THE UNIVERSITY OF PARDUBICE

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Development of a Methodology of a Traffic Monitoring Using Video Recordings for Traffic Accident Analysis

A Summary to the Doctoral Thesis

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ANOTATION

The doctoral thesis „*Development of a Methodology of a Traffic Monitoring Using Video Recordings for Traffic Accident*“ introduces a complex method for automatic computational evaluation of a selected dynamic quantity used in a traffic accidents analysis praxis from video recording from traffic surveillance cameras. The procedure follows the selection of suitable input data in form of video recording and a robust detection and tracking SW implementation and fine-tuning for the particular use. A calibration method is developed and tailored to the use case in the thesis. After obtaining the data, a suitable data processing and smoothening methods are introduced and implemented. As a conclusion, a statistical processing of a non-sudden braking is provided which has a real use in the traffic accidents analysis praxis.

KEYWORDS

automatic traffic analysis, automatic image processing, non-sudden braking

CONTENTS

1. INTRODUCTION

When solving road accidents, a knowledge of kinematic and dynamic quantities, that represent a common driver behaviour in non-sudden situations, is often required. These quantities are then compared to those evaluated from the situation to determine, how sudden situation it was for drivers. Currently, in the forensic praxis of traffic accidents analysis, there is no clear definition where the value of the threshold between sudden and non-sudden reaction lies. There are multiple different assumptions introduced and applied.

The aim of the thesis was to obtain data describing a normal behaviour of drivers that are fully independent and, what is important, without awareness of the drivers, whose drives were measured. In order to obtain such a data sample effectively, an own software is developed. This software is able to go through surveillance videos of desired traffic locations automatically and evaluate desired kinematic and dynamic quantities. The accuracy of the software is verified by experiments, when quantities computed by the software and the same quantities measured physically in the vehicle are compared.

This doctoral thesis also includes a review of state-of-the-art methods for automatic detection and tracking of objects, calibration, data processing etc. In order to fulfil goals of the thesis, the most suitable methods are selected, adjusted to the particular case and merged in a complex procedure.

2. OBJECTIVES OF THE DISSERTATION THESIS

In order to achieve the purpose of this thesis, several specific objectives were set and are presented in this chapter.

- **Develop a method suitable for automatic traffic analysis.**
- **Provide a particular application of the method.**
- **Validate a precision of used method.**
- **Evaluate a non-sudden braking deceleration quantity for use in the traffic accidents analysis praxis.**

Formulation of a scientific hypothesis: The developed system based on an automated traffic analysis is capable of extracting kinematic and dynamic parameters of vehicles from traffic camera recordings with sufficient precision to be applicable for analysis of driver behaviour in real traffic conditions. (The hypothesis will be either confirmed or rejected in the end of the thesis).

3. BACKGROUND OF THE PROBLEMATICS

In the main thesis, a theoretical background and related works and progress of other authors of automatic object detection and tracking is provided both for the method of background subtraction and CNN-based methods. Also, for the problematics of the image calibration two methods are introduced: Perspective'n'point (PnP) and Vanishing point acquisition method. These methods are described and an overview of related works is provided. As the last part of this chapter, a background from forensic praxis is explained. In the following chapter, the significance of the quantity of non-sudden braking in the expert praxis is described together with several approaches that are being used in the analysis of traffic accidents.

3.4. Non-sudden braking in the traffic accidents analysis context

In a road traffic, vehicle deceleration is not only a technical parameter but also a behavioural phenomenon strongly influenced by human perception and comfort. Drivers generally avoid applying the maximum available braking capacity unless confronted with a critical situation. Instead, under everyday conditions such as approaching an intersection, a pedestrian crossing, or a red traffic light, they tend to decelerate smoothly and in a manner they perceive as comfortable. This type of braking, often referred to as *non-sudden braking*, represents a form of deceleration that does not surprise passengers, maintains vehicle stability, and remains within a range commonly practiced by most drivers in normal traffic flow.

From the perspective of forensic analysis, the concept of non-sudden braking is of particular importance. A model situation can be a traffic accident on a crossing or hitting a pedestrian or cyclist. The expert has to evaluate the technical cause of the collision between them and puts themselves questions like „How suddenly did the vehicle on a secondary road / pedestrian created a sudden obstacle to the vehicle on the main road with the right of way?“ or „Could the driver on the main road have stopped before the place of collision if he/she braked only non-suddenly?“. Here the non-suddenness of braking has its value because according to the Czech law Act No. 361/2000 Coll., on Road Traffic, the give a right of way means „*the obligation of a driver not to start or continue driving or a driving manoeuvre if the driver who has the right of way would have to suddenly change direction or speed.*“. Following this definition, it is the key to evaluate if the driver on the main road could have stopped if he/she had braked non-suddenly.

Review of existing approach in the Czech republic

In the Czech forensic community, several approaches are applied when estimating the threshold of non-sudden or comfortable deceleration. Since no uniform definition exists, experts rely on different assumptions and reference values, depending on their methodological preference and case context.

Bradáč (1997) and Bradáč et al. (2021) in his work emphasized that the assessment must always consider the particular conditions of the situation, such as road surface friction. In accident analysis, the expert must examine the driving behaviour of all vehicles and determine the moment when it should have become evident to the priority driver that their right of way would not be respected.

In general, there are currently three main legitimate approaches in the forensic praxis that define the non-sudden threshold, related to:

- vehicle's braking capability,
- regulatory references,
- subjective perception.

Approach related to vehicle's braking capability

One of the most frequently used approaches is to relate non-sudden braking to the vehicle's maximum technically achievable deceleration, dependent on current adhesion conditions. In this interpretation, the comfortable or non-sudden level is assumed to be approximately one half of the maximum value. For typical passenger cars, where the maximum achievable deceleration under good adhesion conditions lies around 8 $m \cdot s^{-2}$, this results in a threshold close to 4 $m \cdot s^{-2}$. This value is commonly cited in expert practice as a representative limit that distinguishes ordinary braking from emergency intervention.

Approach related to regulatory references

Another line of reasoning is based on regulatory standards. Czech technical regulations, harmonized with international ECE requirements, prescribe a minimum braking performance that vehicles must achieve in order to be approved for road use. According to UN/ECE Regulation No. 13-H, which is incorporated into Czech technical regulations (Vyhláška č. 341/2014 Sb.), the minimum required mean fully developed deceleration (MFDD) for passenger cars is 5.8 $m \cdot s^{-2}$. Some forensic experts propose that non-sudden braking can be estimated as approximately half of this regulatory minimum, yielding a threshold near

2.9 $m \cdot s^{-2}$.This approach has the advantage of being directly linked to legally defined criteria, but it may be more conservative compared to the “half of maximum” assumption. (UN/ECE Regulation No. 13-H; Vyhláška č. 341/2014 Sb.)

