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ANALYSIS OF VIDEO RECORDINGS IN ACCIDENT RECONSTRUCTION

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Abstract:

Selected methods of quantitative analysis of video recordings are presented, which can be used to analyse images from both fixed cameras (highways, intersections, etc.) and vehicle-mounted cameras. The article deals with the use of video recordings in the reconstruction of road traffic accidents. Many drivers use digital video recorders (DVRs), the so-called dashboard cameras, which record the situation in front of or behind the car while driving. There are also many places where cameras are installed, such as highways, intersections, etc. In some situations, such recordings can be important evidence in establishing liability for a road traffic accident. However, in most of these cases, the video recording is only analysed qualitatively, while the article shows that a lot of quantitative information can also be obtained from the video recording, such as speeds, accelerations and directions of movement of the vehicles. Analysing the image of the camera moving with the vehicle is more difficult, but possible thanks to the analysis methods presented in the article. The reconstruction of a road traffic accident event using the presented methods can be carried out on the basis of recordings made with the help of recording devices that capture images of different quality. It is not necessary to know the parameters of the camera recording the image. However, knowing these parameters makes the analysis much easier. In addition, reference was made to the problems of image analysis that experts have to deal with when reconstructing accidents. It was pointed out that video recordings should be analysed using different methods depending on the situation they represent. The influence of the quality of the recording (resolution, distortion, image sharpness, recording speed, etc.) on the usefulness of the recording for obtaining quantitative information is also discussed. Finally, a method for estimating the uncertainty of the results is presented. The article confirms that it is possible to determine selected parameters of vehicle movement based on the analysis of the DVR recorder.

Keywords: *accident reconstruction, traffic accident, video analysis, digital video recorder (DVR), dashboard camera*

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1. Introduction

The reconstruction of a road traffic accident is a multi-stage process. One of these stages is the determination of the speed, acceleration, energy and trajectory of the vehicles involved in the accident. Obtaining this information is one of the most difficult tasks in accident reconstruction. The information on the basis of which these variables are determined comes from police records, sketches of the accident scene, investigations of the scene and witness statements, among other things. If technically possible, the data from tachographs (ADR), the so-called black boxes (Guzek, 2018), (Guzek and Lozia, 2021), on-board vehicle tracking systems (Qu et al., 2019) and the information contained in tracking devices (Olewiński et al., 2018) are also analysed (Kopencova and Rak, 2020).

Many drivers use DVR (Digital Video Recorder), also known as dashboard cameras, to record the situation in front of or behind the car while driving. If the vehicle involved in the road traffic accident was equipped with such a video recorder, the recording can also be a valuable source of information about the course of the road traffic accident. The video recording of the last moments before the road traffic accident and the recording of the road traffic accident itself could be the most important evidence in establishing liability. In most cases, the video recording is only analysed from a qualitative point of view, i.e. what is visible is taken into account in the reconstruction. The aim of this article is to show that a great deal of quantitative information can also be obtained from video recordings. The methods of quantitative analysis of video recordings are presented here. Extracting quantitative information from video recording is a difficult and complicated process (Verolme and Mieremet, 2017), but as we will show, it is possible. However, regardless of how it is used, video recording is a very valuable source of information in accident reconstruction, which has been confirmed in a paper (Abramowski, 2018).

This article presents the possibilities and limitations of obtaining quantitative information from video recordings captured by common video recorders used by drivers. It also discusses how individual parameters of video recorders have a significant impact on the possibility of obtaining valuable data from video recordings. Finally, the uncertainty assessment of the results is presented, which was carried out using the Monte Carlo method described in more detail in (Wach, 2014), (Okarma and Lech, 2008).

2. Literature review

There are only a few recent publications describing the method of obtaining quantitative data from a video recorded by a simple tachograph or a camera mounted in a vehicle.

Currently, in the vast majority of cases, recordings from cameras installed in vehicles are analysed for quality. They are used to obtain answers to the questions of whether an event took place, who was at fault, etc. (Giovannini et al. (Giovannini et al., 2021). Video recordings from recorders are also often used to increase road safety (Adamová, 2020).

In recording devices with a more complex design, much of the quantitative data is recorded in a hidden form (Kukheon et al., 2021). This data is readable and analysing it can provide many answers about the last seconds before a road traffic accident. Information about the driver's activities. However, many films are recorded by simple recording devices.

The literature also describes the reconstruction of road traffic accidents using footage from cameras mounted in unmanned aerial vehicles (Rok et al., 2020) or the analysis of road traffic by airplanes with video cameras (Outay et al., 2020)

Cameras are also used by autonomous driving systems. The authors present serious problems that exist when analysing images from moving cameras in vehicles compared to fixed cameras, where image analysis is much easier (Yao et al., 2019.).

There are many papers that present the possibilities of using EDR data and show how valuable this data is (Guzek, 2018), (Guzek and Lozia, 2021).

You can find work in the field of robotics where footage from video cameras is analysed, but the vast majority is so-called. Stereovision (Ding et al., 2021). There is also work that uses characteristic points of the environment to estimate velocity, as shown in (Lee et al., 2020), (Epstein and Westlake, 2019).

In the work of Abramowski (2015) and Abramowski (2018), certain assumptions were presented that make it possible to obtain quantitative data from video recordings taken with any type of camera (even old VHS cameras). The method combines photogrammetric methods (Desmoulin et al., 2022) and a modern approach to image analysis. The pixel-based measurements used in the proposed methods are also gaining popularity (Dwivedi et al., 2021). The article is the culmination of work on the image analysis method and presents the method of performing calculations to obtain quantitative data.

