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DIGITAL RECONSTRUCTION OF REAL (NEAR) ACCIDENTS OF VULNERABLE ROAD USERS (VRU) IN THE CZECH REPUBLIC – MODERN TECHNOLOGY BRINGS NEW PERSPECTIVES

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Abstract. Protecting vulnerable road users (VRUs) remains an issue despite significant advances in the development of integrated safety, autonomous driving and cooperative environments. As part of accident/collision processes, the urban area of municipalities continues to constitute a risk environment with a relatively high frequency of serious injuries (VRU) even at relatively low speeds. In order to understand and increase road safety, it is necessary to analyse the causes of traffic accidents in more detail using video recordings, virtual reality (VR) and automated computer vision methods. The state of the art in the Czech Republic is limited due to the absence of high-quality and extensive data sets. This article constitutes a proof-of-concept solution for the digital reconstruction of selected accident/collision events in 4 cities of the Republic, specifically in Prague, Liberec, Česká Lípa and Jaroměř. It makes it easier to identify, parameterize and virtualize the results of a traffic conflict study and can provide input data for the testing and validation of sensors, interaction models of road users' behaviour, and preparation of scenarios for a simulated environment; ultimately it reinforces prevention efforts.

Keywords: Vulnerable road user (VRU), accident/collision events, road safety, virtual reality (VR), photogrammetry, integrated rescue system (IRS), Czech Republic.

1. Introduction

Based on long-term cooperation in the development of cars at Škoda Auto, involvement in preventive IRS programmes and educational activities for primary and secondary schools, we have decided to better understand the occurrence of traffic accidents involving vulnerable road users (VRU) to map the state of the art and subsequently to create a proof-of-concept solution for its detailed analysis. Using the tools of modern technology, such as virtual reality, video analysis, photogrammetry and laser scanning, we obtain a unique insight that helps us understand and evaluate better the key parameters of these adverse events in the context of space and time. Their prevention/elimination remains the key goal in the near future, especially with the contribution of better proposals for sensory functions, both of vehicles and cooperative transport environments, as well as test scenarios as such and more intensive/better preventive and educational activities.

Data collection has been handled in the project using public camera infrastructure, on-board vehicle cameras, 3D laser scanners, cameras and UAVs. The next step is the digital reconstruction itself, with the final export to virtual reality and the subsequent use of HMD technology to simulate and experience a real accident in the digital world. In addition to the methodological procedure of the solution, we have created our own software application serving primarily the IRS units. We have validated the procedures suggested by use and their results by comparing them with the commercial Virtual CRASH solution. The Police of the Czech Republic has successfully adopted our insights into its practice and nationwide trainings of its members have been held to use the created tools. In cooperation with the Czech Police and the Vision 0 platform, preventive actions using VR simulations based on real traffic accidents are still ongoing. In the future, we would like to upgrade our approach from the proof of concept stage to a more robust application in practice.

In the context of the entire work, it is also important to mention the growing need to collect data from accidents that not only have health consequences, but also cause material damage [1]. Both WHO and EU statistics [2, 3] show that vulnerable road users (VRUs) account for more than half of all road accident deaths. In the EU, VRU collisions with a vehicle constitute almost 70 % of the total number of fatal accidents in urban areas.

Data from the Czech Republic have shown a similar trend in the last decade [4]. VRUs generally have a high degree of freedom of movement in an urban environment and tend to break traffic rules, thus showing a greater propensity for accidents and injuries. There are even differences in the behaviour in different cities [5–8]. The statistics show that achieving the Vision 0 goal by 2050 will be difficult.

Despite huge progress in the field of integrated vehicle safety and autonomous driving, collision-free transit and interaction with VRUs in urban traffic remains a challenge [9]. In any case, vulnerable users often cannot avoid death or serious injuries in a collision, even at relatively low speeds, when accident events in urban areas occur. Recognizing VRUs is a much more difficult task for a vehicle, e.g. as part of the functions of the AEB system, than recognizing other vehicles.

2. Research

Most cities are equipped with relatively large camera surveillance systems. Such a developed network offers the opportunity to use video analysis in many areas dealing with traffic safety. There are currently not a lot of research and data sets available in the Czech Republic, which may create a gap due to the insufficient coverage of input data needs for the development of advanced driver assistance systems (ADAS), Automated Vehicles (AVs) and cooperative environments. Video analysis in the form of trajectories and speed profiles provides a description of the behaviour of individual road users at the micro level, which is a key input for many applications, such as assessment of the safety and efficiency of transport systems and infrastructure, or calibration of behavioural models, etc.

This is confirmed by the conclusions of the extensive InDeV Horizon 2020 study [10]. The outputs of the InDeV project, just like Ahmed et al. [11], describe errors in police accident records that occur when measuring the accident site, information on injury rates, vehicles, roadway conditions and the specific environments. The described inaccuracies have a significant impact on any analysis. At the end, the authors recommend greater use and development of a method for studying traffic conflicts (e.g. Swedish Traffic Conflict Technique, DOCTOR – Dutch Objective Conflict Technique for Operation and Research) using video analysis. Data obtained from vehicle on-board cameras and infrastructure as one of the 4 pillars of data sources [12–17] are reported by the consortium P.E.A.R.S. [18], which addresses the development of the ISO standard for traffic safety assessment and for active safety technologies integrated into vehicles using virtual simulation. The reason for obtaining additional input data for development, testing and homologation is the fact that ADAS systems do not cover 100 % of all scenarios, while AV system require 100 % coverage of ideally all possible real critical scenarios [19]. The verification of the functions of ADAS systems vs. VRU in independent testing is described in PEDICRASH and AAA tests and studies, the results of which show limited effectiveness on selected complex scenarios [20, 21].

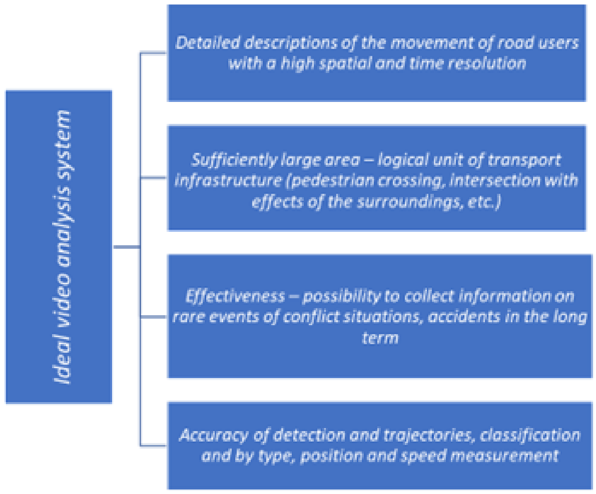

Figure 1. Ideal video analysis system.

