DOCTORAL THESIS

Analysing the Behaviour of Road Users and Estimating Efficiency of Smart Pedestrian Crossing as a Tool for Sustainable Road Safety Improvement

Juri Ess

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Declaration:
Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology has not been submitted for doctoral or equivalent academic degree.

Juri Ess

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Liikluskäitumise analüüs ja targa ülekäiguraja tõhususe hindamine jätkusuutliku liiklusohutuse parandamiseks

JURI ESS

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Contents

List of publications

The list of author's publications, on the basis of which the thesis has been prepared:

I Ess, J.; Antov, D. (2016). Unified methodology for estimating efficiency of traffic calming measures – example of Estonia. *The Baltic Journal of Road and Bridge Engineering,* 11(4), 259–265.

II Ess, J.; Antov, D. (2017). Estonian traffic behaviour monitoring studies 2001–2016: overview and results. *The Baltic Journal of Road and Bridge Engineering*, 12(3), 167–173.

III Ess, J.; Luppin, J.; Antov, D. (2021). Estimating the potential of a warning system preventing road accidents at pedestrian crossing. *Logforum,* 17(3), 441–452.

Author’s contribution to the publications

The author’s contribution to the publications on the basis of which the thesis has been prepared are the following.

I Literature analysis, pre-study experiments, choice of equipment, organising and conducting the pilot study, data analysis, writing and publishing the paper.

II Literature analysis, interview with Leena Pöysti (Liikenneturva), data analysis, writing and publishing the paper.

III Literature analysis, pre-study experiments, choice of equipment, conducting the study, preparing a group of data analytics for preliminary conflict detection, analysing traffic conflict data, preparing input data for PC-Crash, analysing conflict models and simulations, writing and publishing the paper.

Introduction

In contemporary societies, road traffic is an integral part of everyday life. People participate in traffic as drivers, pedestrians, and passengers. They do so because they can, like, and need to. The most common expectations to mobility options are connected to fast, comfortable, safe, and environmentally friendly transportation. However, safety is in a certain sense the most important factor – no one should get injured or killed because of their need or desire for mobility. This makes road traffic safety one of the most important topics in the European Union (EU).

During the last three decades, a dramatic road safety improvement has taken place and the number of road fatalities in the 28 EU countries (including the ex-member United Kingdom) decreased 4.01 times. Estonia showed an even more promising result, having decreased this number 8.3 times. However, the current situation is far from ideal. In 2019, the last year before the COVID-19 pandemic started influencing travelling, the EU claimed about 22,700 road fatalities and over 1.2 million road injuries (European Commission, 2021). In comparison with air traffic, where in 2017–2020 there were no fatal accidents involving European Commercial Air Transport (EASA, 2021), the road traffic statistics are very poor.

The EU sets ambitious goals in terms of improving this situation and reducing the number of road fatalities by 50% every 10 years. However, this goal has never been achieved. In 2000–2010, the reduction was 43%, and in 2011–2019, it was only 23%[1] (ETSC, 2021). Improvement of road traffic safety stagnated in 2013 (see Figure 1). The biggest issue is connected to the number of traffic accidents leading to injury or death, which is practically unchanging – the average decrease in the EU in 2010–2019 was only 4% (ETSC, 2021). The situation is challenging, and the question arises whether the current state of affairs is close to the maximum possible safety level?

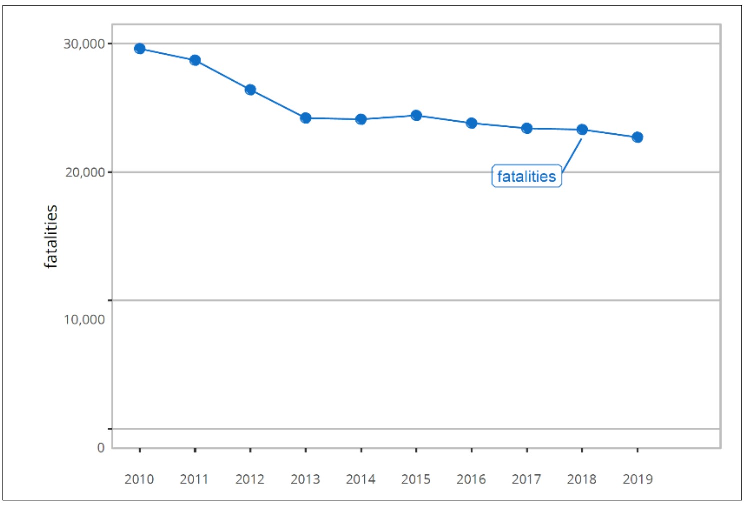

Figure 1. Downward trend in the number of road traffic fatalities in the EU (ETSC, 2021).

[1] The year 2020 is not mentioned here, because respective data it is not representative – as a result of the COVID-19 pandemic, traffic volumes were lower and this had a significant impact on the number of road fatalities (ETSC, 2021).

The goal of this doctoral thesis is to find a perspective direction for future road safety developments, to propose a solution to the problems determined and to estimate its effectiveness.

One of the major road safety problems in the EU are vulnerable road users (VRUs). Pedestrians account for 21% of all road deaths across the EU, while cyclists represent a further 8% (ETSC, 2020). In urban areas, almost 40% of the fatalities are pedestrians. According to the Estonian Road Administration, most vehicle-pedestrian collisions in Estonia are happening at uncontrolled pedestrian crossings. Estonian traffic behaviour monitoring study held in 2020 showed that 38% of drivers do not yield to pedestrians at uncontrolled crossings (Transpordiamet, 2020). The number of pedestrian deaths and serious injuries is decreasing slower than the numbers for motorised road users (ETSC, 2020). This can be explained by the fact that vehicles are becoming safer, but do not offer sufficient protection for VRUs. Improving this situation is rather challenging.

Today, the EU puts big hopes on contemporary technologies, such as the Autonomous Emergency Breaking (AEB) and Cooperative Intelligent Transport Systems (C-ITS). From 2015, all new heavy-duty vehicles are equipped with AEB (European Commission, 2016) and from 2022, all vehicles, including passenger cars, are also be equipped with AEB (Regulation (EU) 2018/858). In the near future, one can expect more smart vehicles with automatic brakes on the European roads, and smarter infrastructure that can communicate with vehicles.

In this respect, one can deploy a new generation traffic calming measure (TCM) – a Smart Pedestrian Crossing[2] (SPC). This is a C-ITS system, which monitors traffic at uncontrolled crossings and detects potential danger much earlier than the driver or the sensor of a vehicle. Such a SPC could warn road users as well as AEB-equipped vehicles of potential danger. But would the SPC be able to solve the problem of yielding to pedestrians and thus improve traffic safety?

In accordance with the goals set for this thesis, the following research tasks (RT) were formulated:

1. to determine the perspective direction for future road safety improvement based on analysis of changes in the road user's behaviour and to propose a respective solution (RT1);
2. to estimate the potential effectiveness of the proposed solution (RT2);
3. to determine the 'must-have' features of the proposed solution (RT3).

The scientific novelty of this doctoral thesis is in designing new methodologies for estimating effectiveness of traffic calming measures (TCM), including intelligent and non-existent measures:

- road safety improvements were analysed through changes in road users' behaviour to outline the problems remaining unsolved;
- there was developed a unified methodology for estimating effectiveness of TCM, which does not assume conducting before-and-after studies;
- there was developed a methodology for estimating effectiveness of a non-existent C-ITS warning system, which uses the traffic conflict technique and microsimulation.

Where was proposed a classification of SPCs based on their functionality as well as a concept of a top-level SPC, which acts on demand and corresponds to the Safe System

[2] It should be noted that Smart Pedestrian Crossing is not a trademark, and the word 'smart' corresponds to the state-of-the-art technology, not to a certain device or product.

approach. The thesis provided important input for development of the state-of-the-art C-ITS technologies. It was found that a C-ITS warning system has strong potential to improve pedestrian safety at uncontrolled crossings, thus, it makes sense to proceed with the development of SPCs adding the outlined essential technological features. It was also found that in many situations on-board systems detecting pedestrians would not ‘see’ the pedestrian in time. It means that the pedestrian safety cannot be guaranteed by the vehicle on its own and input from roadside C-ITS stations is needed. Thus, to ensure rapid and sustainable development in this field, it makes sense to equip the new vehicles with vehicle-to-infrastructure (V2I) or vehicle-to-everything (V2X) communication modules in the standard vehicle configuration.

The results of this doctoral thesis were implemented in designing warning algorithms for a prototype of an SPC that has been developed in Estonia. At the moment of defending this doctoral thesis, the first SPCs are being tested in Tallinn, Viimsi, and Tartu.

Abbreviations

AEB	Autonomous Emergency Braking
C-ITS	Cooperative Intelligent Transport Systems
DBQ	Driver Behaviour Questionnaire
DR	Deceleration Rate
DST	Deceleration-to-Safety Time
EC	European Commission
ENRTSP	Estonian National Road Traffic Safety Programme
ETSC	European Transport Safety Council
EU	European Union
GNSS	Global Navigation Satellite System
I2I	Infrastructure-to-Infrastructure
KPI	Key Performance Indicator
Max D	Maximum Deceleration
PET	Post-Encroachment-Time
P2I	Pedestrian-to-Infrastructure
SAE	Society of Automotive Engineers
SPC	Smart Pedestrian Crossing
SPI	Safety Performance Indicator
TA	Time-to-accident
TalTech	Tallinn University of Technology
TCM	Traffic calming measures
TTC	Time-to-collision
TTC_{min}	Minimum time-to-collision
TTZ	Time-to-Zebra
$TTZ_{duration}$	Time-To-Zebra duration
VMS	Variable Message Sign
VRU	Vulnerable road user
V2I	Vehicle-To-Infrastructure
V2X	Vehicle-To-Everything

1 The theoretical framework and research structure

This chapter describes the theoretical framework of the doctoral thesis as well as the research objectives and structure. The first part describes the road traffic safety challenges in the EU as well as future goals and tools for their achievement. The second part handles classical and surrogate metrics, which can be used for road safety estimation. The third part is dedicated to road users' behaviour as an integral part of road safety and the methods being used to study this behaviour. The fourth part describes TCM as a tool for altering road users' behaviour as well as estimating their road safety effect. The last part explains research structure and shows the interconnection of the research tasks and publications.

1.1 Road safety in the EU and improvement challenges

1.1.1 Vision Zero as a measurable goal

Vision Zero is a popular safety paradigm invented in Sweden and adopted by the EU. It proposes an ethical approach to the health problems associated with road traffic: it can never be ethically acceptable that people are killed or seriously injured when moving within the road transport system (Johansson, 2009).

However, Vision Zero is not a philosophical understanding, but a specific approach to improving road safety. It proposes creating error-tolerance in the road design where all predicted crashes and collisions have tolerable health losses (Johansson, 2009). Examples of such a road design are roundabouts, a speed limit of 30 km/h within population centres, 2+1 roads with midrails, safer roadsides (Rosencrantz, et al., 2007).
According to the Vision Zero philosophy, it is true that 95% of all crashes or collisions depend on human error, but 95% of the solutions are in changing roads, streets, or vehicles. So, the road users' behaviour and road design, being the crucial components of the road safety paradigm, are handled together. Vision Zero questions the tradition of blaming road users for traffic accidents and presumes a new division of responsibility for road safety within the road transport system. The designers of the road transport system should always be ultimately responsible for its safety, while road users are responsible for following the rules and for using this system set by its designers. At the same time, if road users fail to obey these rules, they should not be killed and seriously injured (Johansson, 2009).

The positive trend in reduction of road deaths in Sweden, whose roads are still among the world's safest, has been seen by many as proof of the policy's effectiveness, and today, Vision Zero is internationally seen as a promising road traffic safety policy (Kristianssen, et al., 2018). The Vision Zero approach to road safety was adopted in many countries around the world. The EU set a long-term goal to move closer to zero road deaths by 2050 (Johansson, 2009; European Commission, 2020). It is also important to acknowledge that the concept has also inspired technological innovations in, for instance, the car industry, where several brands are working towards the goal of zero fatalities (Kristianssen, et al., 2018).

1.1.2 Trends and challenges in road safety

The EU adopted the principles of Vision Zero and decision-making on road safety proceeds from the tenet that death and serious injury as a price to pay for mobility is not acceptable. Society does not accept deaths in the air and should no longer accept them on the road. Reducing road fatalities to a number close to zero is expected by 2050.

In the meanwhile, the target was to halve the number of road deaths each decade (European Commission, 2020).

In accordance with the philosophy of Vision Zero, the indicator measuring target achievement is the number of road fatalities (staring from 2020, also the number of seriously injured road users, as well as other KPIs). The first decade-long EU target period was 2001–2010 and it was almost met – the number of road deaths in the EU decreased by 43 % (European Commission, 2020). However, the second 2010–2020 period was less successful (see Figure 2). The overall progress was almost on track with the target from 2010 until 2013 with an 18% decrease. But the good start was followed by six consecutive years of stagnation with only a 6% reduction over the 2013–2019 period. Later, in 2020, there was an exceptional drop of 17% compared to 2019. The 2020 result is strongly related to travel restrictions across Europe due to the COVID-19 pandemic. The overall reduction of road fatalities in 2010–2020 was 36%, while the reduction of serious road traffic injuries was only 14% (ETSC, 2021).

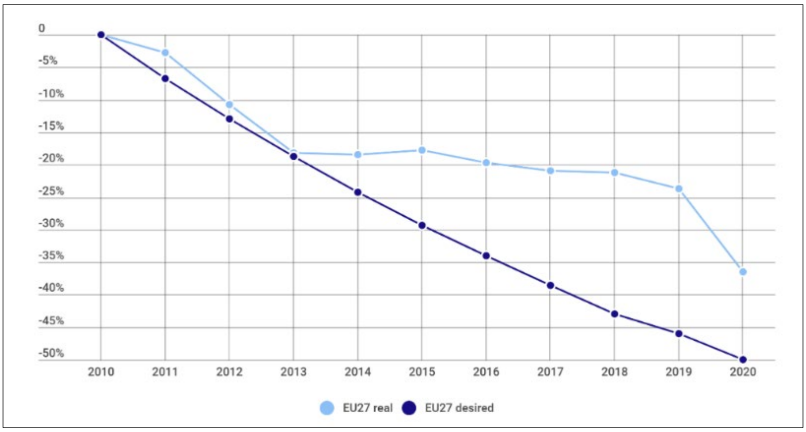

Figure 2. The number of road traffic fatalities in the EU in 2010–2020 and strategic goals (ETSC).

Among other things, traffic accidents give rise to huge costs to society. A recent study estimated the costs of all the reported collisions in the EU to be about 270 billion euros in 2015, which is nearly twice as large as the annual EU budget (ETSC, 2018). Therefore, solving the safety problems would also have an economic outcome.

One of the main issues of road safety in the EU are vulnerable road users, especially pedestrians and cyclists. Pedestrians account for 21% of all road deaths across the EU, while cyclists represent a further 8% (ETSC, 2020). This proportion is high, but in urban areas, it is even worse – almost 40% of fatalities are pedestrians, 12% are cyclists. The number of pedestrian deaths and serious injuries is decreasing slower than the numbers for motorised road users, while a decreasing trend for cyclists has almost stagnated (ETSC, 2020). This can be explained by the fact that vehicles are becoming safer, but do not offer sufficient protection for VRUs. Improving this situation is rather challenging.