Approach related to a subjective perception

Tokař’s study (2014) set out to empirically examine the boundary between “sudden” and “non-sudden” changes in speed. The motivation came from the observation that the traditional definition – a half of the prescribed minimum braking deceleration – may no longer reflect real driving conditions. To test this, a series of controlled braking experiments were conducted using several passenger cars under dry road conditions. Respondents (22 drivers and passengers of varying ages and driving experience) were asked to subjectively classify different braking manoeuvres according to four categories: safe, slightly dangerous, dangerous, and very dangerous. The experiments were performed at an initial speed of 50 km·h^{-1}, with target decelerations of 3, 5, 7 m·s^{-2} and the vehicle's maximum achievable deceleration.

Considering a non-sudden change of velocity as a change that doesn't create any danger, the author assesses the threshold as a "safe" deceleration of 3.8 m·s^{-2}. The author also considers acceptable the „slightly dangerous“ deceleration of 5.9 m·s^{-2} coming from his experiment. As a result, these two values are combined into a value about 4.8 m·s^{-2}. The author proposes to set the boundary not as a single value but rather as an interval in the range of 3.8-4.8 m·s^{-2}. Moreover, provided the maximum deceleration of vehicles typically lies between 8-10 m·s^{-2}, the range 4-5 m·s^{-2} should be considered.

In the following table 1, there is a summary of the currently used approaches with the thresholds:

Table 1 – Overview of current approaches to determine the non-sudden braking threshold

Approach	**Threshold [m·s^{-2}]**
vehicle's braking capability	4.0
regulatory references	2.9
subjective perception	4.0-5.0

Although these approaches provide technically acceptable solutions, they also demonstrate the absence of a uniform standard. Differences in measurement methods, traffic environments, vehicle types, and driver populations lead to varying conclusions. Moreover, the boundary between "comfortable" and "emergency" braking is not sharply defined, but rather situational and context-dependent. This diversity of views underscores the need for further empirical investigation and for defining non-sudden braking in a way that is both scientifically based and practically applicable in forensic expertise.

4. PROPOSED SOLUTION OF AN AUTOMATIC TRAFFIC ANALYSIS

In the thesis, a direct approach to determine a normal driver behaviour was developed. It is not dependent on any artificial values from regulations nor influenced by the awareness of test drivers that are being measured. It is necessary to obtain quantities describing the comfortable driving dynamics directly by observation of a real traffic.

There are several ways to obtain such a quantity describing a natural behaviour of drivers. The first way was to manually measure the desired quantity, which would be very ineffective, time consuming and inaccurate. Hence, the statistical approach of analysing a large amount of data through camera record analysis was chosen to analyse the traffic and the desired quantity in the most objective, accurate and representative way.

4.1. Methodology design

In the thesis the procedure of obtaining data is generally divided into two phases: validation and data acquisition phase. The validation phase consists of a processing of simulated data under controlled conditions and parameters, setting limitations of the SW and then validating its precision directly on a particular crossing using a set of physical measurements. After ensuring that the SW can reliably process data from the particular scene, the video shots of desired manoeuvres are prepared. After an automatic processing by the tracker SW, results are evaluated statistically.

The pipeline of obtaining desired quantities is represented in the scheme in the Figure 1.

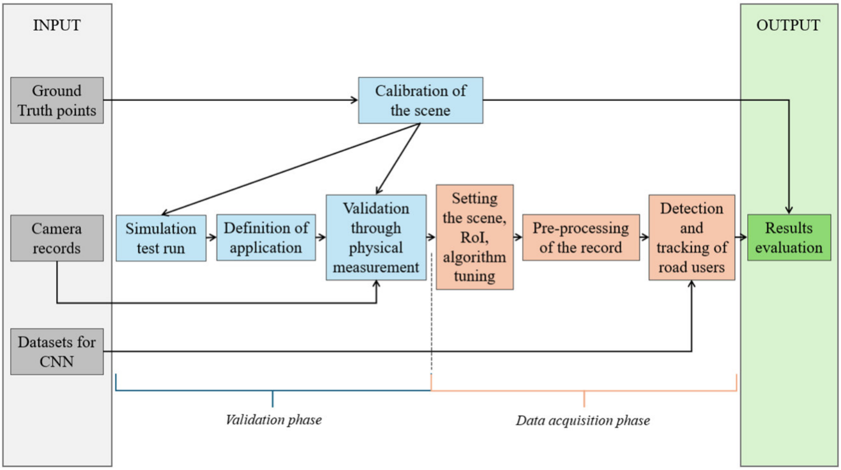


Figure 1 – Pipeline of SW validation and data acquisition (author)

As can be seen from the Figure 1, the pipeline is rather complex and build a complete solution for any traffic analysis. For the purposes of this thesis, there is also in the beginning a test run of the detection & tracking software in a simulation-based environment which helps to determine the most precise application of the SW. Then a validation on real crossing was made and after then the main data acquisition on validated scenes. The whole implementation is being made in python, which is a high-level object-oriented programming language. The code is written in PyCharm IDE, and many in-built libraries are used for various purposes. The individual steps are described in more detail further in the thesis.

4.2. Input data

In the first step all input data must be prepared in a sufficient amount and quality. It is naturally impossible to analyse the driving behaviour by all drivers in each situation. Therefore, a statistical sample of sufficient size was chosen, while such sample must be representative, which means that values of desired quantities obtained in the sample must represent the behaviour of the whole. The following assumptions were applied: no difference of normal driving dynamics between cities in Czech republic, between men and women (impossible to distinguish from the camera records), day time of recording, season, weather etc. In this model situation, only behaviour of drivers of passenger cars in a summer, daytime and dry road will be evaluated. In order to determine a minimum number of samples needed for a representative statistical evaluation, a sample size of 30 was selected as it represents a widely accepted threshold in statistical analysis where, according to the Central Limit Theorem, the distribution of the sample mean approaches normal distribution. This provides sufficient reliability for statistical evaluation while maintaining feasibility in terms of data processing. A target is an evaluation of a 95% percentile assuming a normal centred distribution of a random variable, so ± 1.96 sigma interval.