Real critical scenarios, situations and scenes require high-quality digitization, with the interconnection of driving data, and together with the application of methods using surrogate measures of safety (SMoS), they enable quick proactive solutions to understand all the causal contexts of accident and near-accident events.

The given environment of critical situations can be reconstructed through scanning using multi-image photogrammetry. The output is a cloud of points that is used to create 3D models. The importance in terms of accuracy and time savings of accident site measurements with its subsequent virtualization when using modern measurement techniques by the police and forensic science is indicated, for example, in the papers [22–24]. Other uses are reported, for example, in papers in the field of research on traffic flows [25] or road infrastructure safety [26, 27]. From our own experience, we can mention the application for in-depth research on the transport safety made by teams such as UFO (VW), VDB (Skoda Auto), AARU (Audi). Currently, some service departments of the Transport Police of the Czech Republic already use modern technology, such as UAV photogrammetry and ground laser scanning.

Video analysis including kinematic data and trajectories was used, for example, in research within the PROSPECT project [28], a study from Vancouver, British Columbia, focused on cyclists [29], or an analysis of pedestrian behaviour using walk parameters in Nanjing, China [30].

An innovative approach to data collection was applied in the Ko-PER project containing data from 8 infrastructure cameras and 14 laser scanners. The data contain sequences with object markings, object classes and hundreds of road users [31]. The ideal video analysis processing workflow is described in Figure 1.

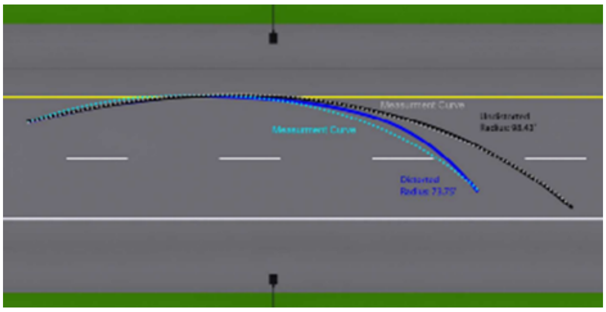

Figure 2. Comparison of tyre marks from distorted and undistorted images.

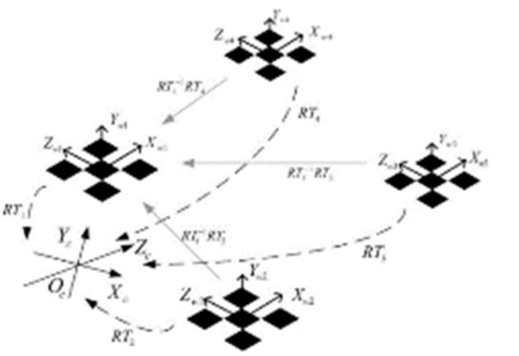

Figure 3. Scheme of a synthetic calibration objects.

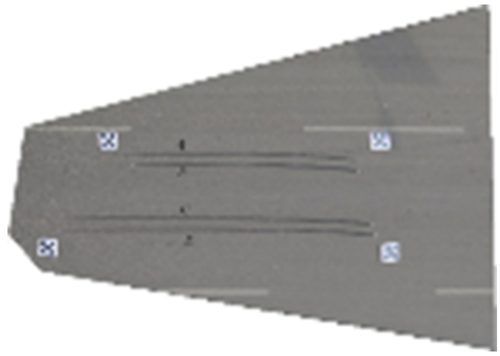

Figure 4. Rectified image of traffic accident.

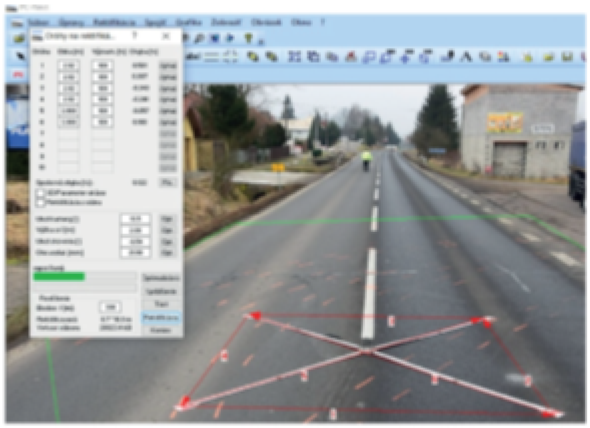

Figure 5. PC Rect software.

The detection of road users is dependent on the complexity of the road traffic environment and is not easy to handle, so it is in the interest of many studies [32–39]. The existence of publicly available data sets and algorithms is important for the development and testing of detectors [40–44].

A very important part of image analysis is rectification; paper [45], for example, evaluates measurement errors based on lens distortion and its impact on photogrammetric measurement of the distorted image; Figure 2 shows how the difference in tyre track measurement can cause a difference in the final results of the accident analysis.

Another study [46] addresses the measurement accuracy affected by calibration with respect to the ratio of area of the calibration object at the accident site or the location of the calibration object using a cluster of small flexible objects. Figure 3 shows a scheme of calibration of the object from the calculation of the homographic matrix H and Figure 4 shows a rectified track image.

Another paper evaluates accuracy using the PC Rect software, see Figure 5 [47].

Trajectory extraction – object tracking with their detection has several approaches [48].

- Manual methods – the analyst will mark each participant based on the specified frequency. The reason for use compared to the automated method is high accuracy, at the same time it does not address the issue of possible occlusion [49], incorrect classification, etc. [50]. However, the extraction may be subject to human error and the number of observations is limited.
- Automated methods – they process the image to identify and track moving objects in sequential video frames. Compared to the manual method, automated methods are not time consuming and there is no human error. It is possible to process a larger volume of trajectories. The problem is the aforementioned occlusion, changes in light, the movement of shadows or the movement of larger groups.

Many current studies deal with the monitoring and prediction of VRU trajectories [50–53].

The basic approaches are shown in Figure 6.

The above procedures are applied to a wide range of software tools developed for trajectory extraction. [53–60]. Most of the similar tools do not explicitly provide for use by other analysts.

Speed measurement There are many different approaches to calculating speed with the application of different methods according to the purpose of the research [61]. For example, the method applied in the Prospect project ensured results among the derived trajectories with a relative accuracy of 0.5–1 m [62]. Another study [63] at low speeds applies the cross ratio method from projective geometry with σ 1.3 % and $\overline{\Delta}$ 1.5 %.

Another article in the field of forensic science proposes a method of estimating the speed of a vehicle in

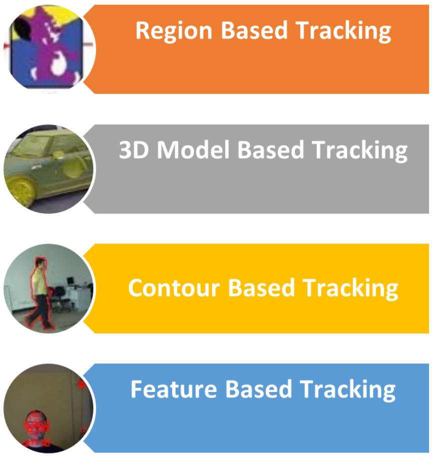

Figure 6. Basic approaches to VRU trajectory prediction.