Another issue which gives cause to worry is connected to the number of serious road injuries. In the previous decade, for all categories of road users, this number was decreasing 2.6 times slower than the number of fatalities. Some fatalities were prevented, for example, by safer vehicles and better post-crash care, but boost the serious injury statistics (European Commission, 2020). But in the context of Vision Zero, serious injury is not much better than a fatality. It means that the main focus should be set on active safety, i.e. the prevention of traffic accidents, not alleviating the consequences.

1.1.3 The next goals and measures to achieve them

Despite all the problems and stagnation in road traffic safety improvement, the EU is holding to its ultimate goal – to reduce by 2050 the number of fatalities and serious injuries on European roads to almost zero. The new target for the period 2021–2030 is to halve road deaths and serious injuries compared to 2020 levels (European Commission, 2020; ETSC, 2018).

The new EU 10-year action programme includes embodying the Safe System approach. It is guided by Vision Zero and aims for a more forgiving road system, which assumes a combination of such measures as better vehicle construction, improved road infrastructure, lower speeds. The idea is that these measures form multiple layers of protection and if one element fails, another one will compensate to prevent the worst outcome (European Commission, 2020; ETSC, 2018).

The progress will be assessed by means of monitoring special KPIs, which can give a more complete picture of the level of road safety and help detect the emergence of problems at an earlier stage. The KPIs will be measured in Member States according to the unified methodology and the long-term goal is to collect comparable data (ETSC, 2021). This approach is, in a sense, similar to Finnish and Estonian traffic behaviour monitoring, which will be addressed later in this chapter. In the initial stage, there will be eight KPIs. Some of them (speed compliance, the use of safety belts, drinking and driving) are directly connected to traffic behaviour, while others (safety of new cars and infrastructure) are linked to other layers of road safety. The first set of KPIs will be completed and refined further over time.

According to the EU Road Safety Action Programme 2020–2030, the top three priorities for action are VRU safety, automation, and reducing the numbers of the seriously injured. Measures planned to achieve the targets vary from increasing enforcement and the reduction of motorised traffic in urban areas to developing interaction of automated vehicles with other road users and road infrastructure. Among the measures addressed to VRU safety, one can outline on-board systems detecting pedestrians and cyclists in close proximity (meant for heavy goods vehicles) and head-on impact protection on A-pillars and the front windscreen (European Commission, 2016; European Commission, 2018b; ETSC, 2021).

One of the options considered was equipping passenger cars with a pedestrian detection system, which identifies the prospective collision and warns the driver and/or applies the AEB. However, the benefit-to-cost ratio was considered to be less than 1 (European Commission, 2015). One of the reasons has to do with technological limitations – the field of vision of the vehicle sensor system is not sufficient to detect pedestrians in time and start braking. The three challenges are the obscuration, high speed, and the small size of pedestrians. For instance, a child running behind an obstacle. These problems might not be solvable in the mid- and far future, and even mitigation does not seem to be possible (European Commission, 2014). Despite that, the European New Car Assessment Programme (Euro NCAP) included AEB systems in their tests. However, it must be mentioned that these tests are conducted in almost ideal conditions – dry road, no precipitation, visibility of at least 1 km (Euro NCAP, 2017).

One of the priority directions of the EU is the C-ITS, which along with automation has the potential to significantly improve road safety. The communication between the vehicle and other vehicles as well as the infrastructure will help the driver make the right decision and adapt to the traffic situation. The deployment of C-ITS services with the highest safety potential should be prioritised, those with a proven road safety record, low cost solutions, and those with a high cost-benefit ratio (ETSC, 2018). One of the priorities here is the application of C-ITS for VRU protection (European Commission, 2018c). Detection of pedestrians plays an important role here as well. However, in this context, it is outlined that sometimes interaction between road users takes the form of communication through eye contact. High-risk scenarios should be identified and analysed, so the system will have to go above and beyond simple detection (ETSC, 2018). ETSC outlines that this area should be a priority for research and testing. At the same time, it is declared that there is a general lack of representative pan-European in-depth collision data to aid technological advancement (ETSC, 2018).

To sum up, the EU has set ambitious targets, which are difficult to achieve, especially taking into account the previous stagnation. A solution is seen in creating a more forgiving road system, which protects road users at different layers. Automation and C-ITS are also a part of this system. This approach assumes the development and adoption of new technologies. However, prior to implementation, research is needed to estimate the effectiveness as well as the cost-benefit ratio of these systems. The issue here is a lack of detailed collision data, which would help make respective assessments.

1.2 Approaches to estimating road safety

1.2.1 What is road safety and how to measure it

The road traffic safety can generally be considered to be the absence of unintended harm to living creatures or inanimate objects (Evans, 2004). Events in which an individual is injured or killed, or material damage is caused as a result of at least one vehicle moving on or off the road, are called traffic accidents (Estonian Road Traffic Act, 2010). They include collisions between vehicles, between a vehicle and a pedestrian, animal, or fixed obstacle.

Road traffic safety is often estimated as the number of road fatalities, injuries, or traffic accidents. The common approach is using rates – one quantity divided by another. For instance, road fatalities per head of population, per thousand registered vehicles, or per billion kilometres of travel. However, the number of fatalities is not the central indicator. As road safety research and practice focus on accident prevention, the number of accidents can be considered the main criterion (Gehlert, et al., 2014). The emphasis is on accidents resulting in injuries and deaths rather than in material damage (Gehlert, et al., 2014).

Common road safety rates are easy to understand, but rather non-informative. Firstly, because the relative rarity and randomness of accidents make them difficult to study without a significant amount of historical data (Elvik, 1988; Elvik, 2009). Secondly, because they are based on the traffic accident reports data and not all accidents are reported (Laureshyn, et al., 2016). And thirdly, traffic accidents always result from many objective factors operating together and classical rates do not provide sufficient information about the causes of accidents (Elvik, et al., 2009). But without a clear understanding of causes, one cannot prevent accidents from happening. Another issue is connected to the ethical aspects – to estimate road safety, one should wait to collect collision data. It means that in order to prevent traffic accidents, we have to wait for them to happen.

For these reasons, surrogate safety indicators (those that do not rely directly on accident data) are used as alternative or complementary methods of identifying safety issues (Laureshyn, et al., 2016). Such approaches to estimation of road safety concentrate on the crash cause-effect relationship on a time scale rather than on a statistical dependence of variables. One of the options here is detecting traffic conflicts, i.e. "observational situations in which two or more road users approach each other in space and time to such an extent that a collision is imminent if their movements remain unchanged" (Svensson, 1998). Traffic conflict studies assume that there are sufficient similarities between actual accidents and 'almost accidents' of the same type (Polders, Brijs, 2018).

1.2.2 The traffic conflicts theory

The traffic conflicts theory is based on the concept that a traffic process can be seen as a number of elementary events, which differ in their degree of unsafety, and there exists some relation between the severity and frequency of events of that severity (Laureshyn et al., 2016). This concept was illustrated by Hydén in 1987 and is commonly known as the 'safety pyramid' (see Figure 3). These events differ in their degree of severity (unsafety), and a relationship exists between the severity and the frequency of events (Hydén, 1987). If this relation between traffic conflicts and accidents is known, it is theoretically possible to calculate the frequency of accidents based on the known frequency of the conflicts (Laureshyn, et al., 2016).

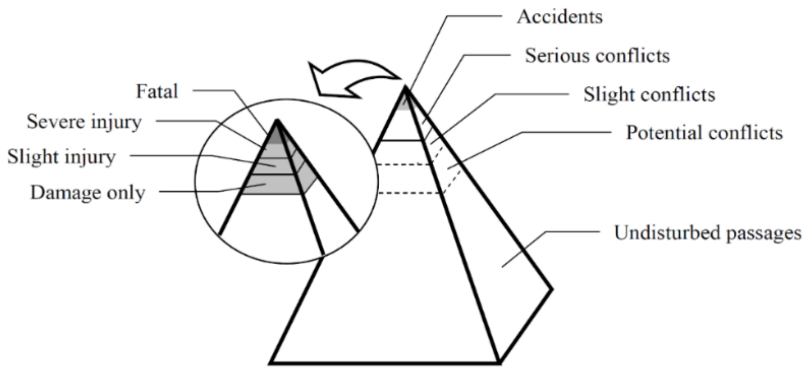

Figure 3. Safety pyramid (adopted from Hydén, 1987).

However, in practice, the task of defining the probabilistic functions that relate to the conflicts and accidents, especially in complex traffic situations, is challenging (Laureshyn, et al., 2016). The probability for each traffic event to develop into an accident depends on the initial conditions, which define a set of possible evasive actions and their respective probabilities. Therefore, the final outcome is a probabilistic function of both the initial conditions and the evasive actions (Davis, et al., 2011). Traffic conflicts can be validated by determining similarities between the process leading to the accidents and the course of events in critical situations or by using statistical methods to determine the correlation between conflicts and accidents (Laureshyn, et al., 2016). Traffic conflicts have different severity, which can be estimated by combining collision risk and injury risk

(Davis, et al., 2011). In turn, collision risk can be assessed by estimating the closeness to the accident as well as the effectiveness of any potential evasive action (Johnsson, et al., 2018).

Reliability of traffic conflict studies depends on the accuracy and the consistency of measurements. In other words, the more accurate are the conflict related measurements (road users' position, speed, etc.) and the more time is spent on observations to collect a sufficient number of conflicts, the more reliable are the study results. The first traffic conflict studies refer to the 1950s / 1960s, when data was collected in the field by human observers, which incurred significant costs in time and efforts (Laureshyn et al., 2016). Cotemporary conflict studies enable collecting video recordings at observation places and utilising special software for data analysis. Examples of such software are Road User Behaviour Analysis (RUBA) used for semi-automatic identification of traffic conflicts and T-Analyst used for determining speeds, trajectories, and different surrogate safety indicators (Madsen, Lahrmann, 2017; Bulla-Cruz, et al., 2020). New technologies help estimate special indicators, which make traffic conflict studies more precise and objective.

1.2.3 Surrogate safety indicators

Closeness to the accident is estimated by means of different surrogate safety indicators, which can be grouped into several 'families'. The most common indicator family is Time-to-collision (TTC), followed by Post-Encroachment-Time (PET) and deceleration (Laureshyn et al., 2016).

The time-to-collision family includes TTC and its variations. TTC is "the time until a collision between the vehicles would occur if they continued on their present course at their present rates" (Hayward, 1971). During the conflict, the TTC value varies over time. Therefore, a proper evaluation requires a continuous monitoring with the identification of the critical value. Usually, this is TTC_{min}, which is the lowest TTC value in the interaction, or time-to-accident (TA), which is the TTC value at the moment the first evasive action is taken by one of the road users (Hydén, 1987). TTC_{min} characterises the nearness to the actual collision, while TA represents a critical moment when a hazard has been detected and the evasive action starts. The limitation of TA lies in the fact that the exact moment the evasive action begins is not always easy to detect, both when it comes to human observers and automated tools (Laureshyn, 2010).

TTC can be used only if the trajectories of the road users are crossing and therefore do not take into account potentially dangerous 'near misses'. For this reason, some studies use the indicator called T2, which shows the expected arrival time of the second (later) road user to the potential collision point. T2 can be calculated also in the case of a non-collision course, which is an advantage compared to TTC. In case of a collision course, T2 equals TTC and allows for smooth transition between the collision course and non-collision course time instances (Laureshyn et al., 2016).

One of the variations of TTC is the Time-to-Zebra (TTZ) which is a time remaining for a car to reach the pedestrian crossing. There is also a TTZ 'spin-off' which is called the Time-To-Zebra duration ($TTZ_{duration}$), i.e. the time during which the vehicle cannot stop before the zebra and the pedestrian is exposed to conflict with vehicle (Laureshyn et al., 2016).

The post-encroachment-time family includes indicators showing how narrowly a collision has been avoided. PET is calculated as the time between the moment that the first road-user leaves the path of the second and the moment that the second reaches the path of the first, i.e. PET indicates the extent to which they missed each other (Allen, et al., 1978). A PET value can only be measured at one point in time. Calculating PET does not assume a collision course and therefore is suitable for defining 'near misses'.

PET-related indicators are Gap Time (GT), Encroachment Time (ET), Time Advantage (T_{Adv}) and others. GT is the time between the entries into the conflict spot of two vehicles, measured from the front bumper to the front bumper. ET is the time that the first vehicle entering the conflict area infringes upon the predicted path of the second vehicle, measured from the rear bumper to the front bumper. Unlike PET, both GT and ET are continuous indicators. T_{Adv} is a predicted PET value, provided that the road users continue with the same path and speed. It provides more insight in the continuous interaction between road users over time and space, compared to measuring a PET value (Laureshyn et al., 2016).

Deceleration is the most common evasive action taken by a vehicle to avoid a collision (Hydén, 1987). As a result, **deceleration-family** indicators can potentially be applied to a large variety of traffic situations, with or without a collision course. Examples of such indicators are Deceleration Rate (DR) and Maximum Deceleration (Max D). DR quantifies the magnitude of the deceleration action of a vehicle at the moment when it begins an evasive braking manoeuvre. Max D is the maximum deceleration rate of the vehicle observed during a conflict event (Gettman, Head, 2003). These indicators assume braking and are uninformative if the driver misses the dangerous situation and does not react (Zaki, et al., 2014).

Closeness to the accident can be also described through the minimal necessary deceleration for a driver to avoid the collision. The respective indicator is called Deceleration-to-Safety Time (DST). Another related indicator is Potential Collision Speed (PCS), which is the expected impact speed in case of a sudden obstruction and limited time and distance to avoid it, for example in case of a chain collision in fog (MacCarley, et al., 2007). PCS takes into account both the reaction time and the braking during the time available before the collision (Laureshyn et al., 2016).

Indicators of the families described above have their pros and cons. TTC is the most common indicator, which allows continuous monitoring of nearness to collision, but it assumes a collision course. PET is not limited to a collision course and is suitable for defining 'near misses', but it can be measured only at one point in time. Therefore, there is no ideal and universal surrogate safety indicator. In practise, the indicator used should include the theoretical aspects important for different settings and should have robust validity and reliability (Johnsson, et al., 2018). To better capture the severity of an event, indicators are frequently combined with other indicators or variables (such as speed) that can provide a better understanding of the situation (Johnsson, et al., 2018).

1.3 How to estimate changes in traffic behaviour

1.3.1 Traffic behaviour and its study methods

Road user behaviour is a key factor in crash risk (Rowe, et al., 2015). Some studies estimate human error to account for about 90% of all traffic accidents (Lund, et al., 2009; Finley, et al., 2015). Major contributing factors to roadway fatalities are drinking and driving, speeding, and failing to wear a seat belt (Finley, et al., 2015). If violations of road traffic law did not occur, the number of fatalities could be reduced by 63% (Elvik, et al., 2009). This makes road users' behaviour in traffic one of the most important aspects of road safety.

Two general approaches to estimating drivers' behaviour can be outlined. These are self-report survey studies and observation studies. One of the most popular tools for survey studies is the Driver Behaviour Questionnaire (DBQ), in which respondents indicate how often they commit particular types of aberrations in traffic. DBQ divides human risk behaviour to errors and violations, and measures these concepts in driver behaviour. Most studies use a four-factor structure (Lajunen, et al., 2004). These are involuntary lapses (considered not dangerous), involuntary errors (considered potentially dangerous), intentional rule violations, and intentional aggressive violations (both considered dangerous) (Mattsson, et al., 2015; Lawton, et al., 1997). Over the other options, DBQ is used to investigate differences in traffic behaviour between countries (Lajunen, et al., 2004; de Winter, et al., 2016).

