotation and tilt of the VR headset in the scene provide insights into gaze variability (Devine, Nicholson, Rafferty, & Herdman, 2017; Artyukh, et al., 2023) and operator visibility. This approach helps determine the reachability of control units, ensuring that operators can interact with machine interfaces comfortably and efficiently.

3. TECHNICAL SOLUTION OF THE DEMONSTRATOR

3.1 Design of the System Solution

As the research into the possibilities shows, not only is there a need to display a good quality scene to ensure the appropriate level of immersion, but there is also a need for accurate and fasttracking of the position of the head, hands, and surroundings. The proposed system solution is illustrated in the block diagram in Fig. 1.

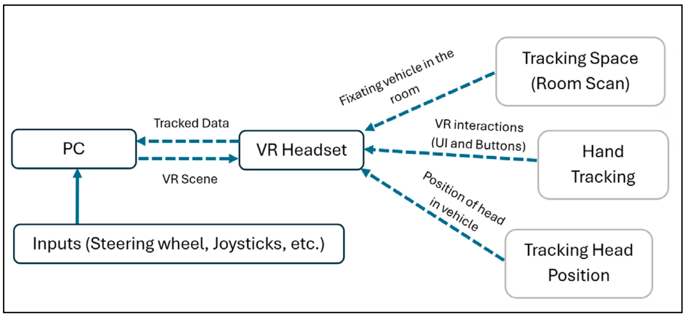

Fig. 1 Block diagram of the simulator setup and data flow.

In our case, it is a complex heavy-machine operator position that needs a variety of controls. The sensitive controls such as steering wheels, pedals, and joysticks are better physical, but the other elements such as UI (user interface) and buttons are designed as virtual ones, to provide both for easy repositioning of the prototype layout of these elements when exploring ergonomics and at the same time speed up the prototyping process itself.

3.2 Specification of Hardware Used

Of the hardware elements used, the VR headset was the most important. For pilot testing, the choice was narrowed down to a standalone device, supporting hand tracking and with the ability to track the environment using the inside-out method, i.e., without the need for tracking markers in space. Due to the complexity of the scene and the lack of computational power, a wireless connection method to the computer was chosen that provides sufficient performance while maintaining the advantages of a standalone headset, such as the comfort of use. The chosen VR headset was Meta Quest 3, which combines sufficient image quality, the ability to connect to a PC for image rendering, reliable hand and head tracking, and good support for software development in Unity.

The vehicle simulator platform (Fig. 2) consists of a steel structure providing the necessary stability and allowing for the attachment of all hardware controls, including a typified heavy-duty vehicle seat. It is a fully adjustable steering column, pedals, and seat arm, equipped with a combination of joysticks. Easy transfer of inputs to the main computer is made simple by using a game steering wheel and pedals.

Fig. 2 The vehicle simulator platform visualization.

3.3 Proposed Software Design

When designing the software solution, it was most important to achieve smooth operation for the greatest possible immersion. The Unity game engine was used as a scenario development tool, which allows for the easy development of VR scenarios and supports surrounding hand and head position tracking.

An essential part of the test scenario was the development of logging software. For this purpose, a C# script was created to track the position of the index fingertip on each hand, as well as the position of the head. This data is recorded at a predefined time interval.

As the first test scenario, a heavy-duty sweeper was selected, statically positioned at a signalized intersection (Fig. 3).

Fig. 3 Sweeper cab positioned at a signalized intersection to investigate.

3.4 Design of Experiment

To evaluate the position of the person in the VR scene, we prepared a set of 8 tasks focused on different body parts and expected movements. Tasks were designed as passive and active tasks. Passive tasks required looking into a specified area of the cabin. Active tasks required active touches and interactions with the controls in the scene. A full list of tasks is presented in Table 1.

Task	Type	Focused on
Hold the steering wheel	Passive	Base position
Check the rear-view mirrors	Passive	Horizontal tilt
Check the traffic light	Passive	Top view
Check the area in front of the cabin.	Passive	Down view
Check the distance from the right curb	Passive	Right side
Turn on the engine	Active	Top view
Move the right brush to the curb	Active	Right hand
Activate water jet/brushes.	Active	Left hand

Table 1. List of performed tasks

A detailed vehicle model was provided by company 1to1design. The interior of the cabin is displayed in Fig. 4.