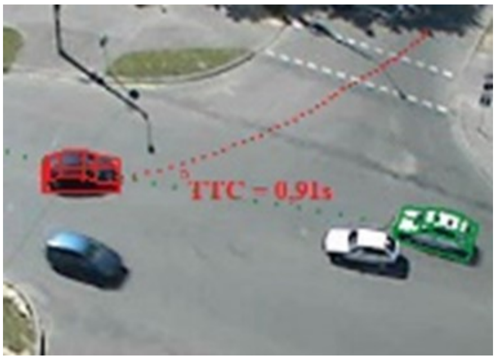

Figure 7. T-Analyst.

a video using a virtual plane and a virtual reference line (VSEM) [64]. The following article suggests reconstructing accidents from CCTV recordings using volumetric kinetic mapping (VKM) [65].

For an overview, we present freely available software applications available from websites with the function of trajectory extraction from video recordings [66].

T-Analyst This is a database solution that makes it possible to select conflicts according to classification. It contains tools for placing predefined shapes (models) in the image, to extract trajectories or derive the speed of the monitored subjects/objects at a certain time (see in Figure 7).

RUBA (Road User Behaviour Analysis) The basis of the approach is a set of detectors that can be connected by logical rules. They are activated by movement and they highlight conflict situations in red. Under favourable conditions, it is possible to remove up to 90 % of the original footage that does not contain relevant information (see in Figure 8).

Traffic Intelligence project It provides a set of tools for the detection, tracking and classification of road users using a tracking algorithm mapping trajectory data and individual interactions (see in Figure 9).

Figure 8. RUBA.

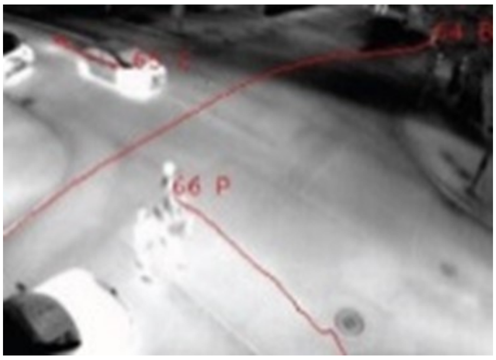

Figure 9. Traffic Intelligence project.

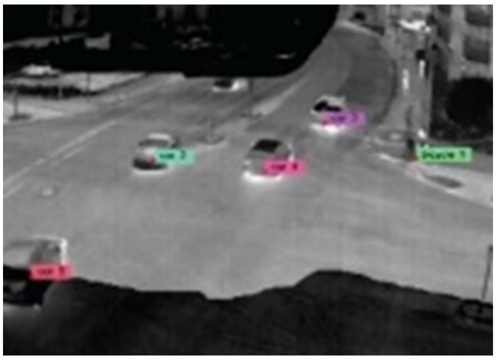

Figure 10. STRUDL.

STRUDL: Surveillance Tracking Using Deep Learning This approach is used as part of the InDeV project under Horizon 2020 as an open-source and free framework for videos captured by stationary cameras. It uses an object detector using deep learning to track and trace movement in the scene (see in Figure 10).

SafeCross It describes an open-source framework for proactive risk assessment of individual accidents. Cyclist detection and tracking is done automatically using advanced computer vision techniques and deep learning (see in Figure 11).

Last but not least, the use of virtual reality is becoming increasingly important for examining critical scenarios. Especially in behavioural research involving HMI. For example, article [67] represents empirical research evaluating different HMI concepts of behaviour

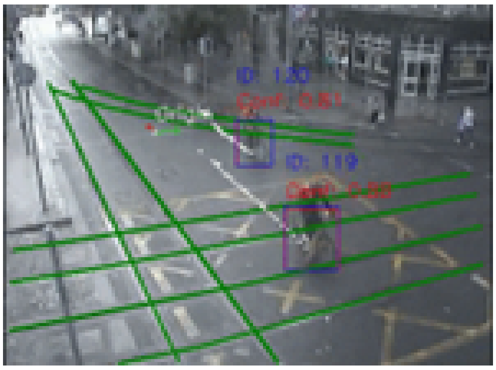

Figure 11. SafeCross.

Figure 12. Interactions in situations with multiple pedestrians.

Figure 13. The test process.

for two pedestrians, see Figure 12. Or study [68] dealing with decision-making processes when crossing the road in VRU vs. inbound vehicle interactions. The process of the test can be seen in Figure 13.

3. Method

Our way of looking at road safety in terms of preventing road accidents is unusual, and thus brings a unique point of view on the whole issue. The created proof of concept called virtual accident experience for real survival uses digital reconstruction of real accident event(s) all the way to the final use of HMD technology. In addition to the methodological procedure, we have created a software application written in Python, designed specifically for the Czech Police. The reason for our own In-house solution is the unavailability of SW licences for programmes to be commonly used by the units of the integrated rescue system. We attach a comparison of the conventional Virtual CRASH method with our method at the end of the chapter; at the same time it serves a validation function. By attaching a roadmap of reconstructed real (near-)accidents, we demonstrate the application in practice. Specifically, this covers the following locations in the Czech Republic: Prague, Liberec, Česká Lípa, and Jaroměř.

3.1. Methodological approach

The methodology for evaluating the 2D movement of an object is based on the image analysis of a recording from a single camera. This is a simple analysis, where the first prerequisite is the movement of the object on the horizontal XY plane. The effect of the Z-axis (bottom-up direction) is not taken into account. The advantage of the whole approach is its use even if we only know the top view of the situation, the bird's eye view/aerial view. For evaluation purposes, only an image from publicly available sources of various map materials, e.g. google.com/maps or mapy.cz, is sufficient. However, these data are burdened by distortion caused by their acquisition at angles of up to 30°. Therefore, for the subsequent refinement of the results, we supplement the map data set with laser scanning of the area; this step will give us the benefits of a real orthographic map. The accuracy of the measurement reaches the maximum uncertainty in units of centimetres, typically up to 2 cm on an area of $600\,\mathrm{m}^2$. The quality of the orthographic map can be exported in high resolution. The basic information for evaluation also includes the sampling frequency of the camera or video recording (FPS). The quality of the images is also influenced by the resolution of the camera, the lens used and the lighting conditions. The resolution of the orthophoto map, in other words the size of the scale – the ratio of the number of pixels to distances $[\mathrm{pix.\,m}^{-1}]$, can also be considered a decisive influence. When using scanner measurement, we can achieve hundreds to thousands of pixels per metre.