Camera records from selected traffic surveillance cameras were obtained from the City Police Department in Pardubice. The decision on which camera records will be taken for the analysis came from evaluation of the simulation test run which will be described in detail further. Basically, the result was that the SW can be reliably and with sufficient precision applied for scenes, where the camera captures at least 5 sec of the manoeuvre of interest, low occlusion and noise and highest possible resolution of the area where the manoeuvre takes place. Considering these requirements, the crossing S.K.Neumanna x Pichlova in Pardubice was chosen.

Another input needed for successful working of the CNN-based detector and tracker is a dataset used for training. The YOLOv7 detector used in this work was pre-trained on the COCO dataset, a large-scale benchmark comprising over 200,000 labelled images and 80 object categories. COCO contains a wide variety of classes directly relevant to this application, including *person*, *car*, *bus*, *truck*, *bicycle*, and *motorcycle*. These categories cover the primary objects of interest in roadside traffic monitoring and provide robust representation of diverse environmental conditions, viewing angles, occlusions, and scales. (Lin, T.-Y. et al., 2014; Bochovskiy, A. et al., 2020)

DeepSORT (Simple Online and Realtime Tracking with a Deep Association Metric) was employed to associate object detections across video frames and maintain consistent identities over time. In this study, the appearance descriptor was taken from the pre-trained DeepSORT re-identification model, which has been trained on large-scale pedestrian datasets such as Market-1501, enabling robust discrimination between different individuals and vehicles based on visual features. As DeepSORT performs online learning of appearance embeddings during tracking, it adapts to the specific scene without requiring additional offline training, making it well-suited for dynamic roadside monitoring scenarios. (Wojke, N. et al., 2017; Zheng, L. et al., 2015)

The ground truth points are generally corresponding points in both image and real-world coordinates used for calibration with a PnP method. Obtaining the image-plane coordinates of points was performed using a custom script, the precise real-world coordinates of the points were acquired using a GNSS station and will be described further in a calibration chapter.

4.3. Objects Detection & Tracking

For the purpose of detect and track the objects of interest, two methods were introduced. For both detection and tracking was firstly implemented a background subtraction method, then due to its disadvantages, a CNN-based methods were finally used.

Background subtraction

To begin the process of automatic object detection, initially a classical approach based on background subtraction using a Gaussian Mixture Model (GMM) was applied. This method is widely used as a foundational step in video analysis, particularly for its simplicity, low computational cost, and suitability in controlled environments. The main idea is to model the background of a video scene using a mixture of Gaussian distributions, where each pixel is represented by a set of Gaussian functions that estimate the likelihood of it belonging to the background over time. Foreground objects are then identified as deviations from this learned background model.

The background subtraction method works on a simple principle, when it separates pixels that belong to the background from pixels belonging to the foreground. A foreground mask is obtained when the background is subtracted from an input frame. It is especially effective in scenarios where the background remains mostly stable and where quick prototyping is needed to validate the viability of automatic detection. (Berg, J. et al., 2022)

In order to build the algorithm to be able to eliminate a high-frequency noise, gaussian smoothening and mathematical morphology operations were implemented. Also, a new *„adaptive mask“* was developed to detect objects that are both close and far from the camera to overcome the perspective distortion. The algorithm firstly detects large object and assigns them an ID. Then the parameters are automatically set to perfectly detect smaller objects, ignoring the areas, where larger objects were detected. By concatenating these two sets of objects a final mask with all objects is obtained. In the following Figure 2, an example of the moving object detection is displayed.

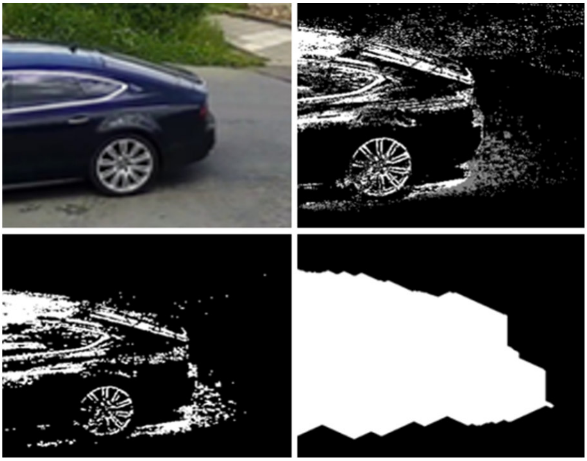


Figure 2 – Object detection with a background subtraction method (top-left: original image, top-right: thresholding, bottom-left: denoising, bottom-right: mathematical morphology)

Despite all efforts to fine-tune this method, the disadvantages based on the core principle of the method prevailed. The model wasn’t able to handle occlusions of objects, track not-moving objects and has a low performance/computational power demand ratio. Therefore, a CNN-based methods were introduced for the particular application.

CNN-based methods

Methods of automatic object detection and tracking based on CNNs are state-of-the-art in the field of computer vision and machine learning. In the following Figure 3 a basic principle is visualized.

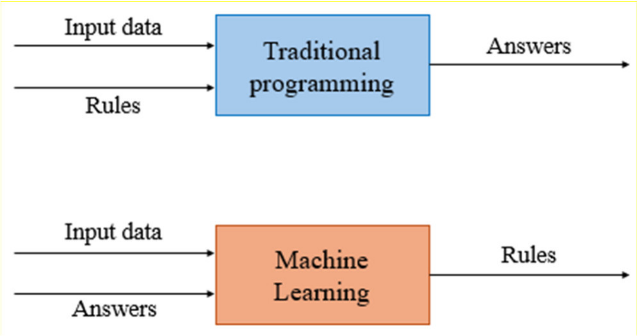


Figure 3 – Traditional programming vs. Deep Learning (TensorFlow, 2022)

Finally, an automatic detection method YOLOv7 has been selected to detect desired objects. The main reasons to choose this method were its speed, further implementation abilities and its accuracy. YOLO algorithms are known to be one of the fastest and are able to perform reliable real-time detections. There are also many modifications of YOLO improving its speed and accuracy. This method is complemented by DeepSORT tracker, which were chosen due to its ability to handle occlusion well, which is the main problem in tracking objects in traffic scenarios. Moreover, DeepSORT uses its own CNN to work with appearance features of objects which makes it more successful when dealing with occlusion.