Observation studies are performed by means of visual field observation or video-based observation. One of the most popular observation study methods is naturalistic driving, which is considered to reflect more realistic driver behaviour than other alternatives (Bao, et al., 2015). However, at the same time, this fails to provide information whether aberrations in traffic are intentional or not. In such studies, specialised research vehicles are used to record a significant amount of data continuously from the driver, the car, and the surroundings (Valero-Moraa, et al., 2013). Naturalistic driving method is used for studying different aspects of risky driving behaviour, such as speeding, secondary task engagement (for instance, cell phone dialling), as well as seat belt usage (Simons-Morton, et al., 2015; Bao, et al., 2015).

As with every study method, both DBQ and naturalistic driving have certain limitations. Weaknesses of DBQ are connected to the subjectivity of the answers and issues with sampling methods (Mattsson, et al., 2015). Limitations of naturalistic driving studies are linked to behavioural modification, as drivers know they are under observation, issues with large amounts of data, and high costs (Valero-Moraa, et al., 2013).

1.3.2 Long-term traffic behaviour monitoring studies

As a rule, studies on road users' behaviour are done within a short periods of time and fail to reveal long-term trends. The only exceptions known to the author are Finnish and Estonian traffic behaviour monitoring studies, which are held annually.

Estonian road users' behaviour monitoring studies are inspired by the respective Finnish experience, so these studies have much in common. The Finnish studies started in 1992 (Liikenneturva, 1999), while the Estonian studies are being conducted since 2001 (Stratum, 2001). The main objective is monitoring the behavioural changes taking place, respectively, in Finland and Estonia.

In 2020, the Finnish traffic behaviour monitoring estimated long-term trends in the following categories (Liikenneturva, 2021):

- proportion of drunk drivers in the traffic flow;
- using seat belts in cars and vans;
- using turn signals;
- using bicycle helmets;
- pedestrians' compliance with traffic lights;
- using reflectors in built-up areas by pedestrians.

At the same time, in 2020, the Estonian traffic behaviour monitoring collected data in the following categories (Transpordiamet, 2020):

- drivers' compliance with traffic lights at intersections;
- drivers' compliance with traffic lights at railroad crossings;

- pedestrians' compliance with traffic lights;
- yielding to pedestrians at uncontrolled crossings;
- using seat belts.

The Finnish and Estonian studies partly deal with the same safety performance indicators (SPIs). These SPIs vary in time. For instance, during the past few years, Estonia excluded the usage of turn signals and Finland excluded drivers' compliance with traffic lights.

Interviews with Finnish researchers dealing with traffic behaviour monitoring revealed certain differences in the methods being used in field observations. As a result, it is impossible to compare Estonian and Finnish data directly, but trends in traffic behaviour in the two countries are still comparable (Ess, Antov, 2017). Hereinafter, the author will describe the Estonian traffic behaviour monitoring studies, which he conducted for five years in a row and knows in detail. The Author of this thesis also designed the renewed and more precise methodology for these studies (Maanteeamet, 2016).

1.3.3 Road users' behaviour monitoring in Estonia

Since regaining its independence in 1991, Estonia showed a dramatic change in road safety. The reduction of road fatalities in Estonia was happening faster than in the EU in general (see Figure 4). In fact, in 1991, the number of road accident fatalities per million people in Estonia was almost twice as high as on average in the EU, but in the previous years, it was very close to the EU average level (or better). Starting from 2001, changes in road users' behaviour in Estonia are accessed by conducting annual observation studies. This allows comparing changes in road safety statistics and other data available to trends in traffic behaviour and proposing directions to work towards for sustainable road safety improvement.

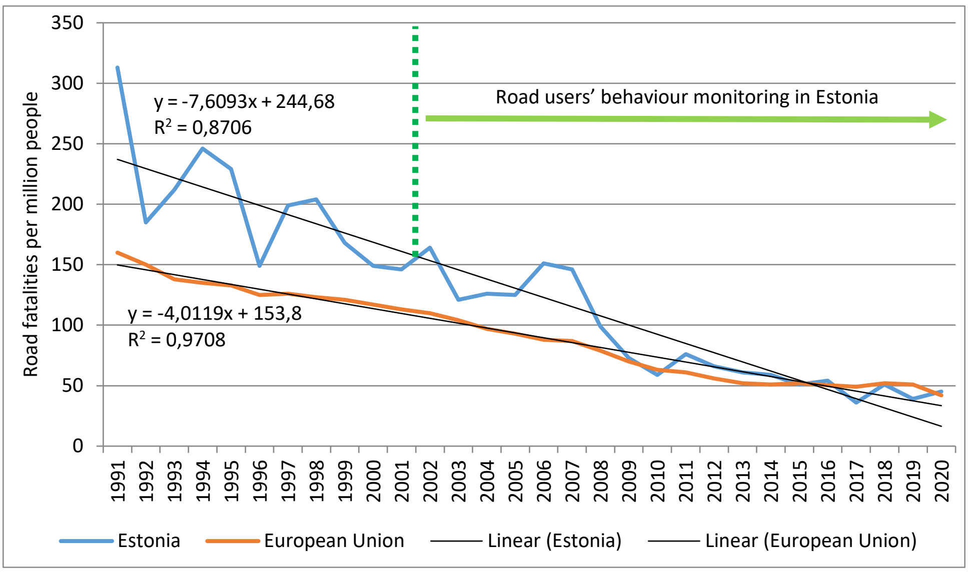

Figure 4. Road accident fatalities per million people in Estonia and the European Union in 1991–2020 (compiled by the author).

Estonian road users' behaviour monitoring is done within an annual state-wide observation study. There are over 100 fixed observation places on urban and rural roads where data is collected, using standardised observation methods. Traffic behaviour is estimated using definite SPIs connected to compliance with traffic rules. Each indicator is an average share of violators among respective observation places. As indicators are measured regularly, they provide a good idea about road users' behavioural trends.

Starting from 2017, monitoring studies are conducted according to a renewed and more precise methodology, thus indicators collected before and after 2017 are not directly comparable. Nevertheless, there are 16 year-long data rows available. These indicators are drivers' compliance with traffic lights, pedestrians' compliance with traffic lights, yielding to pedestrians at uncontrolled crossings, using turn signals, and using seat belts. For other SPIs, such as exceeding the speed limit, compliance with traffic lights at railroad crossings, usage of pedestrians' safety reflectors, data was collected for short periods of time and/or due to methodical issues is incomparable.

Drivers' and pedestrians' compliance with traffic lights is observed on intersections and pedestrian crossings controlled with traffic lights. Before 2017, respective SPIs were calculated by dividing the number of violators by the total number of drivers or pedestrians observed (since 2017, the number of violators is divided by the number of drivers or pedestrians who had a chance not to comply with traffic lights). Yielding to pedestrians at uncontrolled crossings is estimated using episodes. An episode is a situation when a driver has to yield to a pedestrian or pedestrians at an uncontrolled crossing. The share of violators is calculated by dividing the number of violators by the total number of drivers who participated in the episodes. Usage of seat belts is observed both on the front and rear seats of passenger vehicles. Data is collected in four categories – driver, front passenger, rear passenger, and child. The share of violators is calculated in each category separately (for instance, the number of drivers who fail to wear a seat belt is divided by the total number of drivers observed).

It is important to mention that according to the European Transport Safety Council, drinking and driving is one of the major contributing factors to road accident fatalities. At some point in time, official reports of Estonian traffic behaviour studies contained such an SPI like ratio of drunk drivers in the traffic flow. But the respective indicator is rather general and received from the police. Researchers never dealt with detection of drinking and driving offences and do not have information about detection places and methods for calculating this SPI. Therefore, drinking and driving is not a part of traffic behaviour monitoring in Estonia (Ess, Antov, 2017).

1.4 Traffic calming as a measure to alter drivers' behaviour

1.4.1 How to alter traffic behaviour

The studies described it the previous part concentrate on road users' behaviour in typical road environments where drivers, pedestrians, and passengers have a free choice whether to comply with traffic rules or not. However, there are different measures for altering their behaviour, i.e. making road users to behave correctly. Examples of such measures are enforcement, traffic calming, drivers' training, social campaigns, etc.

Enforcement is one of the most effective ways to alter traffic behaviour and is based on the principle that road users try to avoid penalties. The most important is the subjective probability of the offender being caught (Wegman, Goldenbeld, 2006). If a road user estimates the chance of being caught while violating a traffic regulation as high, they will with high probability behave in a law-abiding way. However, the effect of police enforcement will be greater, the higher the intensity and the more unpredictable it is (Elvik, et al., 2009). In practice, the enforcement level has objective limitations, such as costs and availability of police resources as well as a short-term effect. But on certain roads and road sections it can be replaced with traffic calming measures (TCM). These measures place physical, rather than legal, restrictions on the road users' behaviour and can be argued to provide a more socially equitable and efficient solution than regulation (Garrod et al. 2002).

1.4.2 Traffic calming and its efficiency parameters

Traffic calming is the combination of physical and other measures, which aim at reducing the negative effects of motor vehicle use, alter driver behaviour, and improve conditions for non-motorised street users (American…, 2004). Traffic calming assumes that drivers should feel themselves being in an area where a safe speed is lower than 50 km/h and where is a higher probability to meet a pedestrian (EVS 843:2003 Town Streets).

There are various types of TCMs, depending on their character. For instance, there are distinguished vertical and horizontal TCMs. Vertical TCMs include any measure that alters the vertical profile of the carriageway, such as road humps and speed cushions. Horizontal TCMs include measures that alter the horizontal alignment of the carriageway, such as mini-roundabouts, build outs, and chicanes (Mountain, et al., 2005). A question arises how to estimate TCM efficiency, i.e. to understand if the measures are working or not. The difficulty here lies in the fact that there is no widespread or commonly accepted definition of traffic calming efficiency. Commonly efficiency is connected to the goals of the traffic calming project. Therefore, to estimate efficiency of TCMs, one should set exact and measurable goals and base it on the fact whether these goals have been achieved or not (Corkle, et al., 2002).

There are many efficiency parameters being used in studies aimed at estimating TCM impacts. Among the different speed-related parameters known in the literature, mean speed is very often used as a measure for safe driving, mainly because elevated crash risk and severity have been related to an increase in mean speed (Ariën, et al., 2013). Other speed related efficiency parameters are 85th percentile speed, the highest speed, percentage of drivers exceeding the speed limit, 10 mph pace and standard deviation of longitudinal acceleration and deceleration (Ariën, et al., 2013, 2014; Corkle, et al., 2002; Mountain, et al., 2005). Among the other commonly used parameters of TCM efficiency are change in the number accidents leading to fatality and injury, reduction of traffic volumes, traffic noise level, vehicles' emissions, as well as public health impacts (Čygaitė, et al., 2014; Huang, Cynecki, 2001; Lee, et al., 2013). In some studies, TCM efficiency is measured as a delay per TCM during emergency transport (Berthod, 2011), some authors estimate such efficiency parameters as private expenditures in fuel and vehicle maintenance (Jazcilevich, et al., 2015), impact on public transport (Banister, 2009) and cyclists (Pinkerton, et al., 2013). An important TCM efficiency component is public acceptance (Čygaitė, et al., 2014; El-Basyouny, El-Bassiouni, 2013; Garrod, et al., 2002). Nevertheless, the most common efficiency parameters of traffic calming are connected to speed, traffic volumes, and number of accidents.

1.4.3 How to measure the efficiency of traffic calming measures

Analysis shows that the most common method used to determine the efficiency of a TCM is a before-and-after study. It assumes that a street is divided into segments, each of them having a traffic calming measure implemented on it. Selected efficiency parameters, such as the number of traffic accidents, are measured on each segment before implementing a TCM and after that. Afterwards, these parameters for each road segment are compared to each other and respective conclusions are made. However, despite its popularity, a before-and-after study can give misleading conclusions. It happens because of lack of control for regression-to-the-mean (or long-term trends in accident occurrence) or because of ignoring the presence of potentially important confounding factors, such as change in traffic volume and modifications in land use (Granà et al. 2010).

Among the other common TCM efficiency research methods are interviews, microscopic traffic simulation, and the meta-analysis method. The latter assumes collecting and examining data from different studies on a specific theme in order to identify the common effect of a treatment, whether this is consistent from one study to the next. On the contrary, the meta-analysis can be applied to explain the variation when the effect size is not exactly the same in all the studies (Granà, et al., 2010).

TCM efficiency study methods assume acquisition of different efficiency parameters. Some of them can be gathered from databases, for instance traffic accidents' statistics, while other parameters, such as traffic volumes and vehicles speeds, should be measured by researchers. In respect of the latter parameter, it is recommended to hide the presence of the data acquisition devices and avoid possible alterations of drivers' natural behaviour, for instance reductions of speed, which often occur when devices (such as a radar placed on a tripod, etc.) are clearly visible at the side of the street or on it (Pau, Angius, 2001). In this context, a good option is using GPS trackers placed in the car, but it assumes conducting experiments with focus groups.

1.4.4 Traffic calming measures at pedestrian crossings and their effectiveness

At the moment of publishing this doctoral thesis, there is a number of TCMs available, which aim at increasing safety at pedestrian crossings. The most common classic measures are speed limits, road humps, raised pedestrian crossings and lane narrowings, which are mainly used at local roads with lower traffic volumes, as well as and refuge islands, which are commonly used at multilane roads (EVS 843:2016 Town Streets). Additional warning signals are also used, such as overhead and/or in-pavement flashers, variable message signs (VMS) or pedestrian crossing traffic signs, which change their background colour. In some cases, enforcement cameras, which detect non-yielding to pedestrians (Li, et al., 2022).

Literature analysis shows that the most common approach to estimating the effectiveness of TCMs at pedestrian crossings is a before-and-after study, which analyses the change in vehicles' speeds, the number of conflicts or collisions, motorist yielding rates and pedestrian crossing behaviour, e.g. the share of pedestrians who cross the road in the pedestrian crossing (Gonzalo-Orden, et al., 2016; Damsere-Derry, et al., 2019; Federal Highway Administration, 2001; Høye, Laureshyn, 2019; Jateikien, et al., 2016) or the share of pedestrians trapped in the crossing (Van Houten, et al. 2008).

The general outcome of TCM efficiency studies is that installing TCMs reduces speed of vehicles (Gonzalo-Orden, et al., 2016; Gonzalo-Orden, et al., 2018; Damsere-Derry, et al., 2019), increases yielding rates (Høye, Laureshyn, 2019; Federal Highway Administration, 2001) and reduces the number of vehicle-pedestrian conflicts (Hakkert, et al., 2002) as well as the number of collisions and severity of pedestrian injuries (Damsere-Derry, et al., 2019; Jateikien et al., 2016). Many studies showed an increase in yielding rates after the installation of in-pavement warning lights, but this increase may differ depending on the lighting conditions (Fitzpatrick, Sug Park, 2021). Some studies indicate that combination physical measures, such as raised crosswalk with flashers, increase yielding rates (Federal Highway Administration, 2001). At the same time, the efficiency of LED warning signs depends on their location at the crossing and the geometry of the road (Høye, Laureshyn, 2019; Fitzpatrick, Sug Park, 2021). The conclusions about the duration of the positive effect maintenance are contradicting. According to Kannel and Jansen, the effect was maintained for half year (Kannel, Jansen, 2004), whereas Van Derlofske, et al. found that the positive effect diminished during the first year after installation (Van Derlofske, et al., 2003).