The methodology is usable for both static and dynamic (on-board) camera recordings. The principle of evaluation is based on the search for optical pairs of points (places) that are identical for the video recording and the orthophoto map. These points introduce a dimension into the image (there must be a sufficient number of them to achieve better results), which is defined by the orthophoto map. It is advisable to have the distribution of control points in the image especially in those places where the objects of interest move. The control points must be positioned on the XY plane to maintain clarity between the 2D orthomap and the image. Specifically, these are unambiguous contrasting elements, such as corners at pedestrian crossings, footings of traffic signs, curb joints, etc. Since the influence of perspective is not linear, it is advisable to place control points in both directions of the image. The impact of perspective on the results is then significant. We achieve the best results in the case of a record taken from a bird's eye view, similar to an orthographic one. On the contrary, in the case of shooting from a small (low) angle, the quality of the results is reduced; this is the case of an on-board camera, where the angle between the pad and the object is relatively small. The next step is to monitor the movement of the object itself in the image – object tracking. Due to the aforementioned limitation of movement on the XY plane, it is necessary to mark the tracked object at a place as close as possible to this plane, e.g., the point of contact of the tyre with the road. Tracking is performed manually on selected key frames (for reasons of accuracy); the timeline is defined by the sampling rate (FPS). The 2D coordinates obtained in this way in the video recording are converted into their equivalents in the 2D orthophoto map using linear interpolation. The obtained 2D motion coordinates are interlaced with a second-order polynomial across three points, due to smooth transitions between individual key frames. This gives us a two-dimensional description of the movement of objects in space – their position, speed and direction. The on-board record is evaluated with the difference that the above procedure is applied to each frame, or rather a suitable frame, in which control points can be defined with certainty. This eliminates the need to determine the position of the object, because this is the position of the camera itself. The results are influenced by the optical parameters of the camera itself (focal length of the lens and frame size = FOV).

3.2. Created software application

When developing the software tool, we referred to the methodology described in Section 3.1, further dividing it into 3 consecutive phases, shown in Figures 14, 15 and 16. For a clear illustration, we attach a practical reconstruction of one of the locations – Jaroměř (shown in Figures 17– 23.

This deals with the measurement of an accident site – ortho plan, from the accident site survey using more ground or aerial photogrammetry. The aim is to convert the marked tracks into 2D coordinates in scale using manual input and automatic detection based on the set parameters in the image. The format of the text output is compatible with the processes and technical equipment of the police used for subsequent completion of the report on the traffic accident. The application was optimized and subsequently tested.

Implementation of an application for measuring track coordinates in a 2D orthophoto plan using automatic detection has brought the following functionalities (the output is an executable version of the application that has been tested):

- Import of the requested ortho plan,
- Manual entry of track position,
- Automatic track detector using a defined search area, including parameter settings for detection (colour, threshold, gradient),
- Scale definition,
- Definition of the initial point of measurement,
- Orientation of the coordinate system using two points,
- Option to edit the description and annotation of each defined track,
- Option to group multiple defined points into one track,
- Option to introduce GPS 2D coordinates using a TXT file,
- Export of coordinates into a text file and a 2D ortho plan of the scene.

It includes the implementation of an application for dynamic analysis of the course of a traffic accident. The tool makes it possible to use both stationary and on-board camera recordings. The result is a visual interpretation of the trajectory of the traffic accident participants, including information on their speeds. The application and the implementation of annotations were tested again. At the same time, a methodology for defining primitives for the automatic creation of virtual reality was proposed and approved.

In addition, the ortho plan of the traffic accident scene was supplemented with the trajectories and speeds of the traffic accident participants. This allows us to bring important information and a completely new or different view of the specific traffic accident. It also provides data for the "live" virtual reality scene. As part of the implementation of an application for dynamic analysis of a traffic accident using a single camera, the following objectives have been achieved:

- Import of AVI, MP4 or MOV video,
- Basic video editing – selection of the area of interest (video clipping),
- Definition of pairs of points designed to evaluate the position in space using known coordinates from the ortho plan,
- Definition of objects and their points,
- Tracking of points in time,
- Evaluation of 2D coordinates of points and objects depending on time,
- Export of coordinates into a text file,
- Export into a 2D ortho plan of the traffic accident scene.

Export intended for visualizations in a virtual scene.

It includes the development and implementation of an application for automatic creation of a 3D scene of the traffic accident scene based on an orthophoto map supplemented with primitives. The application and the implementation of annotations were tested. Creation of methodological materials for all 3 phases. Application for measuring track coordinates in a 2D orthophoto plan using automatic detection and application of video analysis of the accident event record. An application has been implemented for automatic