Fig. 4 Cabin from the operator's point of view.

4. ASSESSMENT EVALUATION

The main objective of this study was to analyze and visualize the operator's position and movement within the VR scene during training tasks. The novelty of these results lies in the ability to map user interactions, track ergonomic factors, and evaluate decision-making patterns in a simulated environment while offering a deeper understanding of how operators interact with the virtual utility vehicle interface.

The tracking path of the left hand is displayed in blue; head position tracking is displayed in green, and right-hand tracking is displayed in red. Task time duration in seconds is displayed in the top part of the plot. Three key examples that best illustrate the issue are displayed in the following figures.

Fig. 5 shows the passive task *Check the area in front of the cabin*. As expected, the greatest range of motion is observed in head tracking, where it is evident that the person leaned forward in the scene to investigate the specified area in front of the cabin.

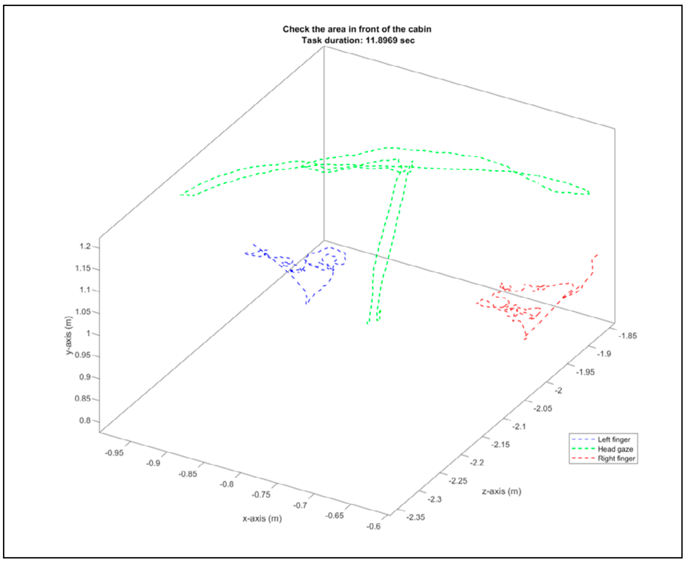

Fig. 5 Visualization of the tracking data during the task "Check the area in front of the cabin".

Compared to Fig. 5, Fig. 6 shows the wide range of right-hand movement while touching controls on the top cabin panel.

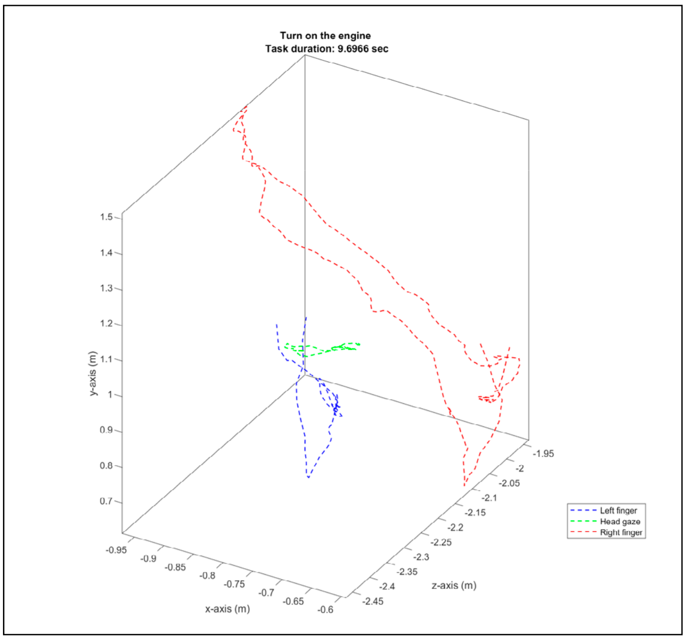

Fig. 6 Visualization of the tracking data during the task "Turn on the engine".