It should be noted that the aforementioned studies analyse TCMs of different configuration and use different methodologies, thus the results are not necessarily comparable. Examples include determining the yielding rate. Without a clear unified methodology, the results can be rather subjective. In the case of Estonian road users' behaviour monitoring studies, this is the most difficult aspect. Yielding rate proceeds from episodes or vehicle-pedestrian interactions at or near the crossing. The pedestrian participates in the episode only if he or she is at a certain distance from the vehicle. For instance, if there is at least one free lane between the vehicle and the pedestrian or a refuge island (the pedestrian has not stepped at it), the situation is not considered to be an episode and the yielding behaviour of the driver is not taken into account (Maanteeamet, 2016a). Precise definition of episodes contributes to the quality of the study results, as in practice it is rather difficult to understand if the driver must yield or not. If the pedestrian is on the other side of a 2+2 road with a refuge island and has not started crossing yet, some drivers may stop to offer the pedestrian to cross the road, but if they do not stop, the situation will be still safe. In other words, the safety aspect might not be connected to the politeness and readiness to help another road user. In practice, it is rather complicated and time-consuming to train a novice observer to use the Estonian observation method but it guarantees the quality of the study results. However, in most studies which estimate yielding rates, the observation method as well as the qualification of the observer is not mentioned or described.

Therefore, one can conclude that it is impossible to estimate different TCMs being implemented at uncontrolled crossings according to one unified methodology. At the same time, in general, it is possible to conclude that these TCMs provide a positive impact on increasing pedestrian safety at uncontrolled crossings.

1.4.5 Classification of smart pedestrian crossings

As it was mentioned before, the term 'smart pedestrian crossing' is rather generic. However, based on their functionality and features, SPCs can be divided into several levels. The author of this thesis proposed the gradation shown in Table 1. It is in a way similar to the levels of autonomous driving developed by the Society of Automotive Engineers (SAE).

Table 1. The classification system of smart pedestrian crossings.

Level	Description
Level 0	a basic pedestrian crossing with road markings and traffic signs 'Pedestrian crossing'
Level 1	the same as Level 0, but with vertical TCM applied (for instance, a raised pedestrian crossing)
Level 2	a pedestrian crossing with a warning system for drivers which works 24/7 (for instance, beacons that are always flashing)
Level 3	a pedestrian crossing with a button-activated warning system for drivers (for instance, overhead or in-pavement beacons which start flashing after the pedestrian pushes a button)
Level 4	the same as Level 3, but the pedestrian is detected automatically; the warnings are addressed to drivers and may be optionally also addressed to pedestrians
Level 5	the same as Level 4, but the system collects traffic data which is used, among other things, to self-improve the warning algorithms; the warnings are addressed to drivers and pedestrians
Level 6	the same as Level 5, but the warnings are addressed also to vehicles, i.e. it is a C-ITS device

Market analysis shows that at the moment of publishing this thesis the most technologically advanced SPCs available, e.g. Smart Pedestrian Crosswalk by Bercman Tehnologies, correspond to Level 5. It 'learns' from the traffic environment and uses narrow artificial intelligence to predict the road users' trajectories. An example of the Level 4 SPCs is SMART pedestrian crossing by Sice. It detects speeding vehicles and warns pedestrians by means of red in-pavement lights. At the same time, it warns the speeding drivers by means of text messages displayed at a VMS sign. Examples of Level 3 SPCs include SeeMe by Amparo Solutions AB and Safe Light by Safe Light OÜ. The first system detects pedestrians with infrared sensors and the second with infrared cameras.

Unfortunately, there are no technical specifications available for the SPCs discussed previously and there is no reliable information about the range and precision of sensors. There are very few independent studies aimed at estimating the effectiveness of these SPCs. However, a study by Høye and Laureshyn showed that 43% of all alarms given by SeeMe were false alarms and in some locations the system missed 30% of pedestrians (Høye, Laureshyn, 2019). This indicates that some of these technologies cannot be very reliable and, thus, their effectiveness may be questionable.

Currently, the effectiveness of SPCs of different Levels cannot be compared directly because of the different methodologies used in studies.

1.5 Research objectives and structure

The general improvement trend in road safety in the EU has stagnated. It means that the old approaches that have been used so far do not give the desired result anymore and it is essential to look for new, more effective solutions. This doctoral thesis aims at finding such a solution and estimating its effectiveness.

The specific research objectives are:

- to analyse changes in road users' behaviour and to outline the unsolved problem, which has a considerable impact to road safety;

- to propose a contemporary TCM-based solution to the outlined problem;
- to understand the general TCM efficiency parameters and to design a suitable methodology for estimating TCM effectiveness;
- to design a suitable methodology for estimating the effectiveness of an SPC under typical vehicle-pedestrian collision scenarios at uncontrolled crossings and to conduct respective efficiency study;
- based on previous findings, to determine the 'must-have' features that would make a Smart Pedestrian Crossing more effective.

To fulfil the objectives of the study, the respective RTs were formulated (see Figure 5). Within RT1, the behaviour of road users is analysed in combination with other road safety data available to define the problem, the solution of which would have a considerable impact to road safety improvements. As a possible solution, a new generation TCM was proposed – an SPC which monitors the traffic situation and in case of a hazard warns the road users and vehicles. Within RT2, new methodologies suitable for analysing TCMs, including 'smart' measures, are designed and efficiency studies are conducted. The new methodologies do not require before-and-after studies and proceed from surrogate efficiency parameters. This makes them suitable for efficiency studies of a non-existent device. RT3 combines the outcomes of previous studies to determine the essential features of an effective TCM to be used at uncontrolled crossings. In the last part of the thesis, the concept of a Level 6 SPC is proposed, which is based at the Safe System approach and can use the methods designed in this thesis to self-evaluate and update the warning algorithms.

This doctoral thesis is based on three publications cited earlier. The relationship of the research tasks with the publications is described below (see also Figure 5).

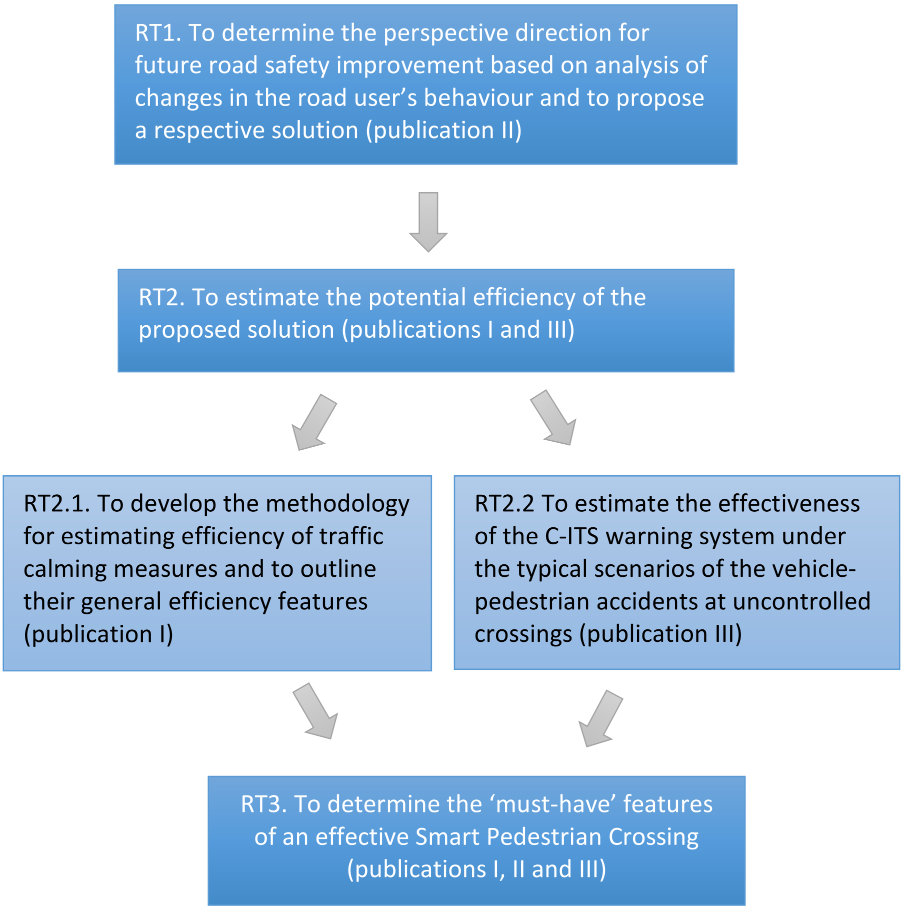

Figure 5. The research structure based on RTs and the author's publications (compiled by the author).

Road users' behaviour is an important component of the road safety paradigm. **Publication II** (Appendix 2) analyses this topic based on the example of Estonia, where annual state-wide traffic behaviour studies are conducted since 2001. These observation studies estimate drivers' and pedestrians' behaviour at typical road sections through compliance with the traffic rules and reveal long-term trends. The publication analyses these trends and compares them to statistics on traffic accidents and police enforcement data. Research estimates the impact of changes in the road users' behaviour to the traffic safety improvement and outlines that not yielding to pedestrians at uncontrolled crossings is the most critical problem which remains unsolved.

Road safety as well as road users' behaviour are directly connected to road design. To reduce the negative effects caused by motor vehicles, alter the behaviour of drivers, and improve conditions for vulnerable road users, different TCMs are used. **Publication I** (Appendix 1) addresses the goals of TCMs, determines their efficiency parameters and describes the new unified methodology for estimating TCM effectiveness. The methodology was tested in the scope of a pilot study conducted in Tallinn and gave important insights, which were used later in these studies.

Taking into account previous findings, **Publication III** (Appendix 3) addresses pedestrian safety at uncontrolled crossings. It estimates the effectiveness of Level 4–6

SPCs based on the traffic conflict technique and the microsimulation of typical vehicle-pedestrian collision scenarios. The research determined typical traffic conflicts at uncontrolled crossings, created their models, and used them to assess the efficiency of the SPC, considering its probability of preventing collisions based on the timing of warning signals and the stopping distance of a passenger car. Furthermore, the conflict models were updated with the common behavioural patterns of road users to analyse possible situation dynamics. Based on the results of the study as well as the findings described in Publications I and II, must-have features of an effective SPC capable of preventing vehicle-pedestrian collisions at uncontrolled crossings were determined. Another result of this work is a unified approach to estimating effectiveness of different level SPCs.

2 Methodology and research design

This chapter describes methodologies developed in the scope of the study as well as the research design. First, the actual problems in road users' behaviour are outlined, after solving which it is possible to improve the road safety. This was done by means of analysing behaviour trends and comparing them to safety related data available. Methodology of the respective study is described in the first part of this chapter. Altering the critical aspects of traffic behaviour can be altered by means of a TCM, but it will have an effect only in case the TCM is effective. So, the second part is dedicated to the methodology of estimating TCM efficiency. It addresses efficiency parameters as well as describes a pilot study, which has been conducted for testing them. The third part of this chapter proceeds with in-depth methods for understanding the typical risk scenarios of vehicle-pedestrian collisions at uncontrolled crossings and the estimation of SPC performance under these scenarios.

2.1 Analysis of trends in road users' behaviour

The aim of the study was to analyse the behaviour of road users in Estonia and to point out actual behavioural problems to concentrate on for road safety improvement. Respective knowledge provides the direction for further studies.

The research was done based on Estonian traffic behaviour monitoring studies. Field observations were conducted annually in certain fixed places across the state (see Figure 6). Respective data was analysed to understand trends. Data rows, which were initially used in the study, cover the period 2001–2016, but in the scope of this thesis, the next period 2016–2020[3] was added to update the results. Analysis was done based only on comparable data.

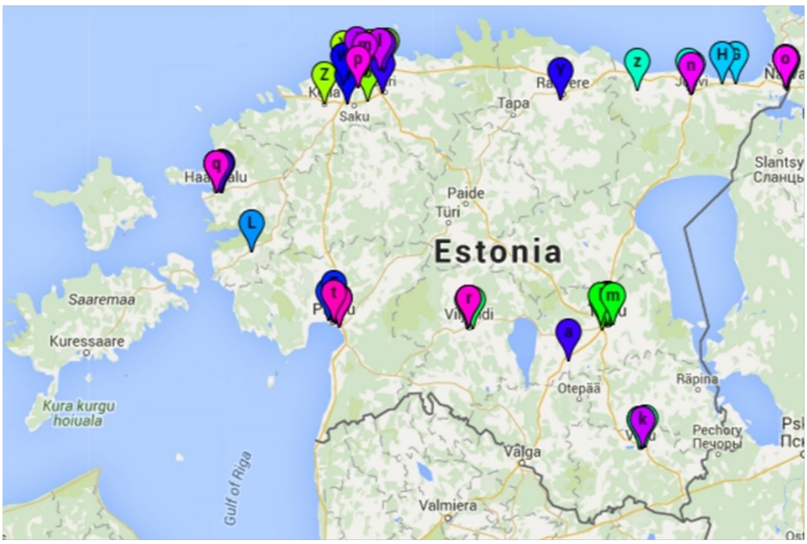

Figure 6. Observation places for Estonian traffic behaviour monitoring in 2001–2016 (compiled by the author).

[3] In 2021, the traffic behaviour monitoring was conducted in a pared-down version and using respective data would not add to the quality of the analysis.

The methodology of Estonian traffic behaviour monitoring assumes estimating compliance with the traffic rules using standardised observation methods. During the period 2001–2016, SPIs were calculated by dividing the number of violators by the total number of road users observed. Each indicator is an average share of violators among respective observation places. It is important to note that an SPI can very within different observation places (see example on Figure 7). For this reason, single values are not treated separately, but average SPIs for each year are put on a timeline to reveal trends.

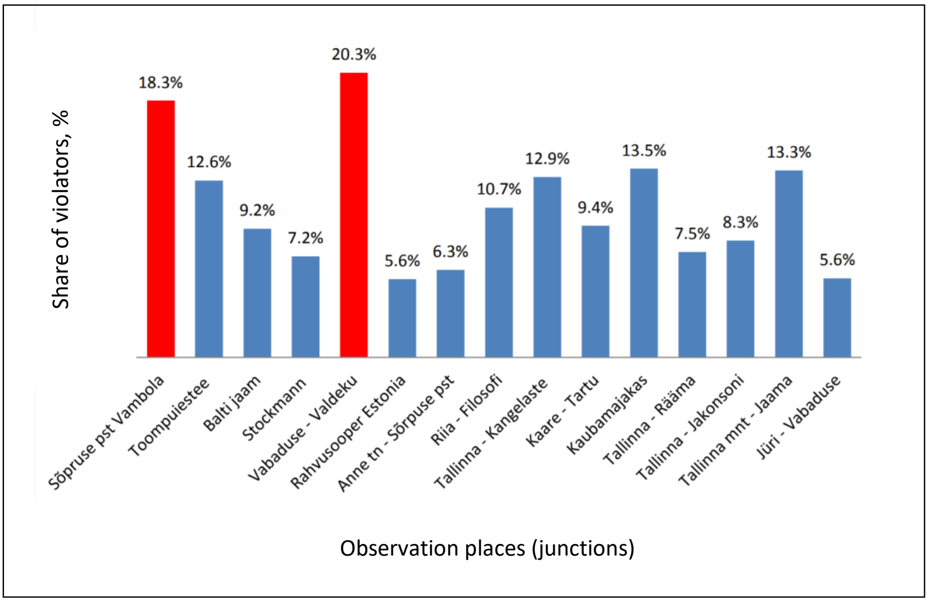

Figure 7. Share of pedestrians who did not comply with traffic lights at different observation places in 2016 (adopted from Maanteeamet, 2017).