A Figure 4 shows the object detection with the YOLOv7 algorithm.

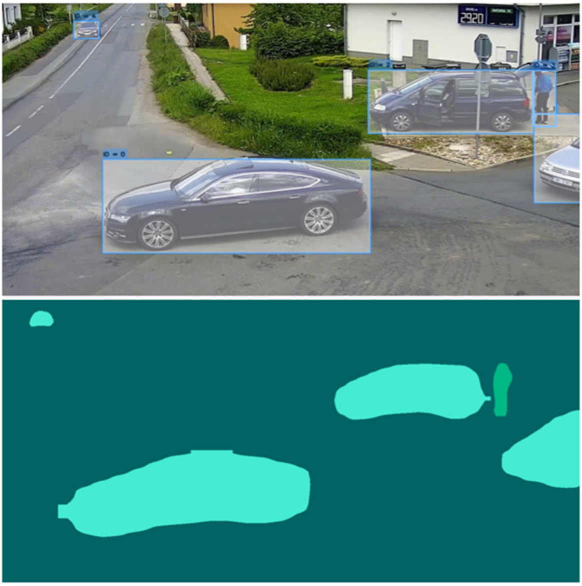


Figure 4 – Detecting objects with YOLOv7 (author)

After a successful detection, localization and classification of objects, a DeepSORT tracker is implemented to track the path of the objects. Each detected object is tracked using a Kalman filter to predict its next position, while a CNN trained for person/object re-identification extracts an appearance embedding. These two cues, motion and appearance, are combined into a single cost metric optimized by the Hungarian algorithm to associate detections with existing tracks. (Wojke, N. et al., 2017)

4.4. Simulation test run

After obtaining and configuring the YOLOv7 detector and implementation of the DeepSORT tracker, it was advisable to perform a test run of the SW to verify its functionalities and identify weaknesses. For this purpose, a simulation in a SW for traffic accidents analysis, Virtual Crash 3, has been prepared. A simulation provides an isolated environment with no occlusions, noise etc. which can be fully customized by the user, e.g. camera position, vehicle path relatively to the camera, kinematic and dynamic parameters are defined and known and also calibration points (ground truth real-world points).

In order to be able to identify the precision, strengths and weaknesses and functionality of the program under various controlled circumstances, the simulations were performed with one car (Škoda Octavia) driving on a straight plain road with two variables: initial speed & deceleration and camera angle towards the longitudinal axis of the road. These configurations were varied as follows:

Initial speed & deceleration

a) $v_{konst} = 50$ km·h^{-1},
b) $v_{init} = 50$ km·h^{-1} and deceleration 4 m·s^{-2},
c) $v_{init} = 80$ km·h^{-1} and deceleration 7.649 m·s^{-2}*.

*for the chosen Škoda Octavia car this was a limit in the Virtual Crash 3 SW.

Camera angle with road

I. 0° (camera and road longitudinal axes parallel),
II. 30°,
III. 60°,
IV. 90° (camera and road longitudinal axes perpendicular).

Combining all these variable levels, 3x4 analyses were performed and evaluated. In the following text only b-III particular example will be shown ($v_{init} = 50\ \mathrm{km \cdot h^{-1}}$ + deceleration $4\ \mathrm{m \cdot s^{-2}}$ and camera angle 60°).

It was proven by the testing that the calibration points layout is especially important and has a direct influence on a calibration precision. By placing the four calibration points, the road plane is defined, which implies the main rules for defining these points: the points must not be colinear and shall be placed across the whole plane (not only along the road). The following Figure 5 shows the difference between the correct and incorrect calibration points layout.

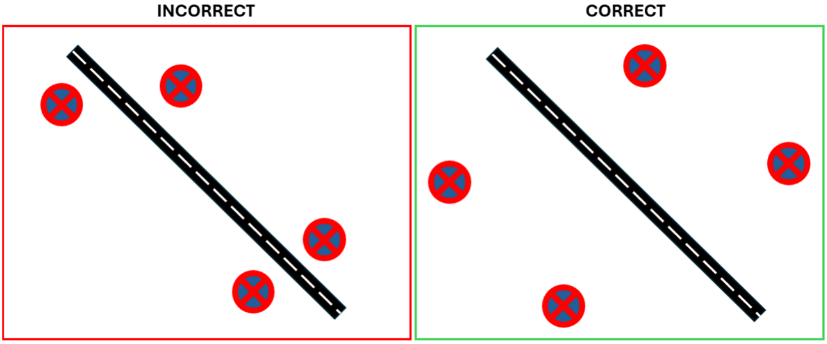


Figure 5 – Layout of the calibration points (author)

For each combination of driving and camera setting, a comparison between simulated (reference) and tracked by the SW curves was performed. Graphs look remarkably similar for all the configurations, only for camera angle 0°, when the longitudinal axis of the camera is parallel to the longitudinal axis of the road, the results are imprecise due to a high impact of the perspective distortion.

The main goal of the simulation test run wasn't to have the simulated and SW evaluated curves 100% equal but to identify the way the SW works in a most robust way and situations that the user must avoid. Below the key learned points from the simulation test run are listed:

- correct layout of the calibration points must be determined,
- camera angle to be ≥ 30° (<30° acceptable with additional validation or when the camera is high enough to obtain a sufficient resolution of the movement),
- delay of evaluated deceleration curve is 1 sec.

4.5. Validation through physical measurement

In order to provide precise validated measurement of the real traffic and drivers' behaviour, it was necessary to perform a validation measurement on the real crossing. Considering the recommendations for calibration coming from the simulation test run, a crossing S.K.Neumanna x Pichlova in Pardubice was chosen. The camera is located high above the road on a roof of a surrounding building which provides sufficient resolution of the movement of measured objects.

Calibration

Method called Perspective-n-Point is based on the knowledge of coordinates of several points in the real world and corresponding coordinates in the image. The main goal is to determine a transformation matrix which can robustly describe the relation between the image and real-world points. The transformation matrix consists of parameters of an intrinsic and extrinsic matrices of the camera which will be described further in this chapter. The minimal number of points needed for the calibration is based on the assumptions made by authors, but generally, when no calibration parameter is neglected, at least six non-colinear points are needed in the 3D coordinate system. Most authors assume the road as planar, which results in the decrease of the minimal number of points to four (z-world coordinate of each point is assumed zero or constant).