Fig. 7 shows frequent movements of the right hand during the task *Move the right brush to the curb*, where the brush controls are placed on the right armrest, and the shift of the head position caused by the tilt of the body for a better view outside of the cabin.

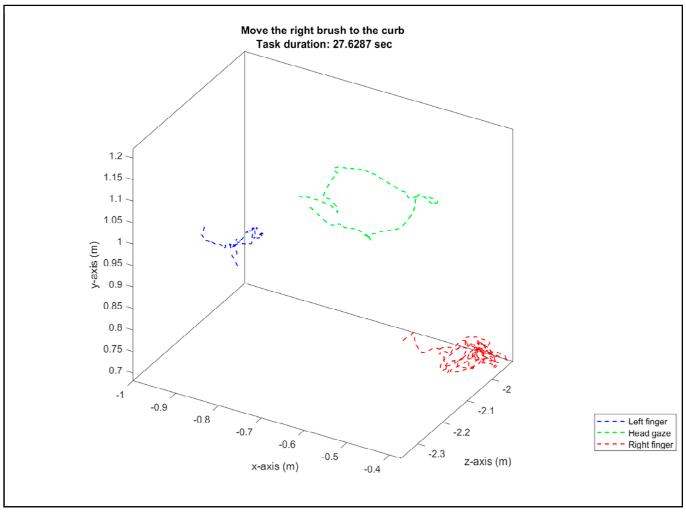

Fig. 7 Visualization of the tracking data during the task "Move the right brush to the curb".

5. DISCUSSION

5.1 Use of VR in Smart City Training Contexts

The integration of VR in training programs for urban utility services presents significant opportunities for improving preparedness and operational safety. Smart cities are characterized by dynamic infrastructure, complex traffic environments, and high demands for service reliability and utilization of up-to-date digital approaches such as digital twins or digitalized urban street environments. VR simulations enable the replication of these specific urban contexts in a controlled environment, including congested intersections, narrow streets, or unconventional traffic flows. These can be adapted to the real areas of the particular city, focusing on the most demanding or problematic streets and/or actions. By allowing trainees to experience and repeatedly practice such situations without physical risks, VR contributes to the development of more competent and responsive operators, which is essential for maintaining smooth operations in smart city settings.

Similar applications of immersive VR environments have been used to evaluate human behavior in complex urban scenarios, such as pedestrian interactions with autonomous vehicles (Bouchner, Novotný, Orlický, & Topol, 2024).

5.2 Practical Value and Analytical Capabilities of the VR Approach

A key advantage of the VR-based simulator lies in its flexibility and analytical potential. Scenes can be adapted to reflect specific training requirements, including rare or hazardous scenarios that would be impractical to reproduce in real life. Unlike static simulators, the immersive VR environment allows the operator to exit the cabin and explore the vehicle surroundings, providing a more realistic spatial experience. The system enables detailed monitoring of user interactions, such as the exact driving trajectory, task completion time, or even quantification of cleaned surface area during sweeping operations. These metrics offer objective feedback on performance and progress, enhancing the effectiveness of the training process.

5.3 Human-Centered Evaluation Through Motion Tracking

The ability to track operator movement within the VR environment supports advanced ergonomic assessment and iterative learning. By analyzing head and hand motion patterns, it is possible to identify whether a trainee is improving over time, e.g., reducing unnecessary motions, or whether the cabin layout hinders their performance. The system can also highlight situations where the operator is forced into constrained or risky movements due to design limitations. This approach not only supports individualized feedback but also allows evaluators to assess whether a specific vehicle design meets the operational needs of a given urban environment.

Integrating active feedback systems, such as an electronically controlled steering wheel and brake pedal, could further enhance the behavioral realism of the simulator (Bouchner & Novotný, Development of Advanced Driving Simulator: Steering Wheel and Brake Pedal Feedback, 2011). This would allow for more accurate monitoring of driver responses to physical control resistance and improve the evaluation of human–machine interaction.

5.4 Study Limitations and Future Work

A key advantage of simulation-based training is the ability to repeat specific scenarios or conduct tasks over extended periods, allowing for the analysis of fatigue-related changes in operator behavior. A challenge specific to virtual reality is the relatively frequent occurrence of motion sickness in some users, which may constrain both the duration and complexity of training scenarios, particularly those involving rapid movements.