Starting from 2017, Estonian traffic behaviour monitoring is being conducted according to a new updated methodology. One of the core differences is connected to the number of observation places and sample sizes – there are less places, but fixed sample sizes for each observation place. This makes data collected in 2001–2016 and after 2017 incomparable. Therefore, SPIs collected in the period 2017–2021 are treated separately with the only aim of giving an idea about the trends in traffic behaviour during the past 5 years.

Starting from 2001, different SPIs have been used and for five of them, there are 16-year-long data rows. These indicators are:

- drivers' compliance with traffic lights;
- pedestrians' compliance with traffic lights;
- yielding to pedestrians at uncontrolled crossings;
- using turn signals;
- using seat belts.

Analysis of the data collecting methods showed that the usage of turn signals is an exception from the general rule assuming fixed observation places. Between 2014 and 2016, studies were conducted at roundabouts, but before 2014, observations were performed at regular junctions and near bus stations. The difference in observation places makes respective data incomparable and trends in the usage of turn signals were excluded from the analysis.

Traffic behaviour trends were analysed for a 16-year period. SPIs were visualised by means of line charts and trend lines. The outcome was compared to road safety statistics, police enforcement data, and information concerning the fulfilment of activities foreseen by the Estonian National Road Safety Programme. Final conclusions were made taking into account all the factors listed above.

2.2 Estimating the efficiency of traffic calming measures

The aim of this study was to work out and to test a unified methodology suitable for estimating the efficiency of a TCM, including more advanced measures like an SPC. The methodology is based on comparing the efficiency of two or more isolated TCMs of the same type, but with various design parameters. It assumes determining certain efficiency parameters, comparing and analysing them (the parameters proposed by the author are described below). Compared to the classical approach, i.e. comparing the number of road accidents before and after the implementation of a TCM, the new method is less time-consuming and more 'ethical' – one does not need to wait for accidents to happen in order to improve road safety.

2.2.1 Efficiency parameters

Estimation of a TCM is based on the efficiency parameters connected to speeds and public acceptance. These were chosen based on the results of literature analysis as well as on availability of data. The parameters are described in deeper detail further on.

85th percentile location speed. When estimating drivers' speed behaviour, it makes sense to proceed from the fact that traffic calming aims to make drives choose a safe speed. Wherein, it is assumed that drivers choose a safe speed not only when crossing a TCM, but on the whole calmed road section. Therefore, drivers' speed behaviour is estimated in different locations (points). These points have been selected based on pre-study experiments and are shown on Figure 8. 85th percentile location speeds at the points 1 and 6 are compared to the established speed limit on a particular road section (or to the safe speed for a particular road situation). The closer these speeds are to the safe speed (or to the speed limit), the more efficient the TCM is considered to be. 85th percentile speed is chosen as an efficiency parameter, as it is not affected by extremums and characterises drivers' speed behaviour in the most objective way.

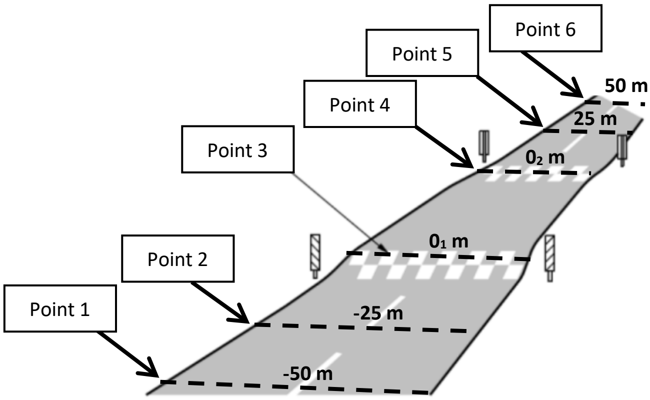

Figure 8. Scheme of the speed measurement points (compiled by the author).

Change in mean location speed. When it comes to speeds, not only compliance with speed limits, but also such a parameter as the smoothness of the traffic flow should be considered. Drivers should not decelerate in front of a TCM without a purpose or decelerate excessively, as it is connected to increased risk of rear-end collision as well as excess air pollution and noise level. Therefore, it was proposed to estimate change in mean location speeds when running a TCM. For these purposes, mean speeds are calculated for points 1–6 (see example at Figure 9). The higher the percentage ratio of mean speed in point 3 to mean speed in point 1, the more efficient the TCM is. Mean speeds in points 2, 4, 5, and 6 are used for better understanding of drivers' speed behaviour when crossing a TCM. Mean speed is chosen here as an efficiency parameter, as it is more informative for describing the change in vehicles' speeds than 85th percentile speed. Pre-study showed that extremums do not distort results significantly, as the majority of drivers cross a TCM with similar speeds.

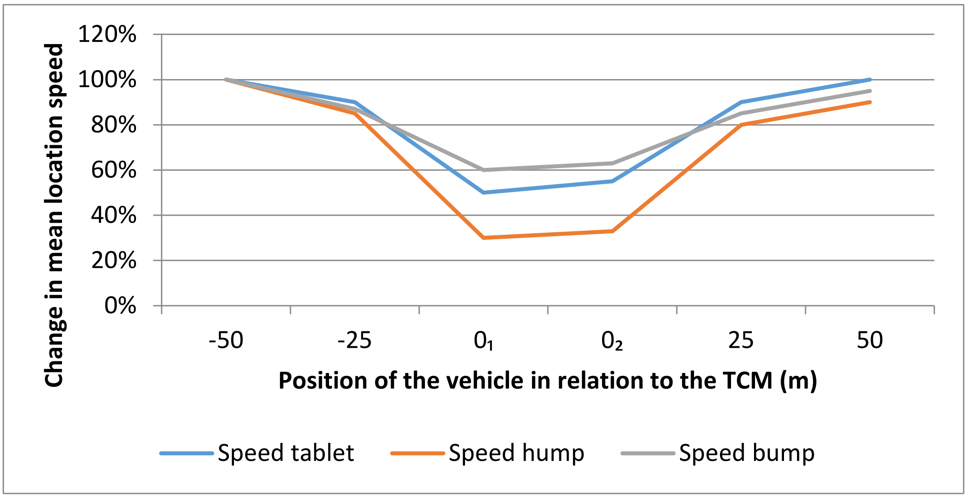

Figure 9. An example: change in mean speeds when running traffic calming measures (compiled by the author).

Public acceptance. Literature analysis has shown that along with other parameters, public acceptance is also widely used for estimating the efficiency of traffic calming. It is logical to consider the opinion of the actual road users. By its nature, traffic calming is connected to certain limitations. Therefore, acceptance of a TCM assumes that people are aware of traffic calming goals and are ready to sacrifice their comfort to some extent to help achieve these goals. The methodology proposes making a connection between the efficiency of a TCM and road users' attitude towards them – the better the public attitude, the more efficient the TCM is considered to be.

Comparison analysis. For each efficiency parameter, the TCMs are ranked according to their efficiency. If there are three TCMs studied, they are ranked by efficiency from 1 to 3, where '1' is the most efficient TCM and '3' is the least efficient TCM. If there are four TCMs studied, there would be four ranks, where '1' is the most efficient TCM and '4' is the least efficient TCM and so on.

Ranks are summed up. As '1' stays for the most efficient TCM, the TCM should get as few points in total as possible. However, one should take into consideration that ranks are given on an interval scale and, therefore, they do not show, but rather indicate, the 'leaders'. Sometimes these 'leaders' should be thoroughly compared to reveal the most effective measure. If the efficiency of two or more measures is practically the same, an additional efficiency parameter can be applied, such as the cost of implementing the TCM.

2.2.2 Data collection methods

Estimation of TCM efficiency is based on determining and comparing the three efficiency parameters addressed above. Two of them are connected to vehicle speed and one to public acceptance.

The need for measuring location speeds determines two suitable study methods. The first is an experiment. Drivers should pass a route with calmed sections with a vehicle equipped with GNSS, which is suitable for measuring location speeds. The second method assumes using an automatic speed measurement system. In this case, both speed and distance should be measured, and, provided with the respective technological level of the system, 85th and mean location speeds can be calculated automatically. The advantage of the first method is the potential for collecting more information. For instance, it is possible to install cameras filming both the driver and the situation in front of the vehicle. In this case, speed data can be compared to video footage, which can give additional input to the analysis of drivers' behaviour. However, it is more time-consuming than the second method, which assumes automatic speed measuring and calculations. In the context of an SPC, the automatic speed measurement would be the best option.

Public acceptance is estimated by means of a survey with multiple choice questions. The survey can be conducted both online and on paper. Respondents should assess their attitude towards TCMs on the basis of a 5-point scale (very poor – poor – fair – good – very good). For each TCM, there is calculated the total number of answers for 'good' and 'very good' and respective rankings are made. The higher the place in this ranking, the more efficient the TCM is. In order to get reliable results, it is highly recommended to accompany questions with pictures of the TCM being studied.

2.2.3 Pilot study and lessons learned

The new methodology was tested by means of a pilot study. The study method chosen was an experiment, which took place in Tallinn in March 2014 and lasted for one month. A sample of 30 drivers whose age and gender structure corresponds to the age and gender structure of all the Estonian drivers was formed. The drivers passed a certain route which has calmed road sections on it. Each section represented one TCM being situated on it.

In order to exclude factors that could affect drivers' behaviour, such as slower moving cars, test trips were held outside rush hours, mainly on the weekends. The speed limit on the calmed road sections studied was 30 km/h. All the drivers were driving the same car. They were told that the aim of the experiment was to estimate the mean speeds of male and female drivers of different age in different road conditions, so they did not know the real aim of the experiment.

Location speeds were measured by means of a Video Vbox device, which determines a vehicle's position with an accuracy of 10 cm and determines speed with an accuracy of 0.01 km/h. Public acceptance was estimated by means of a survey held with all the drivers after each trip.

The pilot study gave trustful results. It confirmed that the developed methodology as well as the efficiency parameters proposed are suitable for estimating TCM efficiency. However, conducting an experiment with the features of a naturalistic driving study was time-consuming. The location speeds were determined with the help of Video Vbox software Racelogic (see Figure 10). The process assumed finding the location and respective speed and typing the value to an Excel document. Afterwards, respective 85th percentile and mean speeds were calculated. This method justifies itself for smaller sample sizes, but for large-scale studies, automatic data collection and SPC calculation would be more suitable.

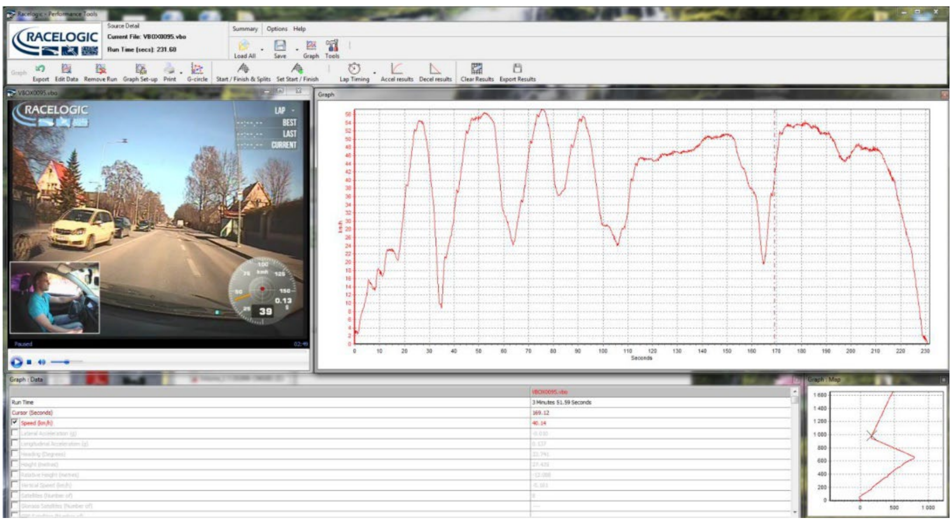

Figure 10. Racelogic interface and data visualisation (compiled by the author).

The pilot study helped validate the choice of efficiency parameters as well as the methodology as a whole. This knowledge is useful for estimating efficiency of an existing TMC and designing a TCM with high performance. These findings were used for determining the must-have features of an SPC. However, the methodology addressed so far uses a quantitative approach and is not suitable for in-depth analysis, which is needed to estimate the potential efficiency of a SPC. Therefore, for further studies, other methods described in the next part were used.

2.3 Traffic conflict study and microsimulation

The aim of the study was to understand in which traffic situations the SPC would work, and to estimate its potential efficiency considering the most difficult scenarios. The final conclusion was made according to the probability of preventing vehicle-pedestrian collisions.

To understand, in which situations the SPC would function, there were conducted traffic conflict studies at uncontrolled crossings. Traffic was filmed in the winter and summer periods. The serious conflicts, which have been determined within the analysis of the collected video materials, were described, and classified into types according to their scenarios. There was selected the most critical conflict of each type and these conflicts were modelled it in PC-Crash. It was analysed whether the SPC can give its warning early enough to prevent collisions. Respective estimations were made based on the stopping distances of the vehicles.

2.3.1 Observation locations and data collection

To collect the data, a large-scale traffic conflict study was held in Tallinn, Estonia. Traffic at uncontrolled crossings was filmed with high-resolution cameras and the video material was analysed to detect serious vehicle-pedestrian conflicts. Observation places have been selected according to the statistics for vehicle-pedestrian accidents at uncontrolled crossings in the period 2012–2017. The selection criteria were:

- number of vehicle-pedestrian collisions in 2012–2017: not less than three;
- no significant changes in traffic management since 2012;
- different types of crossings (number of lanes, safety island);
- speed limit 50 km/h;
- suitability for camera placement (a pole or building near the crossing where it is possible to place the camera).

This approach was chosen to cover conflict scenarios for different pedestrian crossings, and to have accident data for conflict validation purposes. In Estonia, collision data can be found in three databases (maintained by the police, by the Estonian Transport Administration, and by the Estonian Insurance Association). The entries in these databases partially overlap. To cover all the information available, vehicle-pedestrian collision data from these databases was put together and was visualised at a digital map. This approach helped find and delete entry duplicates as well as understand accident hotspot locations. Later, for the conflict validation purposes, the statistics were updated with 2018 data.

As a result, for the purposes of the study, ten uncontrolled crossings of the following types were selected:

- three crossings on 1 + 1 roads without a safety island;
- four crossings on 2 + 2 roads with a safety island;
- three crossings with 3 lanes in one direction with a safety island.