The camera intrinsic matrix K consists of the parameters of this configuration, such as focal length (distance between the barrier and the image plane – film), camera centre (coordinates of the pinhole) and skew (angle of image axis). The following formula describes the way of coordinates transformation from the pixel coordinate system to the world coordinate system.

$$Image\ coords\ (u, v) = [T, R] \cdot K \cdot World\ coords\ (x_w, y_w, z_w)$$

Where the K stands for an intrinsic matrix describing the internal geometry and optical properties of the camera, rotation (angles of the world axes in the camera coordinates) R and translation (camera coordinates of the world origin) T matrix are formed in order to obtain the transformation to the object’s world coordinates. This matrix is called camera extrinsic matrix, and its values change with the change of the camera's position.

Assuming for the purpose of the thesis only camera recordings with a road considered as a planar surface will be used, the parameter z_w can be put as a zero-height level, hence $z_w = 0$.

The unknown is a 3x3 homography matrix *H* combining unknown parameters from the intrinsic and extrinsic matrix. After algebraic adjustments of the formula above, each point in a pixel form can be defined as:

$$u = \frac{h_{11}x_w + h_{12}y_w + h_{13}}{h_{31}x_w + h_{32}y_w + h_{33}}$$

$$v = \frac{h_{21}x_w + h_{22}y_w + h_{23}}{h_{31}x_w + h_{32}y_w + h_{33}}$$

As can be seen from the above two equations, a solution with 9 unknown parameters must be found. However, the last component in the homography matrix h_{33} stands for a scale and can be considered = 1. Considering the assumption that z-coordinate is 0 as the ground is assumed plain, at least 4 corresponding points (each point has two coordinates → 8 known parameters) between the image and the real world have to be provided to find the solution of the system of equations.

Then a general equation will be obtained.

$$A\vec{x} = \vec{0}$$

In this case, A is the matrix of known values of zeros, ones and combinations of known coordinates of points in pixel and world coordinate system and $\vec{x}$ is the flattened matrix of unknown coefficients. The calculation of these coefficients is approximate and based on minimizing the algebraic error, which leads to the problem of eigenvectors.

For the input known points there are several rules that must be kept for convergence. Basically, it is advantageous to provide more than four known points. These points also shouldn't be colinear to maintain the independence of the points. After obtaining the transformation matrix, it is necessary to perform a non-linear optimization using a gradient descent algorithm to minimize a geometric error. (Xu and Wang, 2012; Krishna, 2022)

In this thesis, the ground truth points were obtained by a GNSS total station measurements physically at the crossing using a Leica station which was provided by the Faculty of Transportation Sciences CTU in Prague, Department of Forensic Experts in Transportation. For the measurement, a combination of Leica CS20 controller and Leica GS18 GNSS RTK Rover smart antenna was used.

Validation of the S.K.Neumanna crossing

The position of the camera is located at the roof of a high building which reduces the perspective distortion. There are also several places where drivers have to stop and give right of way which provides a good opportunity to measure a non-sudden braking. The scene was successfully calibrated with the PnP method with a negligible reprojection error.

The main purpose of the physical validation on the particular crossing was to be sure that the evaluated position of the vehicle is correct which was validated by comparing it with the data from GNSS. Using the tracking SW, the test vehicle coordinates were obtained, extracted (as in each scene were usually 10-15 objects at the same time) and calibrated to the same local coordinate system. Measurements of all possible direction of movement of the vehicle were extracted and are displayed in the following overview (Figure 6).

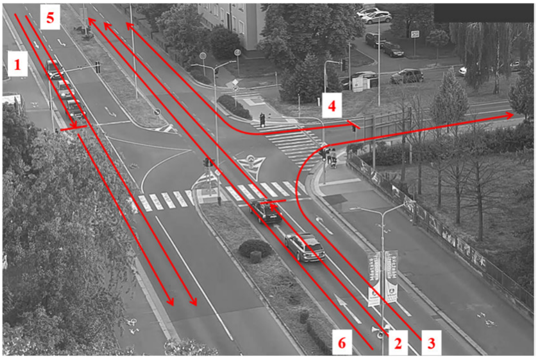
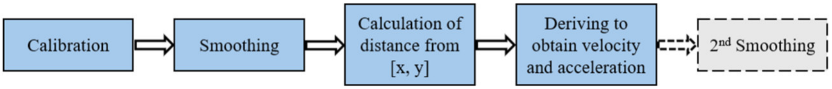


Figure 6 – Overview of validation measurements (author)

As can be seen in the Figure 6, six basic manoeuvres were selected for validation of the correct function of the tracker SW and later for data evaluation.

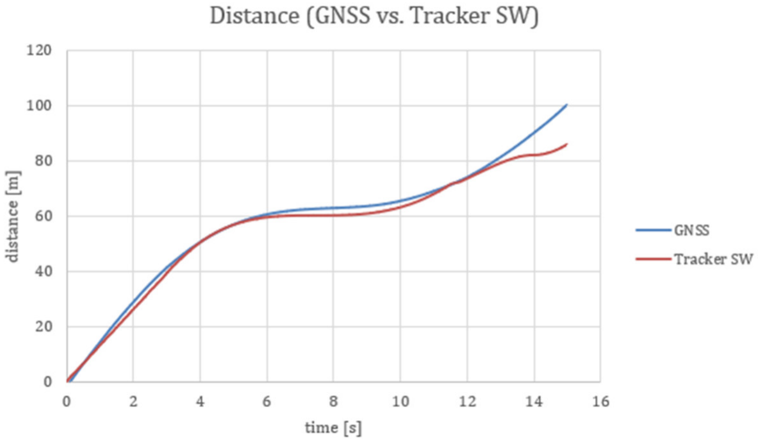
As a first result from the tracking SW, a time, x-axis and y-axis coordinates of the left-bottom, left-top, right-bottom and right-top points of bounding boxes were obtained. At first, a centre of each bounding box was calculated. The coordinates were in an image-plane coordinate system at this point warped by perspective distortion including considerable noise.