3. Use of a video recordings in reconstruction of a road accident

3.1. Video recorders used as dashboard cameras

In the scientific literature on the reconstruction of road traffic accidents, there are only a few publications that deal with the analysis of images recorded with a video recorder. Only if you extend the search to other fields of knowledge such as 3D scanning, autonomous vehicles or robotics will you get more information on video image analysis. Although there are descriptions of video image analysis methods in the literature that allow the distance of the camera to the object to be determined (Li et al., 2013), only a few of these methods can be applied to image analysis for the purpose of reconstructing a road traffic accident. In the available publications (Usmankhujaev et al., 2023), a computer algorithm for determining the distance between a camera lens and an object is usually presented. The limitation of using the algorithm is that the analysed films can be of different quality, which requires an expert to modify the software code to adapt to each analysed film and thus his high knowledge of the programming environment. However, this method can play a complementary role in the process of image analysis for accident reconstruction.

Nowadays, many different electronic systems are used in vehicles which can be used in the reconstruction of road traffic accidents. These include black boxes, GPS position recording, vehicle tracking, etc. However, this type of vehicle equipment is only available in new and higher-end cars as well as in new trucks and buses. Many of the low-cost vehicles are not equipped with this type of electronic system. While it is possible to retrofit a vehicle with the above electronic systems, the cost of installation would not be acceptable to most drivers. In recent years, however, the number of vehicles equipped with cheap video recorders, so-called dashboard cameras (purchase price up to EUR 250), has increased significantly and it is estimated that sales will continue to rise, as the report Dashboard Camera Market Size, Share & Trends shows. Such a video recorder is relatively inexpensive to purchase and easy to install. These undeniable advantages are also leading to an increasing number of these devices in the domestic market of motor vehicle users. The main reason for installing video recorders in cars is to protect themselves in the event of a collision or suspected traffic offence. The aim is to obtain proof of innocence in the event of possible claims for damage caused while driving or parking damage. In such situations, video recordings can be very helpful as they make it possible to see the situation that occurred during the incident. So far, however, the recordings have very often only been analysed from a qualitative point of view. The aim is to explain how the incident took place, determine and identify the perpetrator, determine his image, identify the perpetrator's vehicle, determine his licence plate number, etc.

As will be shown later in the study, the video image contains much more information which, after appropriate processing, provides valuable quantitative information. Analysing the image in this way makes it possible to determine the speed of the vehicles recorded by the camera, which can contribute to a more precise determination of the course of the traffic incident and provide clues as to who may have caused it. By determining the acceleration of vehicles, it is also possible to answer questions about the driver's reaction, e.g. to braking attempts. A change of direction of a moving vehicle can also be determined on the basis of the video recording. The data on the speed of the vehicles in turn makes it possible to determine their energy and use energy methods to estimate the energy of a collision and check the extent of damage to the vehicles.

3.2. Selected information about the principles of operation of video recorders which influence the process of film analysis

The recording devices used in cars consist of an optical system and an electronic system for image processing, as is also used in normal video cameras. However, common devices use lossy compression to reduce the amount of data stored in the device's memory. Lossy compression removes data from the processed video that is irrelevant to the human sense, in this case vision. However, The removed data, which is invisible to the viewer, is essential for the film analysis process. There are various compression standards whose main goal is to save the film in a file with the smallest possible volume while maintaining the best possible quality. However, the reduction in file size is associated with a loss of data, which in the case of a film translates into a deterioration in image quality (Quasim et al., 2020). The video recorder records images in a loop as short video sequences of up to several minutes in length. When the device's memory is exhausted, the oldest files are replaced by new ones so that the video recorder can work continuously. More advanced video recorders record video sequences on the storage medium as well as files that store other data that correlate in time with the recorded image, such as GPS position, acceleration in the three axes of the Cartesian reference system, speed and time.

In the case of video recorders, the parameters necessary for a quantitative analysis of the video (determination of the vehicle movement parameters) are as follows

- the focal length (in mm) of an optical system, which defines the distance between the centre of the focusing lens and the point on which the light rays are focused,
- the dimensions (expressed in mm) of the photosensitive matrix on which the light rays focused by a lens according to the scheme in Fig. 1.

It should also be noted that in both cameras and camcorders, the optical system is subject to an optical defect known as distortion (Martschinke, 2019).

It is important that film sequences are recorded with a resolution in which the aspect ratio of the image corresponds to that of the photosensitive matrix. If this condition is not met, a gross reading error occurs and the results can show deviations of several tens of percent. However, if the recording was made in a different aspect ratio, a corresponding factor must be entered to correct the error. The time of the video can be recorded on the recording as a clock or it can be obtained from the analysis of the recorded video. The standard for video recordings is 25 to 30 frames per second. Frame rates above 25 fps result in the human eye seeing a smooth image. If you record in this mode (25 fps - frames per second), the time interval between successive frames is 0.040 s = 40 ms. This is an assumption that is not always true and will be explained later in this article. There are many video recorders on the market today that have different recording speeds of up to 120 fps. When analysing a film sequence lasting several seconds, such a high recording speed is not necessary. At a recording speed of 120 fps, each subsequent frame of the film is recorded every 0.0083 s = 8.3 ms. During this time, the speed of the vehicle changes only slightly.