2.3.2 The pilot and the main traffic conflict study

The conflict study consisted of two parts – the pilot study (held in winter 2017–2018) and the main study (held in summer 2018). At the main stage of the study, there were 10 observation places and traffic was filmed for at least 10 working days in each location. During the pilot study, there were five observation places and traffic was filmed for five days at each location.

The pilot study revealed several issues with camera systems and orthophotos used for conflict analysis in T-Analyst. The first camera systems consisted of an action camera with a SD-card and a power bank. They did not justify themselves, as the workload of changing power banks and memory cards did not correspond to the number of conflicts detected. In practice, it meant that each observation place had to be visited twice a day. Another issue was connected to the orthophotos. During the pilot study, they were taken from the geoportal of the Estonian Land Board. These orthophotos were only 1 or 2 two years old, but still did not correspond to all the details of the real situation at the crossing (the most common example – old and new marking lines). These details are, however, important for accuracy, as points of the orthophotos are matched with the same points in the video and the more points are matched, the better the software accuracy when calculating conflict parameters.

During the main study, more advanced camera systems were used, which consisted of a security camera with a Wi-Fi connection and a vehicle battery stored in a box placed on a street pole (see Figure 11). Cameras were placed at the height of approximately five metres and a Wi-Fi connection was used to tune the filming angle. Programmed timing was used to stop filming for the night hours between 1 a.m. and 6 a.m., which allowed extending the battery run time and optimising the usage of the SD-card capacity. The workload of the observation place maintenance dropped to two visits a week. For conflict analysis, the software used pictures taken from a drone before starting the filming instead of orthophotos. If road markings were partly erased, additional spots were drawn with white paint on the asphalt. These dots were small and did not disturb the road users, but helped increase accuracy when calculating conflict parameters.

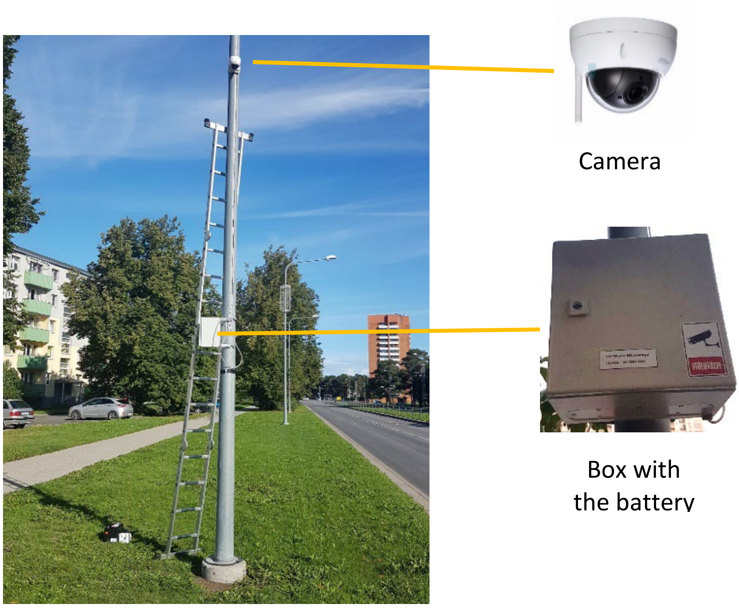

Figure 11. Video recording system used within the main study (compiled by the author).

2.3.3 Determining and classifying serious conflicts

The video material was analysed for determining all the potential traffic conflicts. It was done both by using the semi-automatic software RUBA and by manual review. However, the share of semi-automatic analysis was very low since the software produced too much 'noise' in the timestamps, as it was impossible to place cameras at a height that would provide a filming angle optimal for the software.

All the potential conflicts were exported into single video files for further analysis and determining severity. They were classified into two groups – serious conflicts and other situations. When making this classification, it was considered that there is no generally accepted way to distinguish serious vehicle-pedestrian conflicts, as common indicators used to estimate the risk of collision fail to consider the risk of pedestrians' injury (Laureshyn, et al., 2016; Johnsson, et al., 2018). At the same time, the most validated indicator is the subjective score set by trained traffic conflict observers (Laureshyn, et al., 2016; Svensson, 1992). So, for these reasons, severity of conflicts was determined by a team of researchers (including the author) visually, taking into account closeness to serious injury for the pedestrian. In case of doubt, researchers proceeded from the calculated impact speed – a conflict was classified as serious if the impact speed was 20 km/h or higher. This threshold was chosen because respective studies (Roséna, et al., 2011) show that starting from this impact speed, the health risk for pedestrians starts increasing. The impact speed was calculated for a flat surface (without incline angle) according to the formula, which is provided below.

$$V_{impact} = V_{vehicle} - (TTC_{min} - t_r - t_u - t_a - 0{,}5 \cdot t_s) \cdot \varphi_x \cdot g \quad (1)$$

where t_r is reaction time (0.8 s); t_u is transfer time (0.2 s); t_a is response time (0.15 s for passenger cars); t_s is pressure build-up time (0.36 s for passenger cars); ϕ_x is coefficient on static friction; g is gravity constant.

If TTC_{min} is lower than the brakes' application time ($TTC_{min} < t_r + t_u + t_a + 0{,}5 \cdot t_s$), the vehicle will not decelerate, and the impact speed will be equal to the vehicle speed ($V_{impact} = V_{vehicle}$).

Parameters for the calculations were collected with the help of T-Analyst. This software allows combining orthophotos and a camera view to create a system of coordinates and calculate the speed of road users, TTC, T2, and other conflict parameters (see Figure 6). In case of 'near-misses' when there was no collision course and therefore it was impossible to calculate the TTC, T2 was used as the closest possible value to TTC. In case of a collision course, T2 equals TTC and allows for a smooth transition between the collision course and non-collision course time instances.

Figure 12. Determining conflict parameters with T-Analyst (Ess, et al., 2021).

All the serious conflicts were described and information about drivers' and pedestrians' reactions to danger as well as the weather and lighting conditions was systemised. The conflicts were classified into types based on the similarity of their circumstances. For each conflict type, the most serious conflict was determined. In case of doubt, when assessing the seriousness of conflicts, researchers proceeded from the calculated impact speed as well as the risk of serious injuries.

2.3.4 Traffic conflict microsimulation and estimation of SPC effectiveness

The most serious conflicts of each conflict type were microsimulated, using PC-Crash, which is a professional software used for traffic accident analyses. Besides the other features, it allows animating pre-accident situations and watching them from different perspectives (see Figure 13). Conflict microsimulation was performed by an accredited court expert in traffic accident reconstruction.

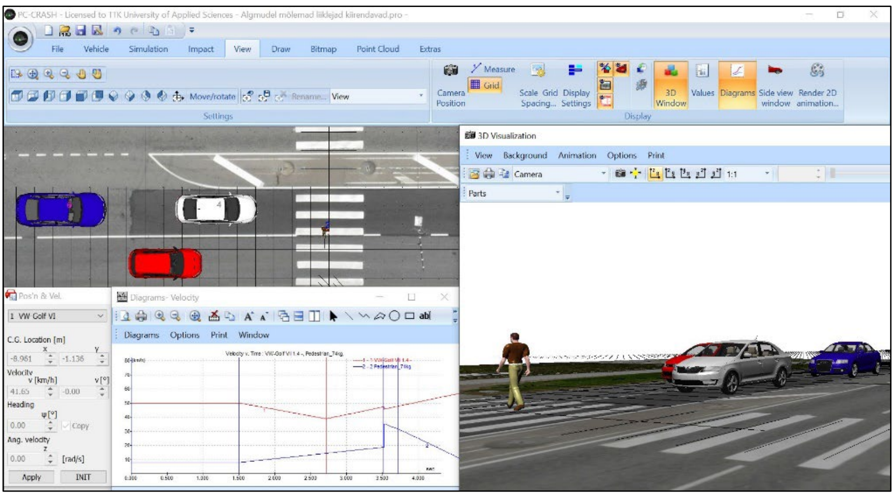

Figure 13. Using PC-Crash to analyse traffic conflicts (Ess, et al., 2021).

To create the PC-Crash models, data retrieved from T-Analyst was used (the trajectories, speeds, and accelerations of road users as well as drone photos).

The conflict models were analysed to understand the circumstances, such as field of vision and visual distraction. Based on the stopping distance, the timing of C-ITS warning signals was determined, i.e. the last moment to provide the warning signal. It was analysed whether this timing is realistic and whether the driver could see the warnings and react in a proper manner (brake with maximum deceleration). The stopping distance was calculated according to the formula below (Bosch automotive engineering, 2007).

$$S_{AH} = (t_r + t_u + t_a + 0,5 \cdot t_s) \cdot V_{vehicle} + \frac{{V_{vehicle}}^2}{2g\ \varphi x} \qquad (2)$$

where $V_{vehicle}$ is the vehicles' speed; t_r is reaction time (0.8 s); t_u is transfer time (0.2 s); t_a is response time (0.15 s for passenger cars); t_s is pressure build-up time (0.36 s for passenger cars); ϕ_x is coefficient on static friction; g is gravity constant. For a self-driving car t_r = 0 s as well as t_u = 0 s, because the driver does not need to react (to assess the situation and to take decision) and to transfer their foot from the gas to the brake pedal.

For the purposes of analysis, two assumptions were made:

1. if the SPC is able to prevent the most severe conflict of a certain type, it will be able to prevent the other (less severe) conflicts of the same type;
2. taking into account the severity of the microsimulated conflicts, they were treated as accidents and prevention of the conflict equalled accident prevention.

Therefore, if the SPC can prevent the modelled conflict, it is assumed that it will be able to prevent vehicle-pedestrian collisions of the respective type.

For each conflict, a team of researchers answered the question 'Would an SPC help prevent accidents?' The question was asked for two scenarios:

1. the evasive action is taken by the driver;
2. the evasive action is taken by the AEB-equipped vehicle.

The answers were given at the scale of yes – likely – doubtful – no, based on the vehicles' stopping distance and the conflict circumstances. Estimation of the SPC efficiency was made according to these answers. At the same time researchers estimate, if the on-board pedestrian detection system needs additional input from the SCP to prevent collision.

It should be mentioned that the research concentrated on warning the driver and the vehicle and did not examine warning the pedestrian. The reasons for that are described in the next part.

2.3.5 Estimation of warning systems for pedestrians

It should be mentioned that initially, researchers intended to also test the third scenario when the evasive action is taken by the pedestrian who hears the audible warning of the SPC. This should be the most efficient way to prevent the collision, as a pedestrian can stop almost immediately. If a pedestrian reacts to the audible warning in the expected manner (instinctively stops and looks around to check for safety), the collision is highly likely to be prevented in almost all the cases. At the same time, pedestrians are less concentrated on the road traffic than drivers and their reaction at the audible warning is less predictable. The pedestrian may not understand the meaning of the warning signal and fail to react. This makes estimating this scenario rather complicated.

To analyse pedestrians' possible reactions, researchers conducted a pilot study. They asked students to pass a certain route by foot according to the digital maps. At this route, there was an uncontrolled pedestrian crossing with limited visibility. Researches mounted a loud speaker behind the traffic sign located at the safety island. When participants were about to step on the crossing, researchers activated the car horn signal from the speaker. Their reaction was filmed and later analysed in the slow motion regime.

The students were holding smartphones in their hands and a small white paper according to which the researchers knew that the pedestrian participated in the study. The students did not know the real aim of the experiment. They started passing the route with the intervals of two minutes. The sample size consisted of 23 people. In two cases, the experiment was unsuccessful due to external factors.

The students' reactions are shown on Figure 14. When hearing the audible signal, 10 participants just looked in the direction of the sound source and proceeded walking without checking the surroundings. 5 students looked around, while 5 did not take any action at all. Only 1 participant stopped before the crossing when they heard the warning signal. Therefore, the desired reactions were observed only in 6 cases.

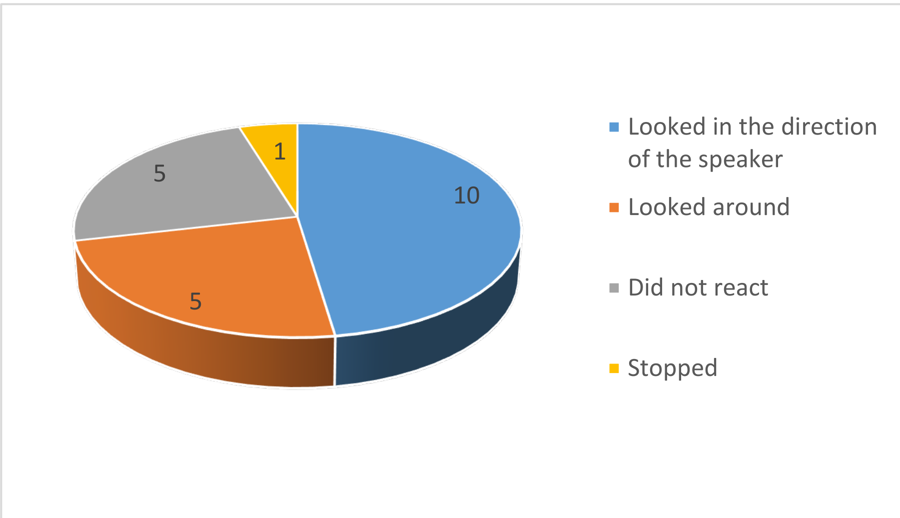

Figure 14. Reaction to the audible warning signal (compiled by the author).

The experiment conditions were not ideal. The results might be affected by the location of the speaker, the loudness level of the warning signal, and other factors. But the pilot study showed that pedestrians' reaction to the audible signal needs additional investigation and that with the current knowledge, it is not reasonable to estimate the efficiency of the SPC in the context of warning the pedestrians.

3 Results and discussion

This chapter describes the results of the studies conducted in the scope of this doctoral thesis. First of all, the most actual traffic behaviour problem to solve is outlined, and as it can be understood from the title of this thesis, it is pedestrian safety at uncontrolled crossings. After that, an approach to prevent vehicle-pedestrian collisions is proposed. The main part of this chapter is dedicated to estimating the potential effectiveness of this approach. The last part of this chapter addresses the concept of the SPC proposed by the author.

3.1 Insights from the road users' behaviour monitoring

The analysis of changes in traffic behaviour was based on the Estonian traffic behaviour monitoring studies for the period 2001 to 2016. Comparable data is available for the four SPIs, which are drivers' and pedestrians' compliance with the red traffic light signal, usage of seat belts, and yielding to pedestrians at uncontrolled crossings.

Trends for all the four SPIs are positive (share of violators was decreasing), but these trends are different. The SPIs can be divided into two groups:

- improvement trends (seat belt usage, yielding to pedestrians at uncontrolled crossings);
- minor changes (drivers' and pedestrians' compliance with traffic lights).

For better understanding of the changes in road users' behaviour, SPIs collected after 2017 with the new methodology were added to the analysis (on Figures, these are shown with dashed lines). This data is not comparable, but still, it helps to understand trends during the past few years of observation.

3.1.1 Improvement trends

As mentioned before, SPIs were changing differently. The best example of an improvement trend is the usage of seat belts (see Figure 15). It is important to note that the rapid change started from a poor initial benchmark and almost in one decade reached the rates which are very close to the maximum.