The following steps were performed to have a complete and processed set of data ready to be compared to the GNSS data. The order of the operations was important in order to avoid increasing any error from the raw data and was chosen as follows:

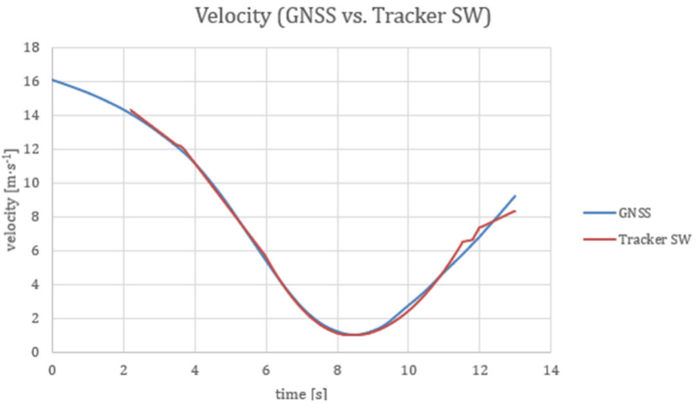


The calibration was performed as first because the smoothing shifts the points and calibration may scale a possible error of the correct but shifted points (homography matrix used for the calibration is non-linear). Moreover, the smoothing in the image plane can distort trajectories under perspective. For smoothing, a Savitzky-Golay, spline and Butterworth methods were combined to supress a high-frequency noise while maintaining the macro trends. Deriving must be done after the smoothing because each little noise at the distance level would be multiplied at the velocity and acceleration level. However, still a second round of smoothing is mostly needed to remove residual waves from the velocity and acceleration functions.

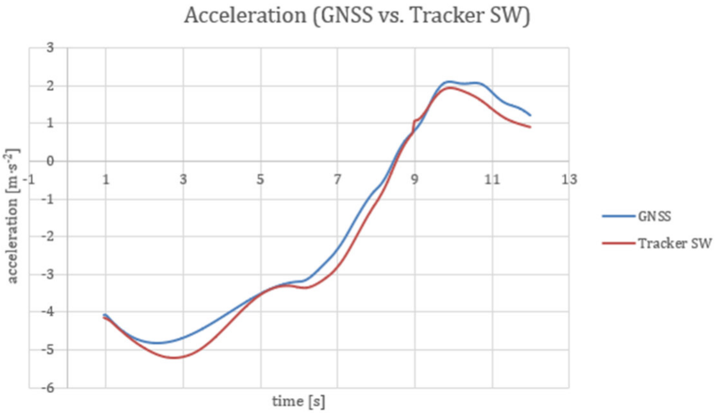
Graphs of the distance, velocity and acceleration are provided, obtained from the GNSS and tracker SW and processed. This is a representation of the drive number 2. The complete set of the graphs for all the six drives is attached to the main thesis as an Appendix 1.



Graph 1 – Distance evaluation from GNSS and tracker SW.



Graph 2 – Velocity evaluation from the GNSS and tracker SW



Graph 3 – Acceleration evaluation from the GNSS and tracker SW

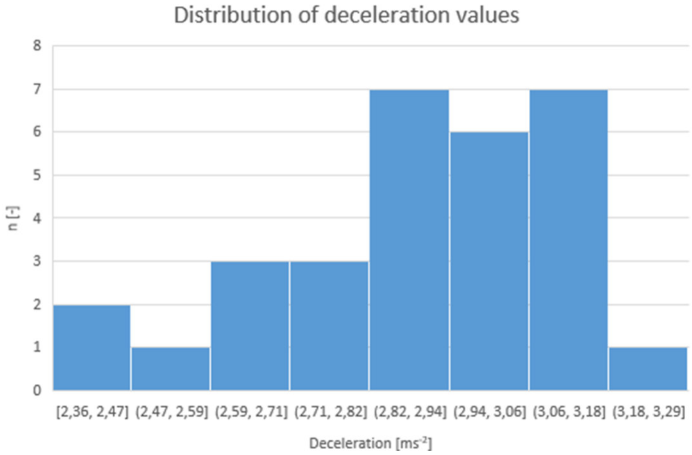
In the distance graph, the curve from tracker SW precisely follows the GNSS curve. Only at the end the tracker SW curve changes direction which is caused by disappearing of the vehicle in the perspective. The same case is the velocity graph. For the acceleration, there is a little irregular offset visible around ca. 0.5 $m \cdot s^{-2}$. It can be caused by the fact that the tracker SW needs more time to stabilize the bounding box after detecting the vehicle for the first time. Considering the GNSS and tracker SW curves from all the validation drives, the SW is precise enough after stabilization of the tracking algorithm to obtain reliable results.

4.6. Data evaluation

As it was already mentioned in the beginning of the thesis, a method of independent observation and then statistical evaluation of the results was chosen. The advantage of this approach is that the subjects of measurements (drivers) were not aware that they were being measured and therefore it is ensured that their behaviour was natural. The measurement was conducted on the S.K.Neumanna x Pichlova crossing in Pardubice as the scene has already been validated by comparison with the GNSS record. Moreover, only data from the straight part of the road were used for evaluation as the turn at the right is partially covered in the scene.

For the purpose of non-sudden braking measurement an already calibrated and validated scene was used. The video records from the crossing were cut to multiple representative samples where there is a good visibility of the measured randomly selected vehicle, no occlusion and the behaviour of the vehicle is not unusual. Then, the video records were automatically processed by the tracking SW, the raw data were automatically smoothened the same way as it was performed in the validation phase and then the mean deceleration of the braking part was obtained.

In order to obtain the non-sudden deceleration value, 30 independent and representative deceleration values were obtained of randomly selected vehicles and statistically evaluated. A distribution of means of individual decelerations is displayed in the graph below.



Graph 4 – Deceleration histogram

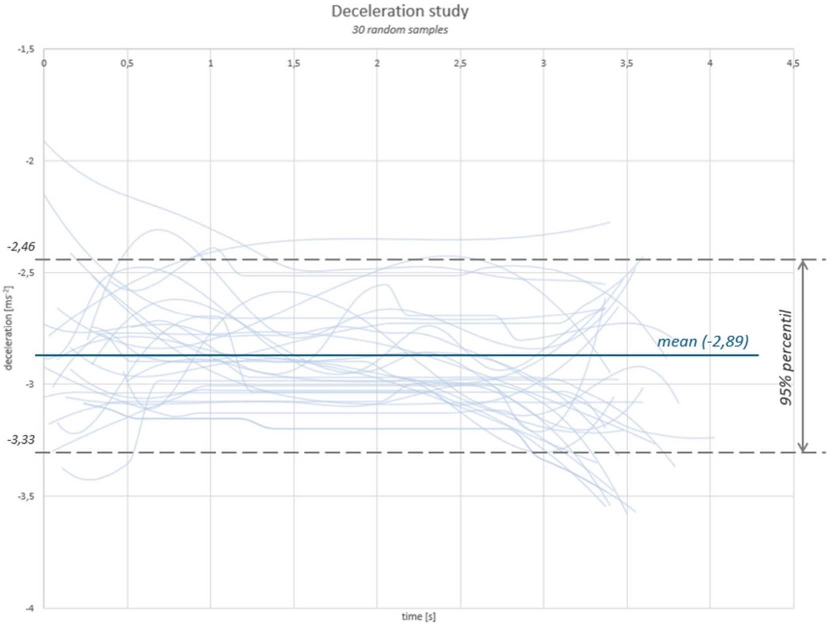
As the character of obtained data is supposed to be normally distributed, a normality tests were performed. A combination of visual assessment Q-Q plot and Shapiro-Wilk test was used for the sample size of 30 measurements and proved in both tests the outcome that the data sample has a normal distribution.