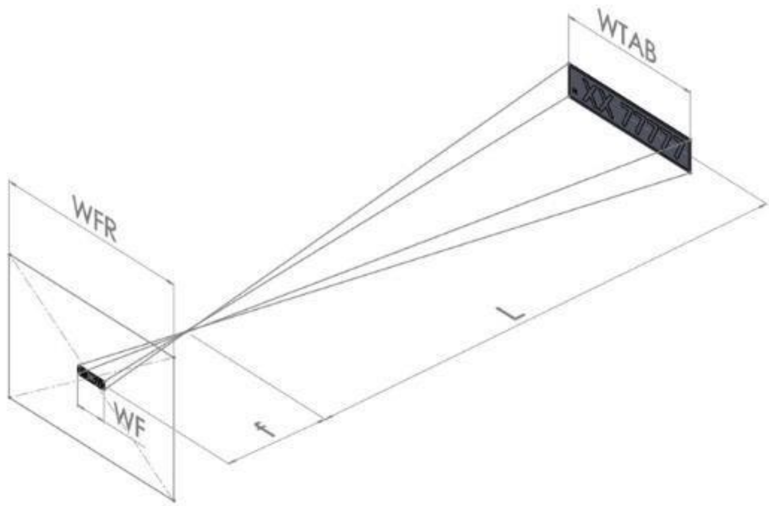

Fig. 1. Scheme of the registration of a characteristic object - a registration plate (L - distance between the vehicle and the video recorder [m], WTAB - the actual width of the number plate [m], f - focal length of the lens of the tested video recorder [m], WF - width of the number plate on the film frame in pixels [px]. WFR - frame width [px])

3.3. Overview of image analysis techniques

The first technique, widely described and employed in robotics, autonomous vehicles, and 3D scanning, is stereovision. It involves the utilization of two cameras observing an object from different angles, enabling the extraction of 'depth' information from the two-dimensional images produced by the cameras. While highly accurate, this technique is also costly and, importantly, not applicable to the present study. Our focus here is on analyzing film sequences recorded with monovision video recorders, commonly used by drivers. Techniques two and three are predominantly employed in robotics and both involve a single camera. The second method employs a camera positioned at a specific height with a variable tilt angle, facilitating the determination of an object's distance from the camera in the horizontal plane. This approach has been detailed in the works of Dwivedi et al. (2021). However, it is not suitable for analyzing videos from video recorders as they are fixed in vehicles and positioned at a height where the focal axis is (approximately) parallel to the vehicle's longitudinal axis. The third technique utilized in robotics relies on image capture using a single camera. This camera should be elevated at a considerable angle relative to the surface on which the robot operates and should be stationary in relation to the robot, as outlined by Ding et al. (2021).

4. Methods of video recording analysis used in accident reconstruction

4.1. General methods of accident reconstruction

To reconstruct a traffic incident, it is essential to determine the position of vehicles over time in the adopted reference system. This can be achieved by analyzing a carefully crafted police sketch from the accident scene or by examining a recording from a video recorder. The use of video recordings enables the determination of vehicle speed and acceleration. Moreover, identifying the vehicle's make, model, and additional load allows for the calculation of the vehicle's mass at the time of the incident and the subsequent computation of collision energy. To reconstruct a traffic event using a video recorder recording, it is also imperative to extract device parameters, including the size of the photosensitive matrix, focal length of the lens, and speed of video recording. These parameters can be obtained from the device specifications or through experimentation with the video recorder. Knowledge of the optical system's parameters of the camera facilitates the calculation of the distance of a characteristic element from the focusing lens (recording device lens). It is crucial to note that selecting an appropriate characteristic object for analysis is of utmost importance, and this is further detailed later in this paper. The distance from the recording equipment to the vehicle outline can be determined by referencing the make and model of the vehicle from technical data. In cases where information on focal length or photosensitive sensor dimensions is lacking, a suitable experiment should be conducted. This involves mounting the video recorder, from which the analyzed recording originates or another copy of the same model, in the vehicle in the same manner as during the event. A known characteristic object should then be placed at various distances in front of the vehicle, and its position should be recorded. This experiment allows for the determination of the relationship between the real size of the characteristic point and its apparent size in the recording, aiding in the determination of optical system parameters for subsequent film sequence analysis. Once the recording device parameters are known, the next step is to select the film frames for analysis. Film frames are recorded at specific time intervals, and understanding the time between successive frames is crucial for determining changes in vehicle position. Analyzing the vehicle's movement over time enables the calculation of its speed. To determine the displacement of a vehicle, it is necessary to identify a characteristic object present throughout the film sequence. The distance traveled by the traffic participant can be determined by measuring the position of the characteristic object in relation to the surroundings, such as picket posts or road signs. In cases without reference points, the optical system parameters can be referenced, as described in works (Abramowski, 2015). Another method involves determining the distance traveled based on two consecutive film frames, using the proportions of objects in consecutive frames superimposed on each other, as further described in the work (Krishnan, 2010). Reconstruction of road events may also benefit from other recorded parameters, such as GPS position and vehicle acceleration. In the analysis of video recordings from video recorders, three groups of scenarios were identified. The first group comprises recordings where analyzed vehicles move in parallel directions, with their turns being either in the same or opposite directions. The second group involves vehicles moving in near-perpendicular directions. The third group includes films depicting vehicles moving in directions intersecting at any angle. Depending on the classification of a given film sequence into a specific group, different methods of analyzing video recordings will be employed. These differences will primarily involve the selection of the characteristic object necessary for video analysis.