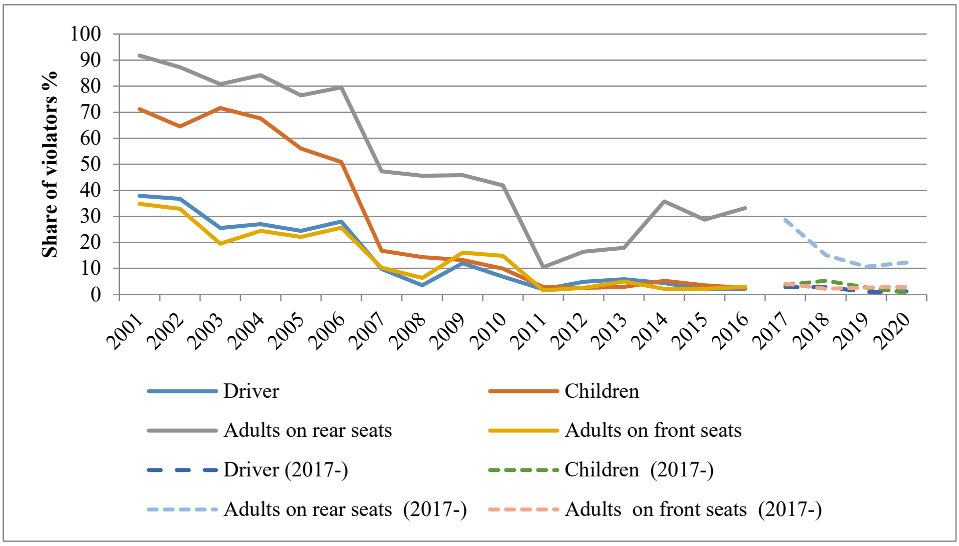

Figure 15. Seat belt use rate in Estonia in 2001–2016 (adopted from Maanteeamet, 2020).

The strongest improvement has taken place in categories of adults on rear seats and children. Due to smaller sample sizes, respective graphs are more uneven compared to the others and the biggest issue is with adults on rear seats (there are not so many vehicles with rear passengers who are adults). There is a high probability that the decrease in the share of violators among adults on rear seats in 2011–2013 was occasional and in 2014, the trend just came back to the right place.

General improvement of seat belt use rates happened before 2011, and afterwards, the positive trend stagnated. Seat belt use rate in the category of adults on rear seats achieved a lower level than the other categories. The data collected during the past four years shows that there is no change in the general trend, but the use of seat belts by grown-ups at rear seats showed faster improvement.

Another SPI which showed an improvement trend is yielding to pedestrians at uncontrolled crossings. Respective data is shown in Figure 16. The graph is uneven and has significant deviations, which are explained by certain methodological issues such as variable sample sizes of episodes for different observation places.

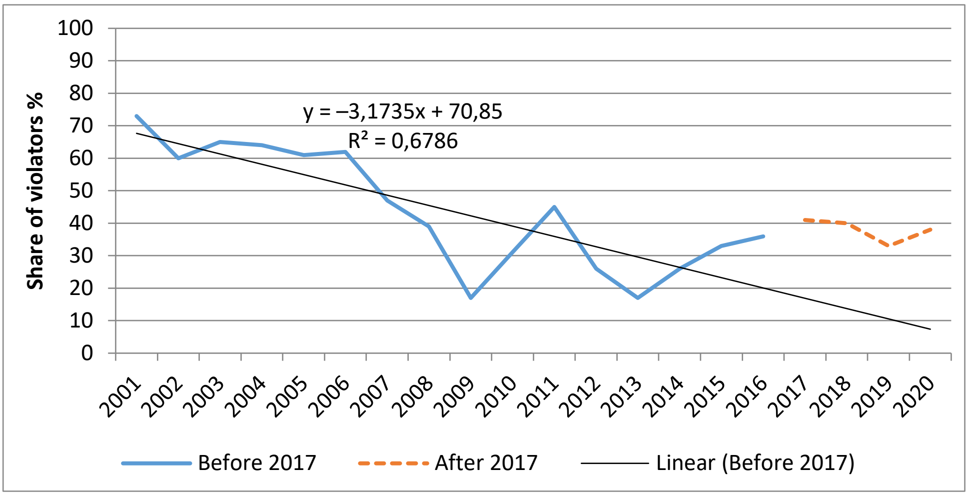

Figure 16. Yielding to pedestrians at uncontrolled crossings in Estonia in 2001–2016 (adopted from Maanteeamet, 2020).

Despite these nuances, the general improvement trend in yielding to pedestrians at uncontrolled crossings is positive. Similarly to seat belt usage, the most rapid decrease in the share of violators started from a poor initial benchmark and took place in the first part of the observation period. However, starting from 2010, the positive trend stagnated. The core difference from the seat belt usage lies in the fact that the share of violators remains stable and high. Observations performed after 2017 do not show any trends – share of violators is significant (around 38%) and it is not changing. Therefore, despite a rapid improvement in the previous decade, drivers who are not yielding to pedestrians at uncontrolled pedestrian crossings remain a very actual road safety problem.

3.1.2 Minor changes in traffic behaviour

The SPIs of the second group, which in 2001–2016 showed only minor changes, are drivers' and pedestrians' compliance with red traffic light. Respective data are given in Figures 17 and 18. Both graphs reveal slight improvement trends, but these are much weaker trends that those of the SPIs discussed previously. To some extent, it is explained by a better initial benchmark – the danger from ignoring traffic lights seems to be very evident, and the situation when most road users are ignoring traffic lights is complicated to imagine. It should be mentioned that after 2017, the share of drivers who do not comply with traffic lights (see Figure 17) is calculated in a different way. Previously, the number of violators was divided by the total number of drivers observed, but after 2017, it is divided by the number of drivers who had an option whether to comply with the red light or not. That is why the share of violators before 2017 has an order of magnitude around 0.9%.

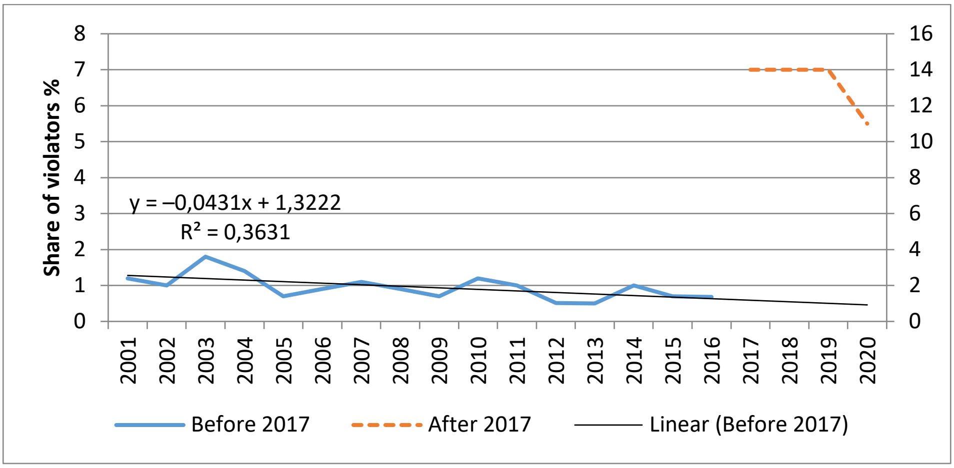

Figure 17. Drivers' compliance with traffic lights in Estonia in 2001–2016 (adopted from Maanteeamet, 2020).

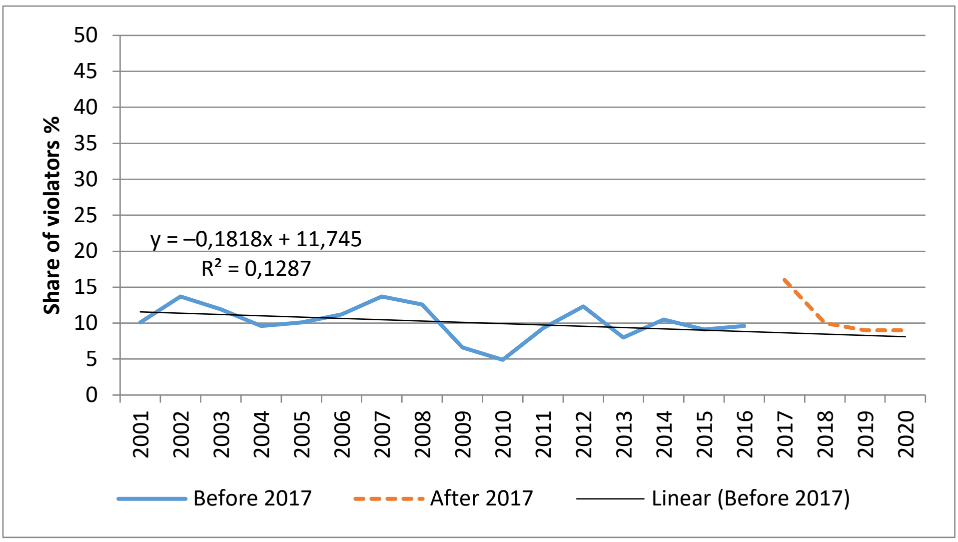

Figure 18. Pedestrians' compliance with traffic lights in Estonia in 2001–2016 (adopted from Maanteeamet, 2020).

Compared to seat belt usage and yielding at uncontrolled crossings, there is no pronounced difference in behaviour trends during the first decade and after that – changes were taking place slowly and gradually. The SPCs collected during the last four years do not show any clear trend – taking into account relatively big scatter, the data row is rather short and it is early to make any conclusions.

3.1.3 Measures for road safety improvement and accident statistics

In the scope of the study changes in traffic behaviour were compared to measures addressed to improving road safety foreseen by Estonian National Road Traffic Safety Programme (ENRTSP) 2003–2015. Estonian Road Administration regularly launched special social campaigns. Their number and focus are shown in Figure 19.

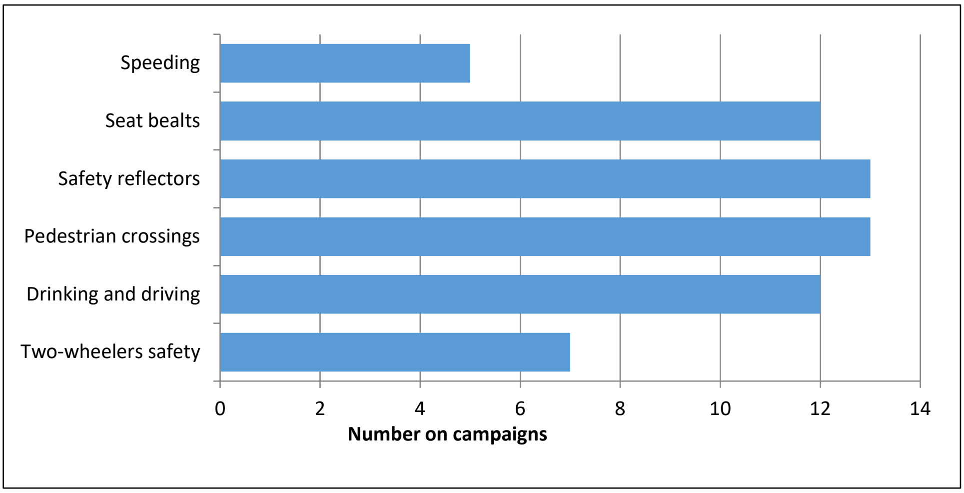

Figure 19. Social campaigns aimed at improving road safety in 2003–2015 (Ess, Antov, 2017).

The figure indicates focus of Estonian Road Administration, but quality and efficiency of these campaigns was not analysed within the study The outcomes of road safety improvement work does not have an immediate effect. It is directed towards changing road users' attitude towards traffic behaviour and it is difficult to estimate them. However, one can understand the focus of the Estonian authorities. Both safety at pedestrian crossings and usage of seat belts were among the priorities, but no campaigns were focused on compliance with traffic lights. This information was complemented with police enforcement data. Due to changes in legislation (introduction of the new Traffic Law in 2011) data was available for 2011–2015. 7% of all the traffic fines were made to drivers ignoring traffic lights and 4% to pedestrians ignoring traffic lights. 4.9% of the traffic fines were issued to drivers and passengers who did not use the seat belts. Taking into account that 48% of all the traffic fines in Estonia are made for speeding, these percentages are pretty high. At the same time only 0.5% of the traffic fines were issued for not yielding at uncontrolled pedestrian crossings.

ENRSP foresaw over 200 different measures and social campaigns and enforcement are only two examples. Numerous other factors contributed to road safety improvement and changes in traffic behaviour, for instance car industry. Due to the nature of the information available it is not possible to determine the contribution of each measure.

All in all, it can be said that all the traffic behaviour aspects analysed in the scope of this study were dealt with by competent authorities.

It is probable that the biggest contribution to road safety improvement was made by changes in seat belt use rates. Major improvements in road safety in Estonia coincide with the improvement of seat belt use rates. At the same time, some studies claim that adoption of lap/shoulder seat belts reduces the risk of life threatening injuries for front seat vehicle occupants by 45%, and the risk of moderate to critical injury by 50% (Chen, et al., 2016). In this respect, there is potential for improvement of seat belt usage on rear seats (by adults), which is still very far from ideal. However, this is unlikely to have a considerable effect as there are very few vehicles with adult passengers in the rear seats. At the same time seat belts are a passive road safety measure that helps to soften consequences of traffic accidents, but fails to contribute to decreasing the number of accidents. In this context, yielding to pedestrians plays a more important role.

3.1.4 The most actual traffic behaviour problem to solve

The study highlighted trends in road users' behaviour observed for 16 years. The question arises, what aspects of road users' behaviour to be dealt with in order to continue improvement of road safety? To answer this question, one needs to have a deeper look at road safety statistics. As a matter of fact, in 1991–2016 road safety in Estonia improved dramatically, but these judgements are based mostly on road fatalities' statistics. At the same time road safety research focuses traditionally on traffic accidents rather than on the number of fatalities. It is particularly important in the case of small sample sizes, which is definitely the case of Estonia.

Unlike road accident fatalities data, trustful accidents statistics are available only since 2003 (see Figure 20). Statistics are presented in real figures. Since 2011, the number of injuries is decreasing very slowly, while the number of accidents is not changing. One can also see that the most significant shifts in fatalities took place before 2010.

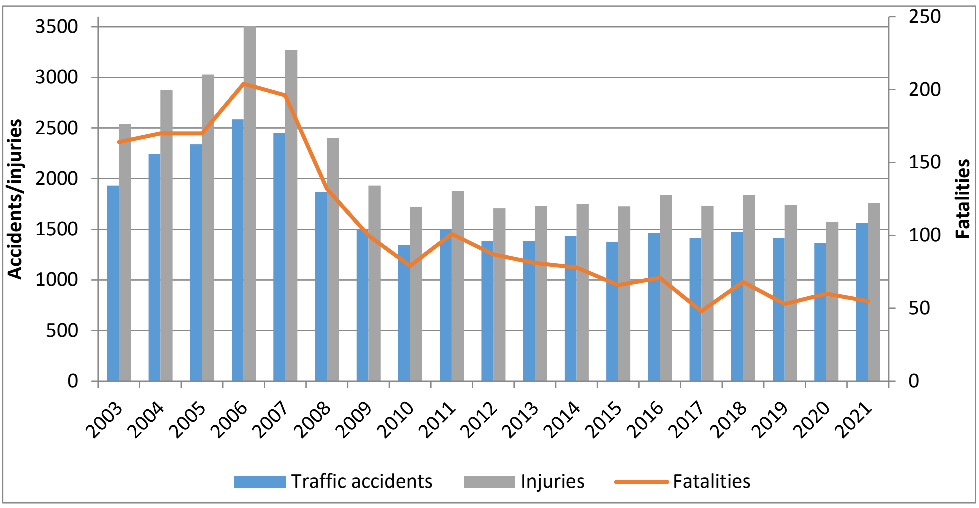

Figure 20. Road accident fatalities and number of road accidents in Estonia in 2003–2020 (compiled by the author).