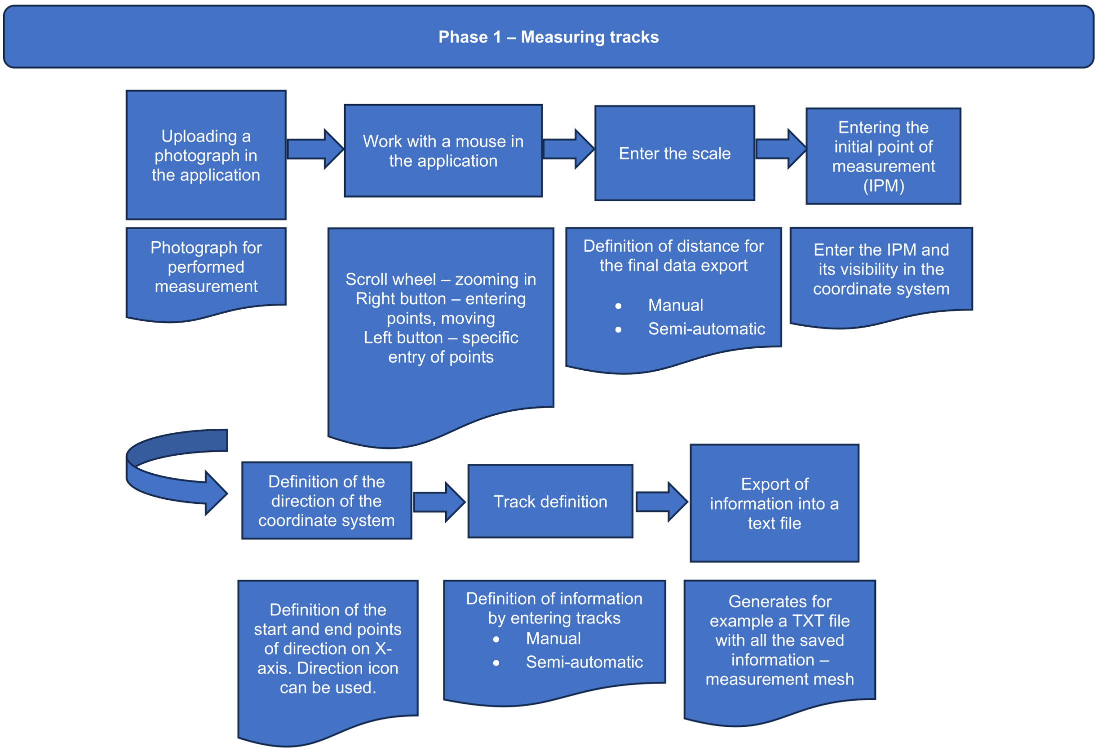

Figure 14. Phase 1 – Measuring tracks

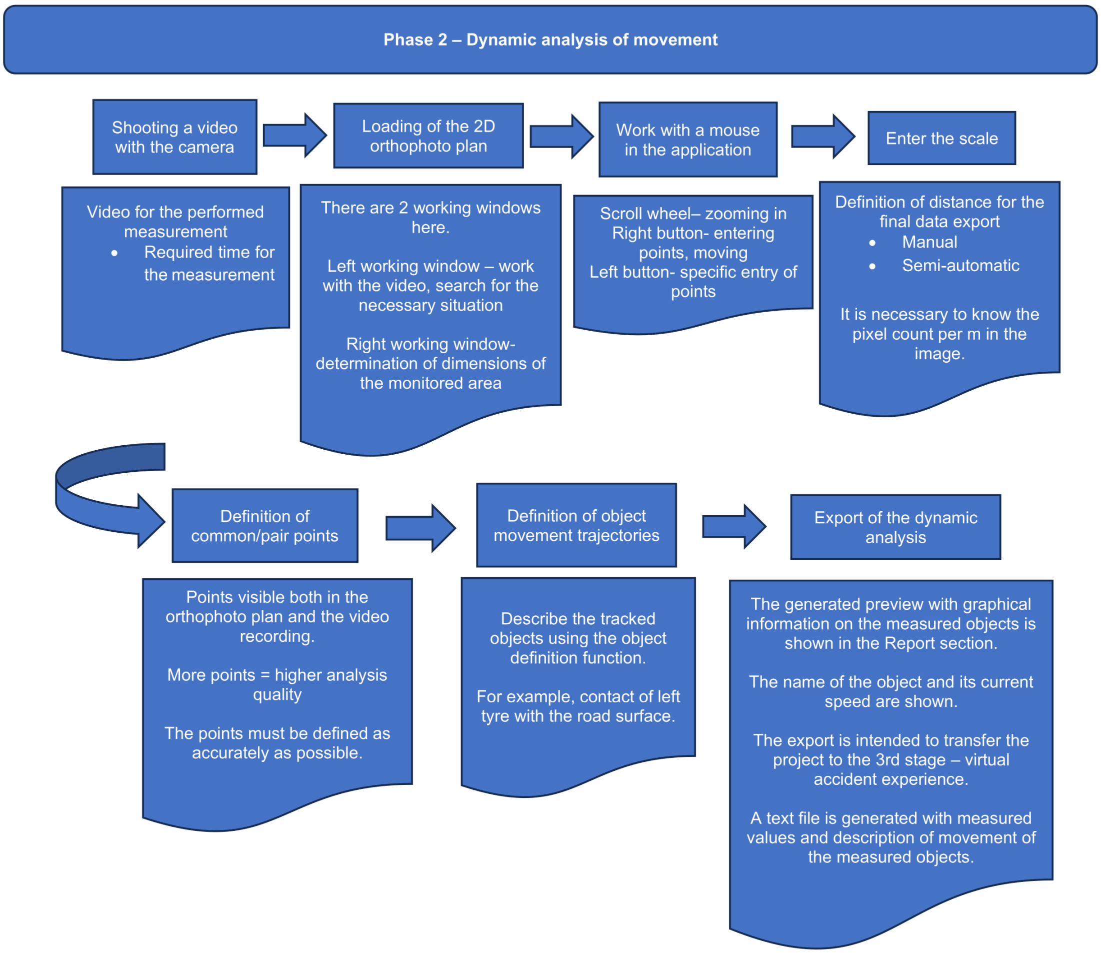

Figure 15. Phase 2 – Dynamic analysis of movement

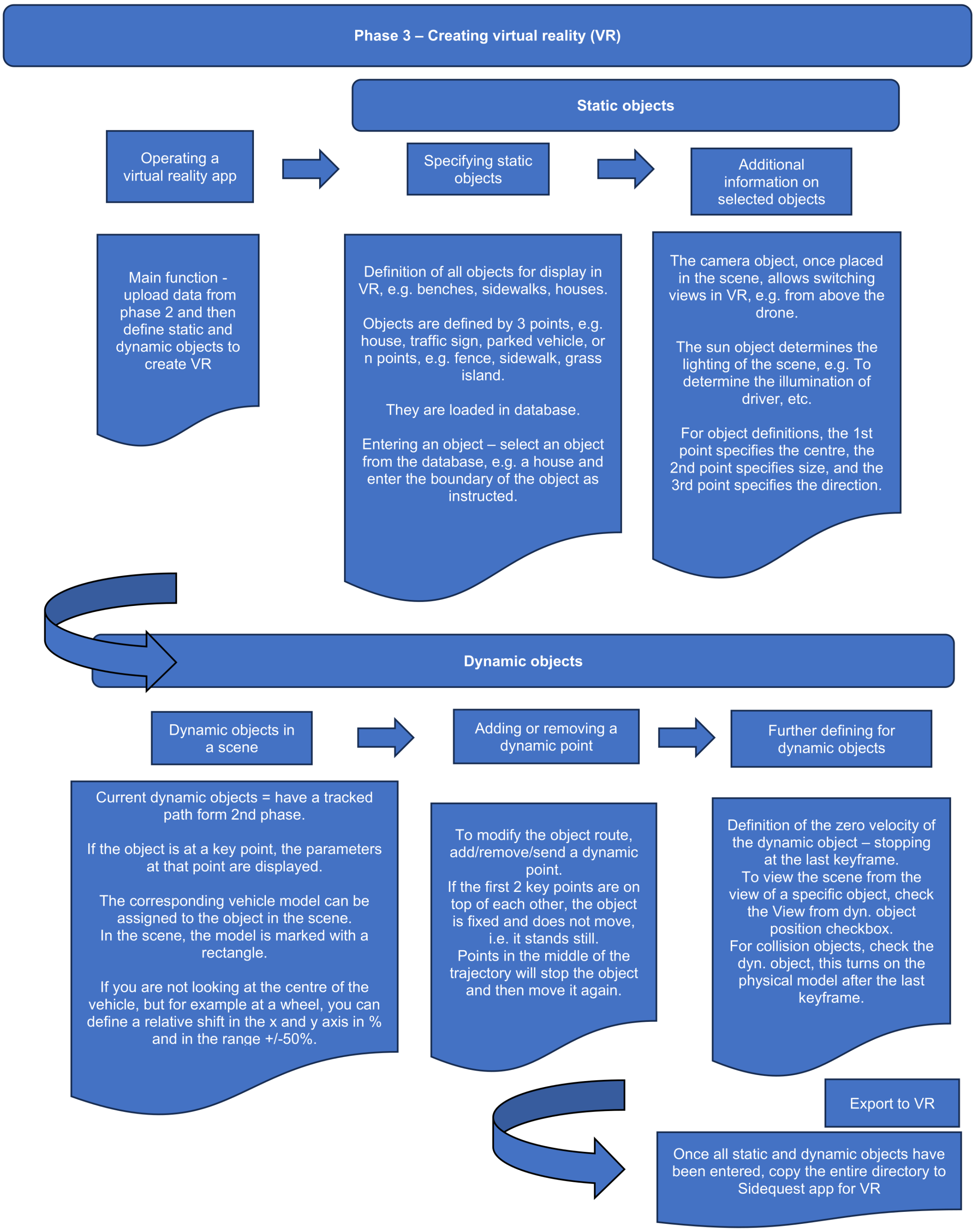

Figure 16. Phase 3 – Creating virtual reality (VR)