4.2. Analysis of video recordings of vehicles moving in parallel directions

When vehicles travel along lanes that can be considered parallel, the number plate serves as a distinctive element. This element, whose dimensions are well-defined and outlined in the Road Traffic Law, provides a consistent and reliable reference point. In the analysis of films featuring vehicles with foreign registration, the standardized nature of international number plates ensures that obtaining information about their dimensions is not a challenging task. Furthermore, the reconstruction of a traffic incident typically occurs post-incident, allowing for the direct measurement of the geometric dimensions of the number plate. As illustrated in Figure 1, the number plate captured in the video possesses known geometric dimensions, which are utilized to ascertain the vehicle's position in relation to the video recorder. The distance of the vehicle in individual frames of the film can be determined using the following relationship:

$$L = \frac{W_{TAB} \cdot f}{W_F} \tag{1}$$

where:
L - distance between the vehicle and the video recorder [m],
W_{TAB} - the actual width of the number plate [m],
f - focal length of the lens of the tested video recorder [m],
W_F - width of the number plate on the film frame in pixels [px].
The unit of measurement of W_F is usually pixels. It is therefore necessary to convert the W_F
value into physical units based on the relationship:

$$W_F[m] = W_F[px] \cdot \frac{V_M[m]}{W_{FR}[px]}, \tag{2}$$

where:
W_{FR} - frame width [px],
V_M - width of the photosensitive matrix [m].
After substituting relation (2), equation (1) takes the form:

$$L = \frac{W_{TAB} \cdot f \cdot W_{FR}}{W_F \cdot W_M} \tag{3}$$

It is essential to commence the analysis by estimating the speed of a vehicle equipped with a video recorder. Two methods are available for such estimation. The first method, expounded in greater detail in the study by Usmankhujaev et al. (2023), involves capturing two photographs. Subsequently, a scaling process should be executed to ensure the alignment of objects in the overlapping images. The estimation of distance relies on calculating the proportions of the geometric size of objects visible in the shot. The second method, presented in this research, aims to determine velocity using environmental elements. This entails identifying two frames within a film sequence where consecutive picket posts occupy the same position in the shots, assuming a predetermined distance of 100 m between the picket posts. If a visual examination of the scene is conducted, it proves beneficial to determine the actual distance between the picket posts. Subsequently, the number of frames between the two shots should be recorded. Armed with knowledge of the recording speed of the video recorder, calculations can be performed using the following relationship:

$$s = \Delta L = (n-1) \cdot 100 \tag{4}$$

where:
s - distance travelled by the vehicle [m],
n - number of picket posts,
ΔL ($L2$ - $L1$) - distance between measured picket posts [m].
To determine the speed, use the relationship:

$$v(t) = \frac{\Delta s}{\Delta t}, \tag{5}$$

where:
v- vehicle speed [m/s],

s- distance travelled by the vehicle [m],
t - time [s],
Δs - increase in the distance of the test vehicle in successive shots [m],
Δt - increment of recording time of successive shots [s].
In the case of determining the speed using the recording time, the time interval between successive analysed frames of the film should be determined. After reading out the time interval, the speed should be determined using the relation in the form:

$$v_{KAM} = \frac{m_i}{\Delta t}, \tag{6}$$

where:
v_{KAM} - camera recording speed [fps],
m_i - the number of frames recorded in a unit of time,
Δt - time increment in which the analysed film frames were recorded [s].
By transforming the relation (6) it is possible to determine the time between successive analysed frames of the film. At the actual recording speed of 25 fps, each frame of the film is recorded every 0.04 s. The time distance between subsequent frames is read according to the relation:

$$\Delta t_{\Delta m} = \frac{\Delta m}{v_{KAM}}, \tag{7}$$

where:
$\Delta t_{\Delta m}$ - time between the analysed film frames [s],
Δm - the number of frames between two analysed frames,
v_{KAM} - video recorder recording speed [fps].
Knowing the distance covered by the analysed vehicle and the time in which this distance was covered, it is possible to proceed to determining the vehicle speed according to the relation:

$$v = \frac{\Delta s}{\Delta t} = \frac{\Delta s}{\frac{\Delta m}{v_{KAM}}} = \frac{\Delta s}{\Delta m} \cdot v_{KAM} \tag{8}$$

where:
Δv - increase in speed of the test vehicle in subsequent shots [m/s],
Δt - increment of recording time of successive shots [s],
Δm - the number of frames between two analysed frames.
To determine the time course of the delay in the recorded shot, a constant value of the delay between successive frames of the film is assumed and this delay is calculated from the relation

$$v = \frac{\Delta v}{\Delta t}, \tag{9}$$

The delay values for successive frames of the film can be determined from the equation:

$$a_n = \frac{(v_i - v_j)}{\Delta t}, \tag{10}$$

where:
a_n - vehicle deceleration between frame n and n- *1*[m/s2],
v_i - vehicle speed in the cage n [m/s],
v_j - vehicle speed in the n-*1* cage [m/s],
Δt - difference in recording time of frames n and n- *1* [s].

4.3. Analysis of video recordings of vehicles moving in perpendicular directions

When vehicles traverse tracks intersecting at close to right angles, the wheelbase of the vehicle captured in the recording serves as the characteristic object for determining the speed of the vehicle equipped with the video recorder. This characteristic object, exemplified by a vehicle with a known wheelbase and real-world dimensions, should ideally be consistently positioned close to the geometric center of the recording. This is particularly crucial due to the presence of wide-angle lenses in many video recorders, which can induce distortions (changes in geometry) in elements located farther from the center of the image. In such instances, correction of the shot becomes necessary, and this can be accomplished by applying appropriate filters available in graphics processing software, such as the Adaptive Wide Angle filter in Adobe Photoshop. Subsequently, the determination of the vehicle's position in several consecutive analyzed shots is imperative for calculating the distance traveled. This involves establishing the position difference in successive shots, guided by the relationship:

$$s_{12} = l_i - l_j, \tag{11}$$

where:
s_{12} - distance travelled by car [m],
l_i - distance of the vehicle from the characteristic point in i-th time [m],
l_j --distance of the vehicle from the characteristic point in j-th terms [m].
It is crucial to measure selected dimensions in each frame. By relating them to the real-world dimensions of the object, it will be possible to determine the conversion factor that allows the calculation of distances covered by vehicles in successive frames. To determine the distances l_i and l_j, the following relation can be employed:

$$l = \frac{l_m \cdot f \cdot W_{FR}}{l_{px} \cdot W_M}, \tag{12}$$

where:
l - distance of the vehicle from the characteristic point [m],
l_m - actual wheelbase of the test vehicle [m],
f - focal length of the lens of the tested video recorder [m],
W_{FR} - frame width [px],
l_{px} - wheel base of the vehicle tested in the shot [px],
W_M - width of the photosensitive matrix [m].
Then, having determined the distance covered by the vehicle in consecutive shots, the vehicle speed should be determined by differentiating the vehicle position during consecutive shots according to the relation (5). The distance travelled by the vehicle may also be determined by taking measurements (in pixels) according to the following formula:

$$l = \frac{L_{OR}}{L_{OP}} \cdot l_p, \tag{13}$$

where:
l - distance of the vehicle from the characteristic point [m],
L_{OR} - actual wheelbase [m],
L_{OP} - read axial distance [px],
L_p- apparent distance of the vehicle from the characteristic point [px].
Knowing the distance travelled by the vehicle subjected to the analysis in successive shots, it is possible to proceed to determination of velocity. As a result, the relation (5) determining the speed will take the form:

$$v = \frac{\frac{L_{OR_{tn}}}{L_{OP_{tn}}} \cdot l_{P_{tn}} - \frac{L_{OR_{tn-1}}}{L_{OP_{tn-1}}} \cdot l_{P_{tn-1}}}{t_n - t_{n-1}}, \tag{14}$$

where:
v - vehicle speed [m/s],
L_{OR} - actual wheelbase [m],
L_{OP} - read axial distance [px],
l_P - apparent distance of the vehicle from the characteristic point [px],
t_n - time of the analysed film frame [s].

4.4. Analysis of video recordings of vehicles moving in any directions

The scenario in which vehicles travel on tracks intersecting at angles significantly different from 0° and 90°, or when their directions are indeterminate, poses the most challenging situation for reconstruction. This difficulty arises from variations in the angular position of the vehicle observed in successive shots captured by the camera relative to its axis. Changes in the vehicle's position and rotation create complications in extracting geometric dimensions of characteristic objects visible in the analyzed film frame. Nevertheless, it is feasible to determine these dimensions or angular positions. To address this, adopting a coordinate system is necessary. Here, the x-axis is aligned parallel to the longitudinal axis of the vehicle, the y-axis is perpendicular to the longitudinal axis, and the z-axis corresponds to the axis of rotation of the vehicle equipped with the video recorder. In cases where the car in the video moves in the xy plane shared by the vehicle seen in the video and the one equipped with the recorder, the rotation about the x-axis can be disregarded. Consequently, only the rotation about the z-axis needs to be determined. However, there may be instances requiring the determination of the position, velocity, acceleration, or energy of vehicles by considering rotation around two or three axes of the coordinate system. In such cases, the relation describing the rotation of a three-dimensional coordinate system, as outlined in (Abramowski, 2018), can be employed. This results in the determination of a matrix describing the rotation of the three-dimensional coordinate system:

$$M = \begin{bmatrix} \cos\beta\cos\gamma & \cos\beta\sin\gamma & \sin\beta \\ -\sin\beta\sin\alpha\cos\gamma - \sin\gamma\cos\alpha & -\sin\alpha\sin\beta\sin\gamma + \cos\alpha\cos\gamma & \sin\alpha\cos\beta \\ -\sin\beta\cos\alpha\cos\gamma + \sin\alpha\sin\gamma & -\sin\beta\sin\gamma\cos\alpha - \sin\alpha\cos\gamma & \cos\alpha\cos\beta \end{bmatrix}, \tag{15}$$

The computation of rotation using matrix calculus has a drawback, particularly when applied in calculations on computers with finite accuracy. If the determination of rotation is executed sequentially, starting with rotation about the x-axis, then y and z, there is a risk of encountering a specific scenario. In this case, following a rotation, the axes of the coordinate system may coincide, leading to a loss of one degree of freedom, known as "gimbal lock." To mitigate this issue, rotation should be determined using quaternions, as detailed in the paper "Dashboard Camera Market Size Analysis Report 2021-2028." Consequently, the relation for determining the point P' will appear as follows:

$$P' = \begin{bmatrix} x_{P'} \\ y_{P'} \\ z_{P'} \end{bmatrix} = \begin{bmatrix} 2(s_0^2 + x_0^2) - 1 & 2(x_0 y_0 - s_0 z_0) & 2(s_0 y_0 + x_0 z_0) \\ 2\ (s_0 z_0 + x_0 y_0) & 2(s_0^2 + y_0^2) - 1 & 2(y_0 z_0 - s_0 x_0) \\ 2(x_0 z_0 - s_0 y_0) & 2(s_0 x_0 + y_0 z_0) & 2(s_0^2 + z_0^2) - 1 \end{bmatrix} \cdot \begin{bmatrix} x_P \\ y_P \\ z_P \end{bmatrix}, \tag{16}$$

Determining the position of the vehicle in cases where vehicle movements occurred at an undefined angle relative to the axis of the video recorder's lens depends on the expertise of the analyst. Both methods presented earlier, utilizing matrices and quaternions, come with their respective advantages and disadvantages. The choice of method for determining position lies with the expert and their experience. By applying the aforementioned relations directly or following transformations, coupled with the dimensions of characteristic elements, it becomes feasible to ascertain the angle of rotation of the vehicle or vehicles captured in shots recorded with the video recorder. Employing the method presented herein allowed, for instance, the determination of the angle of rotation of the car depicted in Fig. 2 in relation to the vehicle with the video recorder. The calculated angle was 29.6°. This value was further validated by measuring the angle on a map within the Google Earth software (Fig. 3), considering the roadway axis before and after the turn where the image from Figure 2 was captured.