As a conclusion, the deceleration measurements can be summarized as follows in the Table 2:

Table 2 – Summary

Quantity	Value
Mean	-2.89
Standard deviation	0.22
Central 95% interval	(-3.33; -2.46)

In the following Graph 5, the evaluated data are highlighted in the deceleration graph.



Graph 5 – Deceleration graph with highlighted statistical values (author)

5. CONCLUSION

In the presented thesis a complex procedure was developed, building a backbone of automatic bulk data analysis from traffic surveillance cameras. The pipeline consists of obtaining input data from traffic surveillance cameras and preparation of scenes as an input for the further steps. The core of the automatic data acquisition is a synthesis of a detection and tracking SW based on a pre-trained CNNs (YOLOv7 + DeepSORT) and their implementation using a suitable dataset for learning (MS COCO). A crucial part in terms of precision is a correct calibration of the scene, using a PnP principle which proved to be versatile and precise.

In order to evaluate the precision and application limits of the SW and calibration method, a validation through simulation and physical measurement was performed. As a first step, drives of a vehicle in a rendered video from simulation under various controlled conditions were processed and evaluated. In the second step, kinematic and dynamic quantities were evaluated from a real measurement on a selected crossing from both the GNSS station and tracker SW and compared together. After a successful validation, a non-sudden braking representing a quantity frequently used in a traffic accidents analysis praxis was evaluated from a random sample from a validated traffic surveillance camera.

The main objectives of the thesis were fulfilled:

- A complex and universal method for not only traffic analysis was developed.
- Its correct application and precision were proven on particular samples of video records from a real crossing.
- The correct functionality and boundaries of the method were determined by two-step validation through a simulation and physical measurement.
- On a validated scene, a non-sudden braking quantity was obtained and evaluated.

Following the critical path for obtaining the non-sudden braking deceleration, the scene has been calibrated creating a homography matrix perfectly fitting the real road plane. As the next step, 30 samples of video shots of random vehicles braking to stop were processed through the tracking SW. The data were smoothened and statistically evaluated, showing that the **non-sudden braking deceleration lies between -3.33 and -2.46 m·s^{-2} (95 % central interval) with a mean of -2.89 m·s^{-2}.**

Relating the evaluated results to a recent forensic praxis of traffic accidents analysis, the result is aligned with the interpretation that the non-sudden braking lies around the value of a half of the minimum required mean fully developed deceleration (MFDD) for passenger cars 5.8 m·s^{-2}, hence 2.9 m·s^{-2} according to the UN/ECE Regulation No. 13-H, and Czech technical regulations (Vyhláška č. 341/2014 Sb.).

The results of the thesis can be used directly in the traffic accidents analysis praxis as a reference value when evaluating the suddenness of an event, which leads to a more precise understanding of the accident configuration and driver's behaviour before it. The method itself is versatile and with minor adjustments can be applied on a variety of cases when an automatic object detection and tracking together with a robust calibration method is needed. Moreover, various proposals on further research are introduced. The practical use of the outcome of the thesis as well of the method itself together with many directions of possible further development highlight the perspectivity of the research.

The initial hypothesis regarding the capability of the developed tracking system to provide sufficiently precise kinematic and dynamic parameters of traffic users has been confirmed under specific circumstances. To achieve a reliable precision, the position of the camera must fulfil rules defined in the thesis. At the same time, the road must be flat, there should be maximally a little occlusion of objects and the movements of objects that are analysed has to last at least 1 second as the SW needs to stabilize after detection. The hypothesis would be confirmed fully (no constraints of the applicability of the proposed system) if wider research of the detection and tracking SW is performed resulting in more precise and robust detection and tracking with lower computational power demand at the same time.

6. FURTHER RESEARCH PROPOSAL

The thesis introduces a complex methodology of obtaining a specific kind of data. Following the pipeline in the Figure 15 of the procedure, there were considered several assumptions which enabled to obtain a robust method and desired results in sufficient precision. Below in this chapter, a list of further research proposals is provided. Conducting and developing of the following research can significantly contribute to the field of automated traffic analysis as well as generally automatic object detection and tracking.

- Evaluating also other kinematic and dynamic quantities (e.g. safe pass time, natural acceleration of drivers, time threshold of braking/accelerating when an orange signal appears on the traffic light etc.).
- Difference between multiple types of cars, year seasons, illumination conditions, time, cities, gender.
- Correction of the offset in the graphs.
- Calibration using aerial images and its precision.
- Error distribution across the whole procedure.
- Correction of the mismatch of positions of the centre of bounding boxes (optical centre of the object in the video point of view and a real mass centre of the object).

Furthermore, it could contribute to the procedure reliability and robustness, if the FMEA or similar analysis would be performed and recommended actions would be implemented.

7. REFERENCES

Berg, J., Jilek, P., Pokorný, J. and Krmela, J., 2022. *Metody předzpracování obrazu pro automatickou detekci účastníků silničního provozu. Perner's Contacts*, 17(2). doi:10.46585/pc.2022.2.2389. ISSN 1801-674X.

Bochkovskiy, A., Wang, C.-Y. and Liao, H.-Y.M., 2020. *YOLOv4: optimal speed and accuracy of object detection* [online]. arXiv preprint arXiv:2004.10934. Available at: https://arxiv.org/abs/2004.10934 [Accessed 20 August 2025].

Bradáč, A., 1997. *Soudní inženýrství*. Brno: Akademické nakladatelství CERM, s.r.o. ISBN 80-7204-057-X.