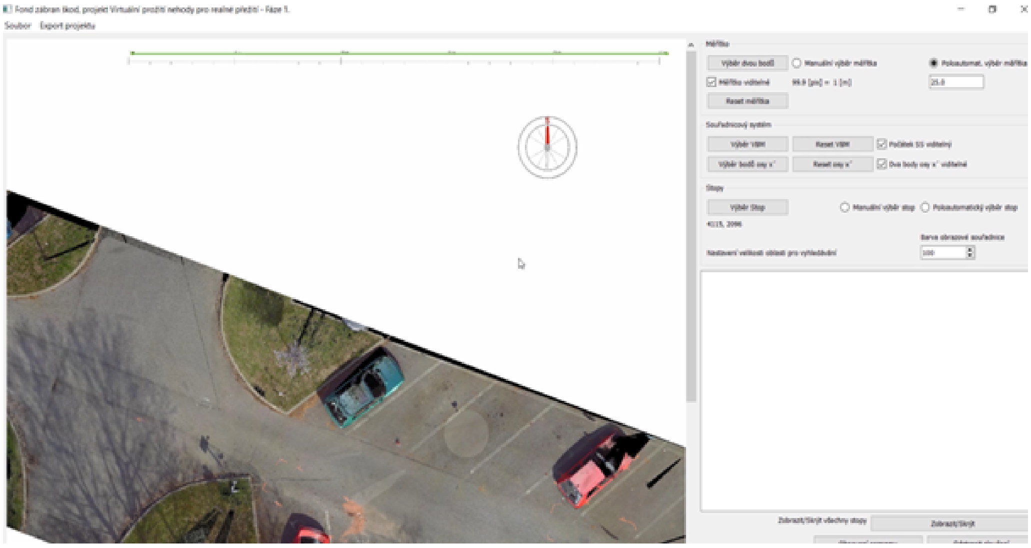

Figure 17. Defining scale.

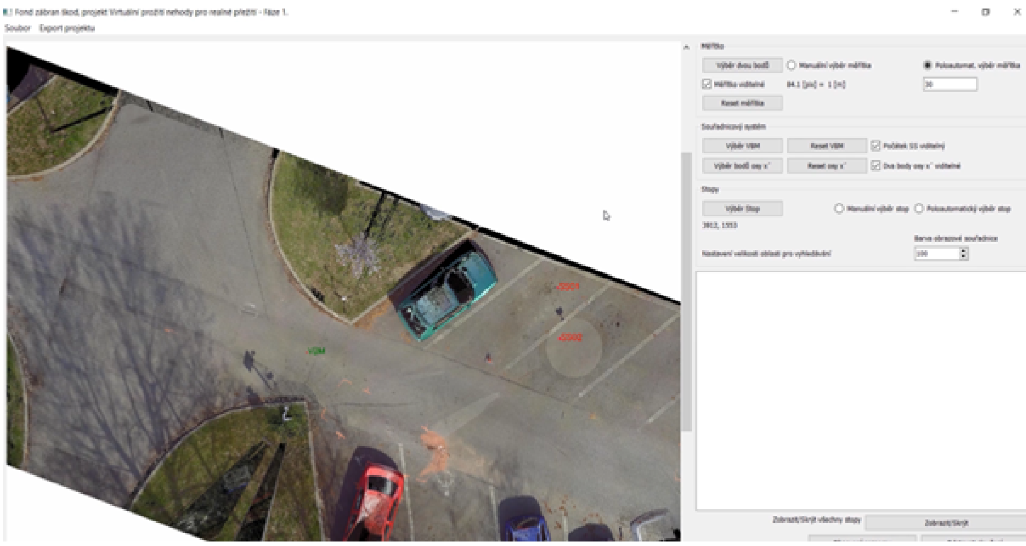

Figure 18. Defining the initial point of the measurement (IPM) and the direction of the coordinate system.

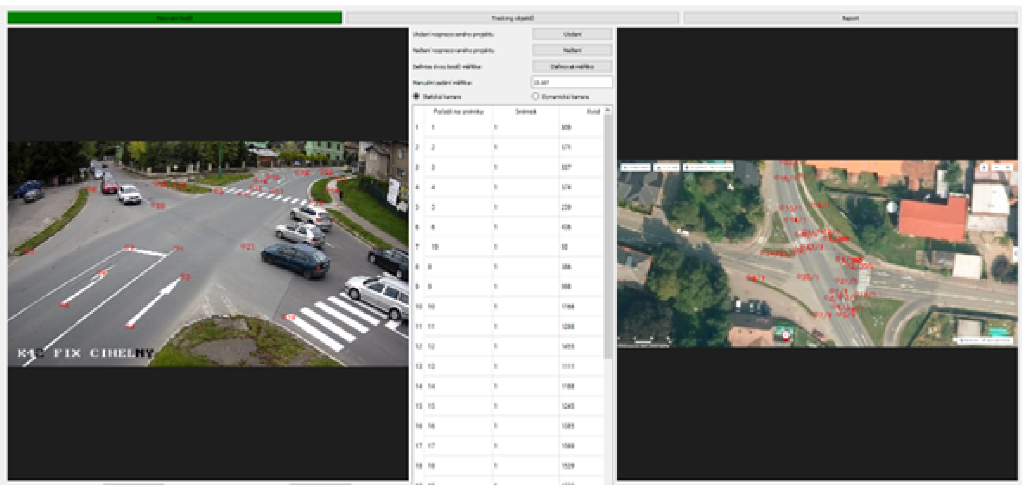

Figure 19. Pairing common points.