Continuing from this point, with knowledge of the angular relationships between the vehicles and the observer, it becomes feasible to ascertain the positions of the vehicles in individual frames. This, when combined with the known time interval between successive analyzed frames, facilitates the determination of the speed, acceleration, or energy of the vehicles.

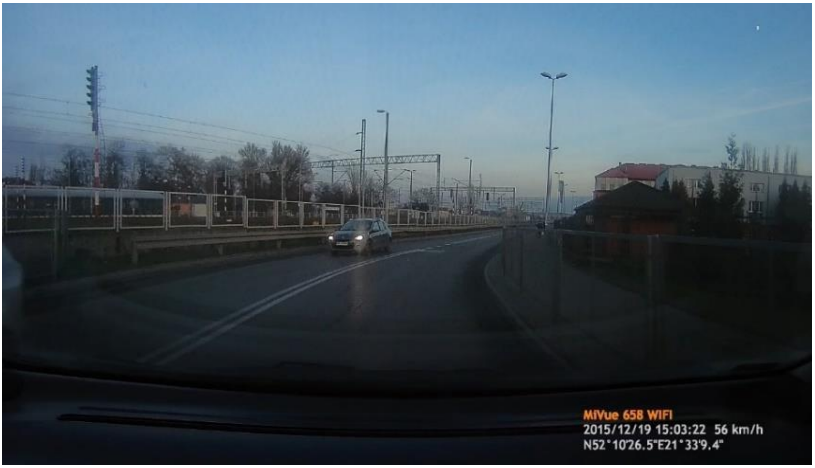

Fig. 2. View of vehicle on curved road

Fig. 3. Confirmation of the calculated rotation angle value in Google Earth

4.5. Reconstruction of vehicle trajectory

From the perspective of road traffic accident reconstruction, mapping the trajectory of a vehicle yields valuable information. Determining the position in consecutive, time-correlated frames also allows for the description of the driver's reactions while driving. The vehicle's movement path can be delineated by establishing its position in successive frames. However, analyzing each frame in this process can be time-consuming. Given the diverse nature of accidents, it is challenging to present a universal scheme for determining the vehicle's path. To address this, the generalized scheme for determining the vehicle's path is divided into two variants. The first variant, depicted in Figure 4, is employed for determining the vehicle's path concerning a globally adopted coordinate system (relative to the environment visible in the recording where the vehicle was in motion). This enables the plotting of the trajectory on a digital map. The second calculation scheme, presented in Figure 5, allows for determining the vehicle's path while considering maneuvers performed by the driver during the analyzed timeframe.

To assess the driver's reaction, the scheme remains quite similar. Input data is derived through video analysis, where pertinent frames are selected for examination. The analysis of the shots involves taking measurements directly or after a preceding photogrammetric transformation.When measurements are taken directly without transformation, it is crucial that the analyzed shots exhibit good quality—sufficient sharpness, brightness, and visibility of the object under scrutiny. In such cases, it can be expected that the measurements will closely reflect reality, and any resulting errors will be minimal. However, if a photogrammetric transformation is applied beforehand, it is important to note that errors introduced during this process will impact subsequent analyses.The magnitude of errors introduced with the data being analyzed may be substantial when a photogrammetric transformation is applied, potentially rendering it impossible to discern small changes in the vehicle's path, speed, or acceleration induced by the driver's reaction.

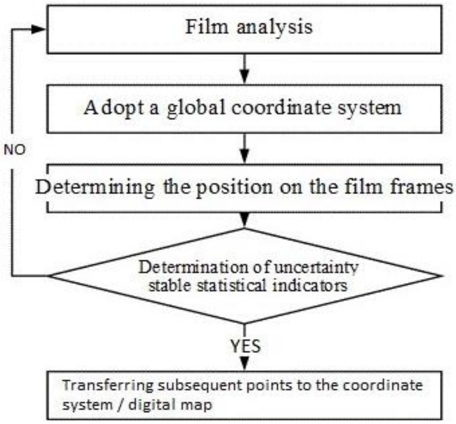

Fig. 4. Schematic drawing of the trajectory of vehicle movement

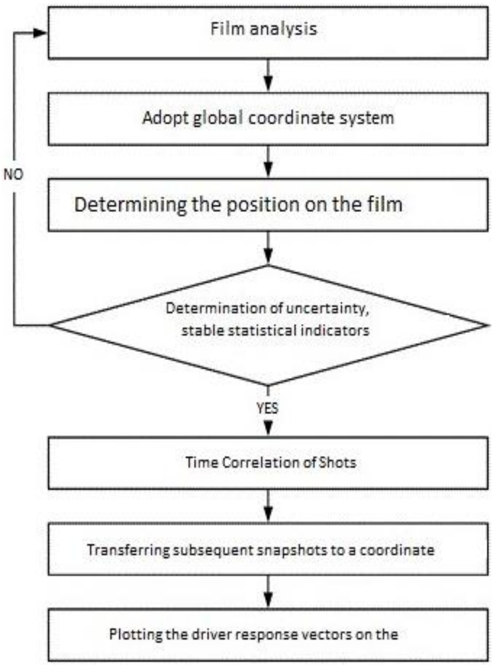

Fig. 5. Schematic diagram of vehicle path determination with consideration of driver's reaction