While this study presents promising insights, it was conducted on a small sample of participants. Future research will therefore focus on repeated trials with a larger and more diverse user group. The main goal is to develop a clear evaluation method for analyzing user movement in the simulation to identify improvements in maneuvering, potential risk situations, or design-related limitations, and to use this information for an objective assessment of trainee performance.

6. CONCLUSION

In this paper, we showed our prototype of a VR training tool for utility vehicle operators. The developed SW and HW make up an innovative tool that takes advantage of the latest development in combined (augmented) reality as well as powerful PC graphics. Such a device can realistically simulate the views and operational environment the operators are exposed to when doing their job. On the other hand, thanks to such a setup (combined VR), the virtual models, the scenes, and the scenarios can be changed "with one click", without requiring the operator to leave their seat. This was approved with a pilot experiment described in IV of this paper.

This study demonstrated the feasibility of tracking key body parts, specifically head movement and fingertip positions, within a VR-based training environment for utility vehicle operators. By analyzing spatial positioning, movement patterns, and task duration, we provided valuable insights into operator interaction in a simulated cabin environment. The results confirmed that VR-based training enables precise motion tracking and performance assessment, offering a foundation for future ergonomic evaluations and operator training optimizations in smart city applications.

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REFERENCES

Akyeampong, J., Nevins, L., Udoka, S., & Carolina, N. (2013). Using digital human modeling to enhance work visibility for excavator. *In IIE Annual Conference. Proceedings. Institute of Industrial and Systems Engineers (IISE).*, (str. 1909). Plzen, Czech Republic. Načteno z https://www.researchgate.net/profile/Silvanus-Udoka-2/publication/288578462_Using_digital_human_modeling_to_enhance_work_visibility_for_excavator/links/5845e5c208aeda69681a608c/Using-digital-human-modeling-to-enhance-work-visibility-for-excavator.pdf

Anacleto Filho, P., Colim, A., Cristiano, J., Lopes, S., & Carneireo, P. (2024). Digital and Virtual Technologies for Work-Related Biomechanical Risk Assessment: A Scoping Review. *Safety, 10*, 79. doi:10.3390/safety10030079

Artyukh, O. M., Lut, K., Dudarenko, O., Kuzmin, V., Kuzmina, M., & Shcherbyna, A. (2023). *Basic ergonomics in automotive engineering: Study guide.* National University «Zaporizhzhia Polytechnic». doi:ISBN 978-617-529-428-4

Bouchner, P., & Novotný, S. (2011). Development of Advanced Driving Simulator: Steering Wheel and Brake Pedal Feedback. *In Proceedings of 2nd Conference on Circuits, Systems, Control, Signals.* (stránky 170–174). Athens: World Scientific and Engineering Academy and Society. doi:ISBN 978-1-61804-035-0

Bouchner, P., Novotný, S., Orlický, A., & Topol, L. (2024). Evaluating Visual Communication Interfaces Between Pedestrians and Autonomous Vehicles Using Virtual Reality Experiments. *Neural Network World, 34*(5), 279-291. doi:10.14311/NNW.2024.34.015

da Silva, A., Mendes Gomes, M., & Winkler, I. (2022). Virtual Reality and Digital Human Modeling for Ergonomic Assessment in Industrial Product Development: A Patent and Literature Review. *Applied Sciences, 12*, 1084. doi:10.3390/app12031084

de Winter, J., de Groot, S., Mulder, M., Wieringa, P., Dankelman, J., & Mulder, J. (2009). Relationships between driving simulator performance and driving test results. *Ergonomics, 52*, 137–153. doi:10.1080/00140130802277521

Devine, S., Nicholson, C., Rafferty, K., & Herdman, C. (2017). Improving the ergonomics of hand tracking inputs to VR HMD's. *25th International Conference in Central Europe on Computer Graphics, Visualization and Computer Vision (WSCG 2017)*, (stránky 167–174). Plzen, Czech Republic. Načteno z https://otik.uk.zcu.cz/bitstream/11025/29748/1/Devine.pdf