Figure 20. Results of dynamic video analysis.

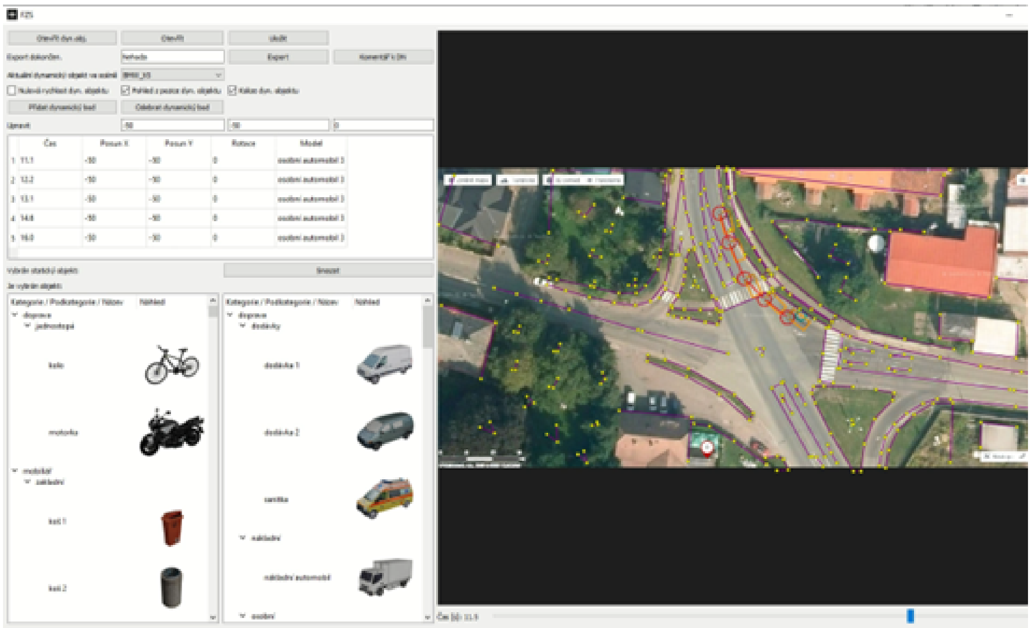

Figure 21. Creating a 3D virtual scene.

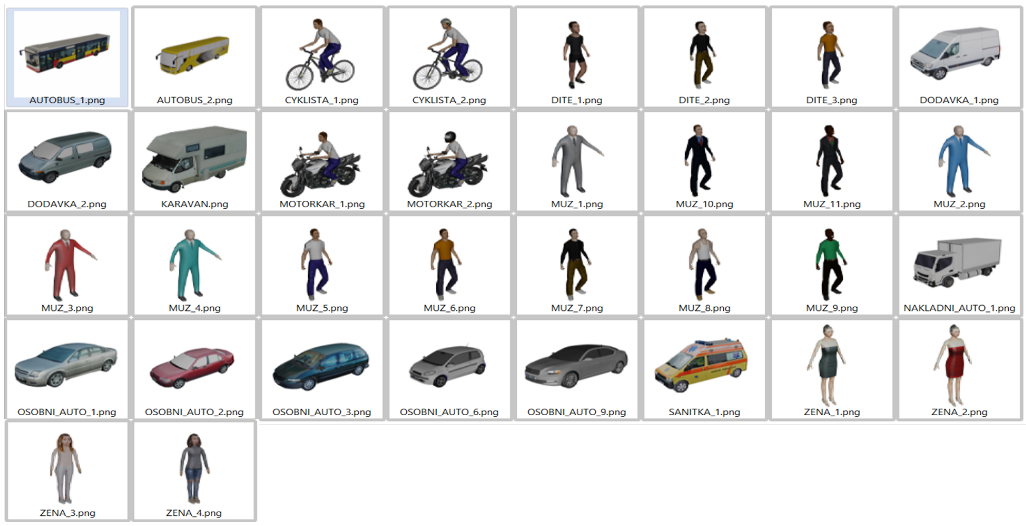

Figure 22. Dynamic VR scene object library.

Figure 23. Vehicle view in the VR scene.

creation of a 3D scene of the traffic accident scene based on an orthophoto map supplemented with primitives. Anonymized video outputs from virtual reality.

As part of the implementation of the application, the planned objectives have been achieved:

- Retrieval of the entered objects from the XML source and additional information,
- Setting of the loaded objects to the specified position and the required rotation,
- Editing of the basic shape of the specified objects based on the control curves,
- Setting of the tracks and speeds of moving objects,
- Loading of specified tracking points, both in space and tied to moving objects,
- Setting of the scene background and lighting,
- Creation of control and information systems and means for previewing the scene.

Example results can be seen in Figures 24 and 25, which depict a reconstructed situation from Liberec, Malé náměstí. Subsequently, validation of the obtained results was carried out on another dataset from Praha, Smetanovo nábřeží, as illustrated in Figures 26, 27 and 28.

3.3. Validation of results from Praha, Smetanovo nábřeží

4. Discussion

The quality of the results is influenced by a number of factors, which are: camera/recording resolution, lens distortion and its type, angle of view of the scene, direction and size of the object's movement relative to the rotation of the frame (effect of perspective), recording sampling rate (FPS) and its stability, contrast between the monitored object and the environment, number of control points, quality of the orthophoto map (number of pix. m^{-1}), video codec used. Each of these factors will more or less influence the result.

From the point of view of a fundamental improvement of the results of the methodology it would be advisable to:

- To perform a lens calibration to compensate for image distortion,
- More effective placement of control points throughout the image. Ideally a regular grid with a size of e.g. 2×2 m,
- Digitize the entire area of interest in order to obtain 3D data. Then define control points directly in the 3D space,
- Use the Z-axis information (3D data) to evaluate the position of the object,
- Try to avoid obscuring significant points in the image (camera position relative to static objects in the camera frame),
- Interleave tracked points using more complex algorithms – 3rd order polynomial using 5 or more points, etc.

5. Conclussion

We have achieved the planned results of the development of a software tool and methodology for the processing of marked tracks from the scene of a traffic accident, taken with multi-image ground or air photogrammetry, 3D scanning, or other methods whose output is an ortho plan (rectified photographic image). The SW application makes it possible to create scenes for virtual reality based on data sets from real traffic accidents. Our effort has also been to identify factors affecting the quality of output data for the needs of safety and efficiency of transport systems, infrastructure or calibration of behavioural models (HMI). At the same time, nationwide training of representatives of the Transport Police and the Czech Police Headquarters has taken place in 14 regions in the use of the software tool and methodology for processing the location of a traffic accident, as well as nationwide training of representatives of the Communication and External Relations Department of the Czech Police Headquarters in the use of the software application and methodology for automatic creation of a 3D scene of the traffic accident based on an orthophoto map supplemented with primitives. In cooperation with the Czech Police and the Vision 0 platform, preventive actions using VR simulations based on real traffic accidents are still ongoing.