5. Discussion of results of the video recordings analysis

5.1. Evaluation of the uncertainty of the results

The primary challenge in reconstructing road accidents lies in the limited data available, particularly when analyzing video recordings from a video recorder. This limitation is closely tied to the temporal nature of road events, which unfold within fractions of seconds. When considering the moments leading up to the event under analysis, the footage available for reconstruction is typically only a few seconds long at most. Another complication in road accident reconstruction arises from the analysis of numerous parameters, each susceptible to errors, thereby increasing uncertainty in the results.The Monte Carlo method, as demonstrated in previous works (Zhang et al., 2020; Dao et al., 2020; Behbahaninia et al., 2022), proves to be a valuable and widely applicable approach in addressing these challenges. Various methods are available for analyzing result estimate uncertainty, but the Monte Carlo method is frequently employed in accident reconstruction (Wach, 2014). This method allows for the presentation of results in the form of a probability density distribution of the calculated parameter.The Monte Carlo method operates on the premise that repeated calculations are performed using a mathematical model. During these calculations, data is randomly selected from uncertainty intervals each time. Consequently, the uncertainty of the result estimate, such as the position of the vehicle (S), can be determined using the Monte Carlo method under the assumption that it is governed by the general relation:

$$S = f(D), \tag{17}$$

where: $D = \{x_1, x_2, \dots x_n\}$ - is the data vector obtained from the camera image analysis. The determination of the uncertainty is based on a repeated calculation of the distance S for data generated as random variables with a normal distribution, where each element of the data vector must be within the range corresponding to the uncertainty of its estimate. From a practical point of view, the statistical distribution of the individual random variables - the elements of the data vector - is described by quantities:
$\boldsymbol{x}^\wedge{}_i$- average value.
σ_i - standard deviation.
Assuming a calculation confidence level of 99%, the value of the standard deviation can be determined from the so-called 3 σ rule:

$$\frac{\Delta x_i}{3} = \frac{x_i^{MAX} - x_i^{MIN}}{3}, \tag{18}$$

The series of distance values S calculated for random values, after performing calculations for a sufficiently large number of random variables, has a distribution close to the normal distribution. Consequently, it is possible to apply to its analysis the mathematical apparatus appropriate for a normal distribution, and thus - to calculate its mean value S ^ and standard deviation σ, and thus the uncertainty of the result, assuming a confidence level of 99%:

$$S = \hat{S} \pm 3 \cdot \sigma. \tag{19}$$

The calculation is carried out in the loop shown in the diagram in Figure 6 (iteratively) until the statistical indicators of the result, i.e., the mean value and standard deviation, have stabilized.

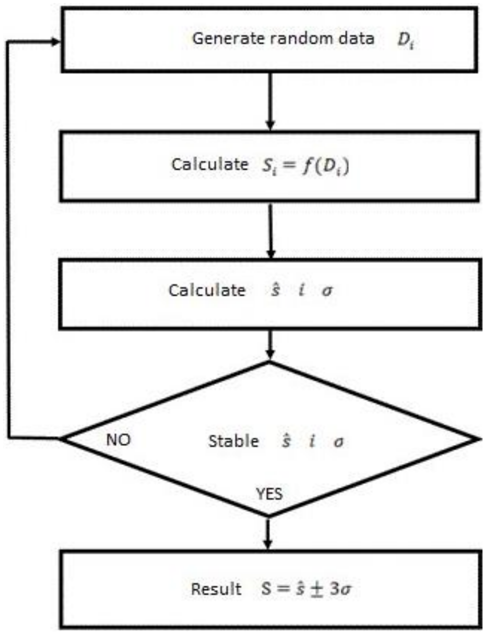

Fig. 6. Schematic of the calculation until the mean and standard deviation have stabilized

The methods discussed in this paper for determining the time between successive frames of a film are meaningful only if the exact interval between successive analyzed frames is known. Relying on the average number of frames recorded in each unit of time may introduce a significant error in a particular case. To illustrate, consider a brief analysis focused on determining the vehicle speed with a video recording speed specified by the manufacturer as 30 fps (frames per second). The calculated distance of the vehicle between consecutive frames was 0.4 m, resulting in a calculated speed of 12 m/s, assuming the recording speed provided by the manufacturer was 30 fps. However, if, for various reasons explained later, the actual recording speed of the device at a given moment is only 25 fps, the calculated actual speed of the vehicle will be 10 m/s. A difference of 2 m/s from an actual speed of 12 m/s represents a sixteen percent error.

5.2. Limitations in the use of the proposed methods

Utilizing the average recording speed of the camera for calculations, involving the average number of frames in each unit of time, is accurate only in the case of old-type cameras with unalterable recording parameters. In the video recorders available on the market, changes in the filmed environment, such as variations in light intensity, automatically adjust the exposure time for each frame. Consequently, the time between subsequent frames in the recorded image changes, as illustrated in Figure 7. This graph depicts the speed of a car determined by differentiating the distance covered by the car between the analyzed frames of the film.

To determine speed A, the actual recording time of the analyzed frames was employed. For speed B, the average time between consecutive frames of the film was utilized, taking the form indicated in the presented image:

$$(n_j - n_i)\cdot\frac{1}{29{,}97}, \qquad (20)$$

where:
n_j – j-th frame of the film,
n_i - the i-th frame of the film,
29,97 - the recording speed of the video recorder as stated by the manufacturer.

The reason for the large differences during velocity changes presented in Fig. 7 is that successive film frames were recorded at different time intervals.