Eswaran, U., Eswaran, V., Eswaran, V., & La Rosa, S. (2023). INTEGRATING VIRTUAL REALITY WITH INTERNET OF THINGS: ARCHITECTURES, APPLICATIONS AND CHALLENGES. *i-Manager's Journal on Augmented & Virtual Reality (JAVR), 1*. doi:10.26634/javr.1.2.20154

Grandi, F., Peruzzini, M., Campanella, C., & Pellicciari, M. (2020). Application of innovative tools to design ergonomic control dashboards. *In Transdisciplinary Engineering for Complex Socio-technical Systems–Real-life Applications*, 193–200. doi:10.3233/ATDE200077

Grandi, F., Peruzzini, M., Zanni, L., Campanella, C., & Pellicciari, M. (2018). Digital Manufacturing and Virtual Reality for Tractors' Human-Centred Design. *In Transdisciplinary Engineering Methods for Social Innovation of Industry 4.0*, 702–711. doi:10.3233/978-1-61499-898-3-702

Li, Y., Yuan, W., Zhang, S., Yan, W., Shen, Q., Wang, C., & Yang, M. (2024). Choose your simulator wisely: A review on open-source simulators for autonomous driving. *IEEE Transactions on Intelligent Vehicles, 9*, 4861–4876. doi:10.1109/TIV.2024.3374044

Morana, G. (2024). *Impact of Imaging and Distance Perception in VR Immersive Visual Experience.* PhD thesis, University of Hertfordshire, United Kingdom. Načteno z https://uhra.herts.ac.uk/bitstream/handle/2299/27468/17070885%20MORANA%20Giuseppe%20Final%20Version%20of%20PhD%20Submission.pdf?sequence=1&isAllowed=y

Morra, L., Lamberti, F., Prattićo, F., La Rosa, S., & Montuschi, P. (2019). Building trust in autonomous vehicles: Role of virtual reality driving simulators in HMI design. *IEEE Transactions on Vehicular Technology, 68*, 9438-9450. doi:10.1109/TVT.2019.2933601

Morse, C., Mokhlespour Esfahani, M., & Krishnan, S. (2024). ErgoReality: A Virtual Reality Simulations Software for Ergonomic Analysis of Workstation Design. *In Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 68*, 659-662. doi:10.1177/10711813241260293

Pfeffer, S., Rößler, M., Maag, S., Langwaldt, L., Schunggart, L., Strigel, M., . . . Ochtrop, M. (2024). Virtual Ergonomics - Ergotyping in virtual environments. Human Interaction and Emerging Technologies (IHIET 2024). *Proceedings of the 12th International Conference on Human Interaction & Emerging Technologies, 157*, 306–315. doi:10.54941/ahfe1005490

Stefan, H., Mortimer, M., & Horan, B. (2023). Evaluating the effectiveness of virtual reality for safety-relevant training: a systematic review. *Virtual Reality, 27*, 2839–2869. doi:10.1007/s10055-023-00843-7

Topcuoğlu, O. (2018). *Exploring the potentials of virtual reality technology for user evaluation of a shunter locomotive driver cabin.* Master's thesis, Middle East Technical University, Turkey. Načteno z https://open.metu.edu.tr/bitstream/handle/11511/27382/index.pdf

Vincenzi, D. A., Mouloua, M., Hancock, P., Pharmer, A. J., & Ferraro, J. C. (2023). Human Factors in Simulation and Training: Application and Practice. V D. A. Vincenzi, *Human Factors in Simulation and Training: Application and Practice.* Boca Raton: CRC Press. doi:10.1201/9781003401353

Wynne, A., Beanland, V., & Salmon, P. (2019). Systematic review of driving simulator validation studies. *Safety science, 117*, 138–151. doi:10.1016/j.ssci.2019.04.004

Zhang, Y., Chen, K., Sun, Q., & Carolina, N. (2023). Toward optimized VR/AR ergonomics: Modeling and predicting user neck muscle contraction. *In ACM SIGGRAPH 2023*, (stránky 1–12). doi:10.1145/3588432.3591495