Finally, the paper has presented the verification of a method to obtain parameters such as speed and distance at a certain time, thus enabling the acquisition of SMO identifiers even when using a lower-quality video recording.

6. Future work

A follow-up study of traffic conflicts will be carried out using appropriate camera systems. The examined

Figure 24. Dynamic motion analysis results.

Figure 25. Digital reconstruction (left) and simulation in Unity and VR (right).

Estimated i nput parametrs - intervals +/- 1,5 km/h																	
video sampling frequence [Hz]				25						movemenmt in the X-axe					movement in vector		
middle values	x[m]	y [m]	z [m]	video snap	time [s]		velocity [km/h]		delta s [m]	delta t [s]	acceleration [g]	acceleration [g]		vector delta s [m]	acceleration [g]	acceleration [g]
Start	14,5	7,1	1,1	0,0	0,0											
Initial	0,4	6,9	0,7	32,0	1,3	track 0	39,5	track 0	14,0				track 0	14,1		
Evasive	-1,6	6,8	0,7	36,0	1,4	track 1	46,3	track 1	2,1	0,2			track 1	2,1		
Colision	-6,6	6,3	0,6	45,0	1,8	track 2	49,4	track 2	4,9	0,4	7,772	0,5	track 2	5,0	7,810	0,1
Stop	-19,5	4,6	0,4	102,0	4,1	track 3	20,5	track 3	13,0	2,3	0,509		track 3	13,1	0,513	

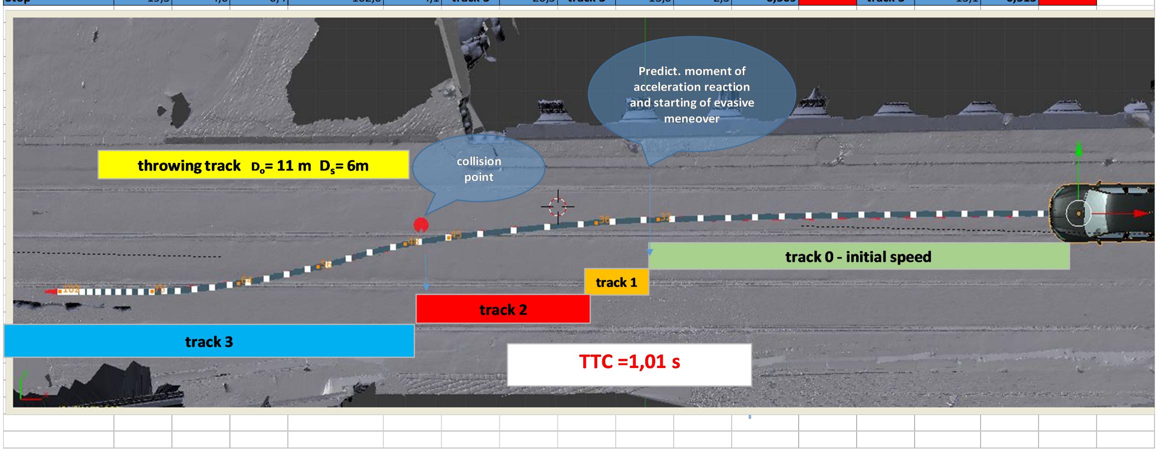

Figure 26. Accident analysis – video record.

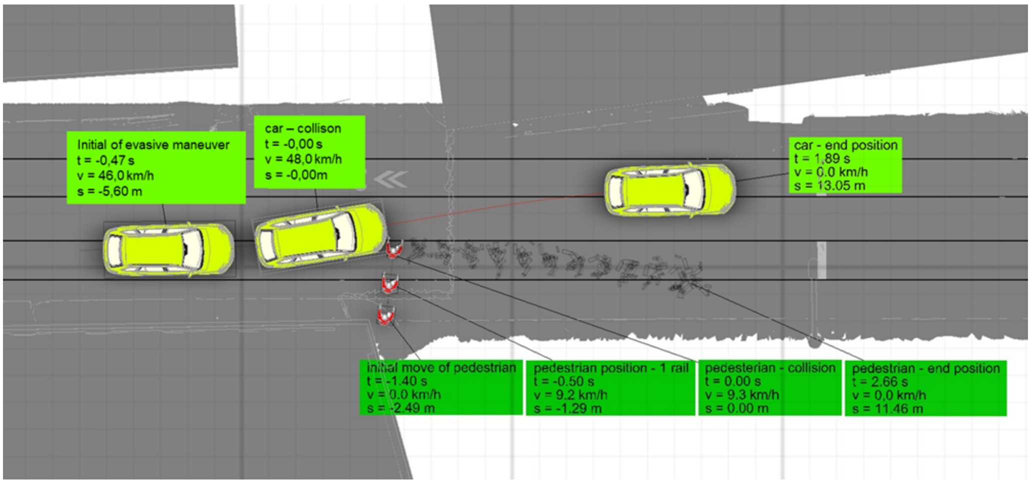

FIGURE 27. Accident analysis – conventional method.

Comparison of method - Vehicle		
	Conventional reconstruction Speed [km/h] (deviation ± %5)	Video reconstruction Speed [km/h] (deviation ± %5)
Initial of evasive maneuver	46	46,3
Collision	48	49,4
End position	0	0

Comparison of method - Pedestrian		
	Conventional reconstruction Speed [km/h] (deviation ± %5)	Video reconstruction Speed [km/h] (deviation ± %5)
Initial move of pedestrian	0	0
Pedestrian position 1 rail	9,2	10,8
Collision	9,3	11,9
End position	0	0

FIGURE 28. Accident analysis – methods comparison.

critical situations will include primarily collisions, potential collisions and traffic conflicts between pedestrians and vehicles, secondarily between pedestrians and cyclists, cyclists and vehicles, e-scooter riders, e-micromobility users, and other road users. A holistic approach will be applied to the acquired video data set to detect VRU intentions using cooperative methods. Intention detection will consist of basic primitive motion prediction, e.g. standing, moving or rotating. The subsequent trajectory estimate will be evaluated and categorized. This will be preceded by the selection of a suitable detection algorithm based on the DL architecture or a combination using the Bayesian BDL probability with the application of e.g. Fast-RCNN, R-FCN, Faster R-CNN, YOLOv5 or SSD.

Most accidents are due to human error. Therefore, it is advisable to add in the future a system view of the communication interface between the operator (driver) and the artificial system (vehicle, its parts). This will be achieved by using knowledge from the Driving Simulations Research Group at CTU, developing interactive vehicle simulators, scenario generation technologies and experiments using appropriate methods. Instruments working with psychophysical measures, advanced analytical and classification tools can add extra value to the results [69–78].

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