Another crucial parameter influencing the feasibility of image analysis is the resolution at which the video was recorded by the video recorder. Figures 8, 9, and 10 showcase an image recorded at a resolution of 1920 x 1080 pixels, resulting in a file size of 2 MP (megapixels), while at a resolution of 4000 x 3000 pixels, it yields a size of 12 MP. The disparity in image quality on a printout may not be substantial, but when assessed using a computer monitor operating in 4K mode (with a resolution of 3840 x 2160 pixels), the difference in image quality becomes significant.

At the time of printing this article, it was not feasible to unequivocally establish the correlation between the resolution of the recorded video and the distance from which the geometric dimensions of the registration plate can be accurately determined. This variation arises from differences in the construction of popular video recorders, as illustrated in the attached pictures in Figure 8. Both pictures were extracted from a film with the same resolution of 1920x1080 pixels, depicting the same road scenario. However, the photo shown in Figure 9 exhibits much clearer details. Consequently, in this photo, the geometric dimensions of the license plate can be identified even when the visible car was at a greater distance from the vehicle equipped with the video recorder compared to the photo in Figure 8. This implies that with the MiVue 658 DVR, the speed of the vehicle can be determined from a greater distance than with the camera of the Samsung Galaxy S5 smartphone. The decisive factor in this scenario is not solely the resolution of the sensor but, to an even greater extent, the quality of the lens.

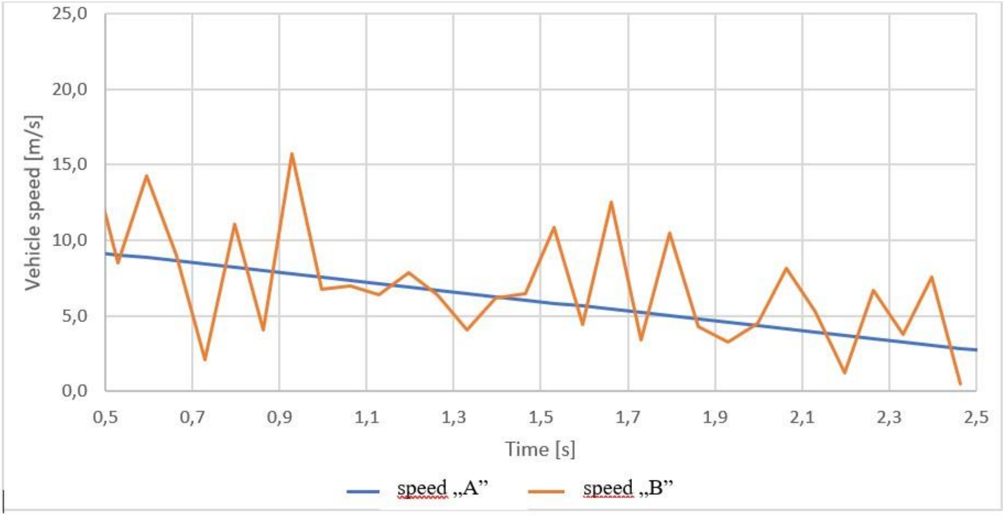

Fig. 7. The speed of the car calculated from the different times that can be read during the analysis of the video

Fig. 8. A frame of a 2MP movie with 1920 x 1080 pixel resolution captured with a Samsung Galaxy S5 smartphone

Fig. 9. A 2MP frame of a 1920 x 1080 pixel video captured with the MiVue 658

Fig. 10. A frame of a 12MP movie with a resolution of 4000 x 3000 pixels captured with a GoProHero 7 Black sports camera

6. Conclusions

Based on the conducted research, it has been demonstrated that the analysis of video recordings from cameras placed on the vehicle's dashboard can provide valuable information for reconstructing road events. These observations encompass not only qualitative data but also quantitative aspects, such as vehicle speeds, their mutual positions, and angular orientations. Through mathematical transformations, such as differentiation, it is also possible to obtain speeds or accelerations of both vehicles in the recordings and vehicles with mounted cameras. The study underscores the significant impact of recording device parameters on the potential utilization of video material in the reconstruction of road events. Various factors, including the quality of the optical system and potential defects arising from imperfections in the manufacturing process, resolution, and light intensity, influence the quality of the recording. These factors affect the ability to measure vehicle registration plates and conduct further analyses. A critical concern is the speed of film recording by the video recorder, as the time interval between successive frames may deviate from the manufacturer-specified recording speed and may also change during recording. Factors such as the time of day during recording, light intensity, and the quality of the camera's optical system can additionally impact the recording's quality and, consequently, its suitability for accident reconstruction. During the research, determining the distance between vehicles and the camera – crucial for utilizing the recording in the analysis of a road incident – proved challenging due to the diversity of the aforementioned factors influencing the analysis results. Currently, the authors are concluding the research phase on the impact of parameters, such as resolution and optical system parameters, on the accurate determination of the distance from which vehicle motion parameters can be precisely determined. The paper will be published in the near future.

At present, it is important to emphasize the substantive value of this article for individuals involved in the field of road accident reconstruction. As presented in the article, the procedure for obtaining results is accurately described and easy to verify or replicate. This is of great significance in legal proceedings where errors can incur significant financial and social costs. In the case of inaccurately estimated speeds, the freedom of a potential witness-offender is also at risk.

The undeniable advantages of estimating speed and other parameters using the method presented in this article include a thorough understanding of how the algorithm works. In the case of tools based on artificial intelligence, neural networks, deep learning, etc., this is not entirely known. Another undeniable advantage is the ability to perform reconstruction by individuals without programming skills or knowledge of advanced software systems.

Abbreviations

3D: Three dimensional
ADR: Accident data recorder
DVR: Digital video recorders
GPS: Global Positioning System

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