Bradáč, A., Semela, M., Kledus, R., Bilík, M., Křižák, M., Mikulec, R., Bucsuházy, K., Belák, M., Mičunek, T., Frydrýn, M., Nouzovský, L., Svatý, Z., Radová, Z., Fryšták, M., Vojtíšek, T., Pokorný, J. and **Berg, J.**, 2021. *Teorie a praxe analýzy silničních nehod*. Brno: VUTIUM. ISBN 978-80-214-6209-0. doi:10.13164/usi.book.tpasn.

Česká republika. Ministerstvo dopravy, 2000. *Zákon č. 361/2000 Sb., o provozu na pozemních komunikacích*. Sbírka zákonů, částka 101/2000. Praha: Ministerstvo dopravy ČR.

Česká republika. Ministerstvo dopravy, 2014. *Vyhláška č. 341/2014 Sb., o schvalování technické způsobilosti a o technických podmínkách provozu vozidel na pozemních komunikacích.* Sbírka zákonů, částka 134/2014. Praha: Ministerstvo dopravy ČR.

Krishna, N., 2022. *Camera Calibration with Example in Python*. *Towards Data Science* [online]. 27 January. Available at: https://medium.com/data-science/camera-calibration-with-example-in-python-5147e945cdeb [Accessed 5 December 2022].

Lin, T.-Y., Maire, M., Belongie, S., Hays, J., Perona, P., Ramanan, D., Dollár, P. and Zitnick, C.L., 2014. *Microsoft COCO: Common Objects in Context*. In: *Computer Vision – ECCV 2014. Lecture Notes in Computer Science*, vol. 8693. Cham: Springer, pp.740–755. https://doi.org/10.1007/978-3-319-10602-1_48

TensorFlow Tutorials. *TensorFlow* [online], 2022. Available at: https://www.tensorflow.
org/tutorials [Accessed 5 December 2022].

Tokař, S., 2014. *Analýza pojmů náhle x nenáhle pomocí experimentu*. In: Schejbal, J. and Bradáč, A. (eds.) *Sborník příspěvků konference Expert Forensic Science 2014*. Brno: Vysoké učení technické v Brně, Ústav soudního inženýrství, pp. 283–295. ISBN 978-80-214-4852-0.

United Nations Economic Commission for Europe (UNECE) (latest revision) *UN/ECE Regulation No. 13-H: Uniform provisions concerning the approval of passenger cars with regard to braking.* Geneva: UNECE.

Wojke, N., Bewley, A. and Paulus, D., 2017. *Simple online and realtime tracking with a deep association metric*. In: *2017 IEEE International Conference on Image Processing (ICIP)*, pp. 3645–3649. IEEE. Available at: https://doi.org/10.1109/ICIP.2017.8296962

Xu, H. and Wang, X., 2012. *Camera calibration based on perspective geometry and its application in LDWS*. *Physics Procedia*, 33, pp. 1626–1633. Available at: https://doi.org/10.1016/j.phpro.2012.05.262

Zheng, L., Shen, L., Tian, L., Wang, S., Wang, J. and Tian, Q., 2015. *Scalable person re-identification: a benchmark*. In: *2015 IEEE International Conference on Computer Vision (ICCV)*, pp. 1116–1124. IEEE. Available at: https://doi.org/10.1109/ICCV.2015.133

8. AUTHOR'S PUBLICATIONS

Jilek, P., Šefčík, I., Verner, J. and Berg, J., 2019. *System allowing adhesion force change of road vehicle. Engineering for Rural Development: Proceedings of the 18th International Scientific Conference Engineering for Rural Development (ERD 2019)*, Jelgava, Latvia, 22–24 May. Jelgava: Latvia University of Agriculture, pp. 1876–1882. ISSN 1691-3043. e-ISSN 1691-5976.

Jilek, P., Krmela, J. and Berg, J., 2020. *Modification of the adhesive force on a vehicle by reducing the radial force reaction of the wheels. Transport Problems 2020: Proceedings of the XII International Scientific Conference and IX International Symposium of Young Researchers (TRANSPORT PROBLEMS 2020)*, Katowice, Poland, 30 November–2 December. Katowice: Silesian University of Technology, pp. 345–353. ISBN 978-83-959742-0-5. ISSN 1896-0596.

Jilek, P., Krmela, J. and Berg, J., 2021. *Modification of the adhesive force by changing the radial reaction on vehicle wheels. Transport Problems*, 16(1), pp. 179–186. doi:10.21307/tp-2021-015. ISSN 1896-0596. e-ISSN 2300-861X.

Jilek, P. and Berg, J., 2021. *Optimization of device allowing variation of adhesion force for road vehicle testing at safe speed. Engineering for Rural Development*, 20, pp. 373–378. Jelgava: Latvia University of Life Sciences and Technologies. doi:10.22616/ERDev.2021.20.TF078. ISSN 1691-3043. e-ISSN 1691-5976.

Jilek, P. and Berg, J., 2021. *Umístění svaru a jeho vliv na koncentraci napětí. Perner's Contacts*, 16(2). doi:10.46585/pc.2021.2.1738. ISSN 1801-674X.

Jilek, P. and Berg, J., 2021. *The adhesion force change of an experimental road vehicle. Manufacturing Technology*, 21(5), pp. 634–639. doi:10.21062/mft.2021.083. ISSN 1213-2489.

Bradáč, A., Semela, M., Kledus, R., Bilík, M., Křižák, M., Mikulec, R., Bucsuházy, K., Belák, M., Mičunek, T., Frydrýn, M., Nouzovský, L., Svatý, Z., Radová, Z., Fryšták, M., Vojtíšek, T., Pokorný, J. and Berg, J., 2021. *Teorie a praxe analýzy silničních nehod*. Brno: VUTIUM. ISBN 978-80-214-6209-0. doi:10.13164/usi.book.tpasn.

Berg, J., Jilek, P., Pokorný, J. and Krmela, J., 2022. *Metody předzpracování obrazu pro automatickou detekci účastníků silničního provozu. Perner's Contacts*, 17(2). doi:10.46585/pc.2022.2.2389. ISSN 1801-674X.

Jilek, P., Berg, J. and Sadjiep Tchuigwa, B.S., 2022. *Influence of the weld joint position on the mechanical stress concentration in the construction of the Alternative Skid Car system's skid chassis. Applied Sciences – Basel*, 12(1), p. 397. doi:10.3390/app12010397. ISSN 2076-3417.