The original aim of ENRTSP was decreasing number of road fatalities to 100 by the year 2015. As this goal was achieved earlier (in 2009), there were set two additional goals – by 2015 the average number of road deaths for three years should not exceed 75 people per year and the average number of injuries for three years should not exceed 1500 people per year. The latter goal has not been achieved by now. Decrease in the number of accidents is stagnating for over 10 years and this is the core problem – reduction of accidents would lead to decrease in the number of fatalities and injuries. In this context vehicle-pedestrian collisions play an important role. According to Estonian Transport Administration in 2011–2019 on average one of the four road fatalities was a pedestrian. In the EU the share of pedestrians in all the road accident fatalities is approximately 21% (ETSC, 2020). Pedestrian safety problem is very actual in Estonia. Despite all the work done in the scope of ENRSP, pedestrian safety is still recognised as the main road safety problem of Estonia. The final report of ENRSP concluded in 2016: 'Pedestrian safety remains a burning issue; especially in the big cities' (Maanteeamet, 2016b).

According to Estonian Transport Administration, more than 70% of all car-pedestrian collisions are happening on main streets of the four bigger cities (Tallinn, Tartu, Pärnu, and Narva) and most of them – at uncontrolled pedestrian crossings. Both traffic behaviour monitoring data and accident statistics show that not yielding to pedestrians is an issue. Amongst the other reasons this could be due to insufficient enforcement.

Despite rapid improvement in the first decade of 2000-s, the share of drivers who yield pedestrians at uncontrolled crossings is still not sufficient. For instance, in the traffic behaviour monitoring study conducted in 2020, there were only three crossings out of 10 crossings observed where the share of violators was beneath 30% (see Table 2).

Table 2. The share of drivers not yielding to pedestrians within observation places in 2020.

#	City	Observation place	Number of drivers	Number of violators	Ratio of violators
1	Tallinn	Linnamäe	107	13	12%
2	Tallinn	Rävala	175	78	45%
3	Tallinn	Magdaleena	222	119	54%
4	Tallinn	Akadeemia tee	113	30	27%
5	Tartu	Pikk tn	110	23	21%
6	Tartu	Sõpruse sild	136	56	41%
7	Narva	Kangelaste pr.	149	73	49%
8	Narva	Kreenholmi ksk	133	53	40%
9	Pärnu	Endla teater	155	60	39%
10	Pärnu	Mai Selver	127	41	32%

Source: adopted from Transpordiamet, 2020.

The analysis shows that pedestrian safety at uncontrolled crossing is the number one road safety problem for Estonia. Educational work and bringing more enforcement' focus to road users' behaviour at pedestrian crossings is likely to have an effect on road safety statistics. However, in practice, it is rather difficult because of the bureaucracy machine and lack of police resources. One of the options is the application of alternative measures such as safer solutions for uncontrolled pedestrian crossings. The vision of the author for road safety improvement is increasing safety of pedestrian crossings on main streets of bigger cities. This can be done applying contemporary ITS solutions to prevent vehicle-pedestrian conflicts. In this context, the question arises of how to assess the efficiency of these measures in conditions where sample sizes are small, and traffic accident statistics are not sufficiently precise. Solving these issues helps the further improvement of traffic behaviour and with high probability the improvement of road safety.

3.2 Smart Pedestrian Crossing as a solution for uncontrolled crossings

3.2.1 Pedestrian support in C-ITS systems

Although C-ITS systems as well as autonomous driving are developing rapidly, only little attention is paid to pedestrian safety and comfort. The main goal in the industry is solving the congestion problem, and the focus is at autonomous traffic management (Kokuti, et al., 2017, El Hamdani, et al, 2020).

Only a few pedestrian protection solutions have been proposed so far. These are limited mainly to Traffic Light Controllers (TLC) and Road Side Units (RSU). For the TLCs sensors, cameras, detectors, and push buttons are integrated to traffic lights to detect the presence of pedestrians and notify vehicles. But these systems have certain disadvantages. The use of the TLC is limited to specific parts of the road, where are installed traffic lights. Another issue is that a TLC system assumes that the road users will respect traffic rules, which cannot be guaranteed (El Hamdani, et al, 2020).

A RSU system collects data to share it with the road users. It can be used to detect surrounding pedestrians using its sensors and forward information to occluded vehicles (Ojala, et al., 2019). RSU can enable the road to communicate with vehicles and pedestrians through Infrastructure to Infrastructure (I2I), Vehicle to Infrastructure (V2I) and Infrastructure to Pedestrian (P2I). A I2I communication can be used to exchange traffic conditions in different road segments and V2I to share data with vehicles. Through P2I pedestrian position is sent periodically from his smartphone to the vehicles nearby and/or RSU to predict and avoid possible collisions. In its turn, RSU sends pedestrians alerts of possible danger (El Hamdani, et al, 2020). This strategy, however, is limited to the pedestrians carrying a smartphone. Intelligent systems were also proposed to enable a vehicle to communicate information to the pedestrian by using speakers or light colours (Rasouli, Tsotsos, 2019).

Another example of the use of infrastructure for pedestrian protection is the use of Virtual Traffic Lights (VTL) for crossing management. VTL processes data and share information for all the cars in the area as well as determines the individual traffic lights for each vehicle (Rapelli, et al., 2020). The VTLs use V2I and have been proposed for vehicular traffic management at intersections, not for pedestrian crossings. However, integrating pedestrians into the VTL paradigm could be by utilizing RSU as a traffic light in a centralized system. The virtual light value can be transmitted to both vehicles and pedestrians using V2I and P2I communication using smartphones (El Hamdani, et al, 2020).

Not only infrastructure, but also vehicles can have pedestrian protection systems. The vehicle can theoretically predict a possible collision by analysing the output of its own cameras and sensors. If a pedestrian is recognized, then the system uses pedestrian motion models to track and predict their reaction and motion trajectory. Based on trajectories, the system employs necessary actions, for instance, decelerating (Musleh, et al., 2010).

Although there have been made certain steps towards integrating pedestrians into C-ITS systems, support for safe pedestrian crossing still remains a technical gap (El Hamdani, et al, 2020).

3.2.2 A Level 6 Smart Pedestrian Crossing

Taking into account road users' behaviour at uncontrolled pedestrian crossing, accident statistics and the EU priorities in increasing road safety, the author proposes a concept of a Level 6 SPC. It is a C-ITS device, which is installed at the crossing and monitors the traffic situation. Its task is to warn drivers, pedestrians and vehicles of potential danger.

The project 'Technical Feasibility Study of Smart Pedestrian Crossing Solution' proved that the concept of SPC is technically feasible (Tallinn University of Technology, 2017). There has been made a physical prototype which successfully passed laboratory testing and confirmed the project results. Further R&D work resulted it the next prototypes, which will be handled in the next parts of the thesis.

3.2.3 Basic functionality according to efficiency parameters of TCM

In a broad sense, the SPC is a new generation TCM. Both the SPC and classic TCMs serve the same purpose – make drivers choose safe speeds to ensure road safety – with the only difference being that classic TCMs do not 'understand' if there is a risk of collision or not. Therefore, when analysing the efficiency of the SPC, one can proceed from TCMs.

Research showed that efficiency of TCM can be measured by means of surrogate safety indicators. Classical indicators such as number of road fatalities or traffic accidents are not applicable – there is no need to wait for accidents to happen in order to assess in the SCP was efficient or not. Contemporary technologies make it possible to collect different data, such as vehicles speeds, and even detect conflicts. The indicators measured can be taken over from classical TCM. These are basic efficiency parameters – closeness of 85th percentile speed to safe speed, adequate change in mean speeds when passing a TCM and public acceptance. Knowledge gained in the scope of the pilot study on estimating TCM efficiency can help to understand these indicators and adopt functionality of SPC accordingly.

One of the pilot study findings correspond to a contradiction in speed indicators. For instance, in the context of closeness of 85th percentile speed to safe speed the most effective were 'aggressive' measures such as speed bumps (see Table 3). This is logical because drivers understand the necessity of choosing moderate speeds to pass the high vertical TCM. But at the same time reduction in the mean location speed when passing a speed bump (in the location 0_1 m) was as high as 50% (see Table 4). In other words, the drivers had to decelerate to a speed which is approximately two times lower that the safe speed. They braked excessively, and this affected the smoothness of traffic flow as well as environment.

Table 3. Mean 85th percentile location speeds, km/h.

Traffic calming measures	**–50 m**	**–25 m**	**0_1 m**	**0_2 m**	**25 m**	**50 m**
Junctions with priority-to-the-right rule	46.15	42.18	38.30	39.37	38.76	40.99
Raised pedestrian crossings	43.14	37.56	19.90	20.30	33.43	36.70
Speed bumps	32.44	29.25	16.98	16.47	30.89	32.60
Raised junctions with priority-to-the-right rule	37.32	35.94	23.01	23.35	34.01	36.26

Source: Ess, Antov, 2016.

Table 4. Change in mean location speeds in relation to location speed.

Traffic calming measures	**–50 m**	**–25 m**	**0_1 m**	**0_2 m**	**25 m**	**50 m**
Junctions with priority-to-the-right rule	100%	91%	68%	78%	85%	88%
Raised pedestrian crossings	100%	89%	40%	40%	76%	85%
Speed bumps	100%	94%	50%	49%	103%	114%
Raised junctions with priority-to-the-right rule	100%	95%	52%	61%	92%	100%

Source: Ess, Antov, 2016.

This highlights the contradiction of choosing the speed. On the one hand, the speed must be slow enough to ensure safety. But on the other hand, it should be high enough to ensure road users' comfort and avoid acceleration after passing the TCM as it is connected to increase of vehicles' exhaust and noise. At the same time drivers' attitude towards speed bumps was rather negative (see Table 5). It means that they are not ready to scarify their comfort to an extent assumed by the nature of 'aggressive' TCM.

Tabel 5. Public acceptance (numbers in the table correspond to the number of drivers who gave the respective estimations).

Traffic calming measure	Very good	Good	Fair	Poor	Very poor	Don't know
Speed bumps	1	7	12	7	2	1
Raised junctions with priority-to-the-right rule	2	15	12	2	1	1
Raised pedestrian crossings	3	12	12	0	1	2
Junctions with priority-to-the-right rule	1	6	7	8	6	2

Source: Ess, Antov, 2016.

In its turn this contradiction corresponds to the general idea of road traffic. It is always a compromise between high speed, safety, comfort, and environmental friendliness. But it should be mentioned that classical TCM cannot adapt to the road, weather, and visibility conditions. Although the road may be empty and traffic conditions may be perfect, a speed bump or another ‘aggressive’ TCM will force drivers to decelerate excessively. At the other hand, a ‘gentle’ TCM, like a junction with priority-to-the-right rule or a simple road marking, will not guarantee choice of proper and safety speed in case of dangerous situation.

Unlike stationary TCM, a smart C-ITS system should ‘understand’ the traffic situation and adapt road users’ behaviour accordingly. In case of no collision risk, it should behave like a ‘gentle’ TCM like a junction with priority-to-the-right rule, but in case of danger it should force the driver decelerated like an ‘aggressive’ TCM like speed bump does.

To sum up, the effective SPC has to adapt to the real situation and give warnings only when it is needed. In this context a question arises in what situations should the SPC perform, and will it be able to provide warning signals in time, so that road users are able to react on them.

3.3 Efficiency of Smart Pedestrian Crossing

To understand in which standard situations SPC would function, there was conducted a traffic conflict study at uncontrolled pedestrian crossings. It took place in 2017–2018 in Tallinn, Estonia and covered 10 observation places. Data collected was analysed and typical critical vehicle-pedestrian collisions were modelled to estimate SPC performance.

3.3.1 Conflict study

Researcher collected and analysed 1512 hours (approx. 2 months) of video material. A total of 283 hours were recorded during the pilot stage and 1229 hours during the main stage of the study. There were determined 90 serious conflicts. Sixteen of them were unclassified (conflicts with alarm vehicles, unusual pedestrian behaviour, vehicle-cyclist conflicts, etc.). 74 serious conflicts were selected for analysis. All of them took place at pedestrian crossings situated at multi-lane roads, while no serious conflicts were determined on 1 + 1 roads.

The chosen conflicts were classified into three types (see also Figure 21):

- one vehicle stops before the crossing while another vehicle in the next lane keeps moving and conflicts with the pedestrian (Type 1);
- a vehicle conflicts with a pedestrian who is about to step to the crossing from the sidewalk or safety island (Type 2);
- a vehicle conflicts with a pedestrian who is already crossing the carriageway (Type 3).

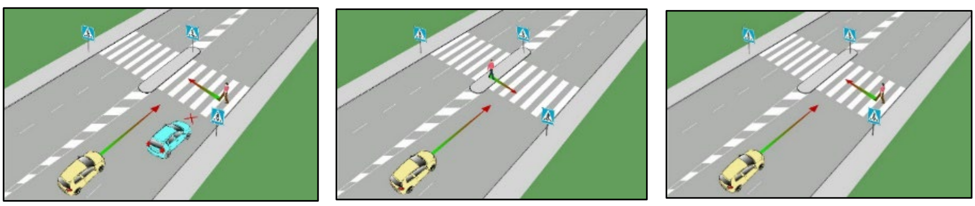

Figure 21. Typical conflicts revealed in the scope of the study (Ess, et al., 2021).

The principal difference between Types 2 and 3 lies in the fact that for Type 2, the pedestrian has not yet started crossing the carriageway and the driver may hope that the pedestrian stops before the crossing. For Type 3, the pedestrian is already on the carriageway; this situation is potentially more dangerous. It should be mentioned that between these types of conflicts there have been determined situations when a pedestrian was approaching both from the right and from the left. As it does not change the essence of the conflict, the author ignored the direction of motion of pedestrians in their classification. Half of serious conflicts correspond to the first type, one third to the third type, and the rest to the second type (see Figure 22).

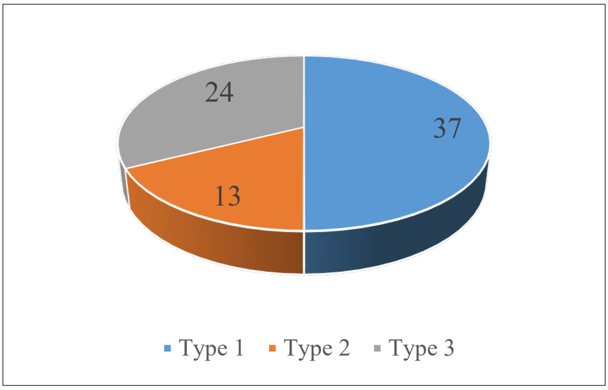

Figure 22. Serious conflicts by types (compiled by the author).

The most common behaviour for drivers who found themselves in a conflict with pedestrian is taking no action at all (52.7%); however, some drivers started accelerating and/or turning away from the pedestrian (see Figure 23).

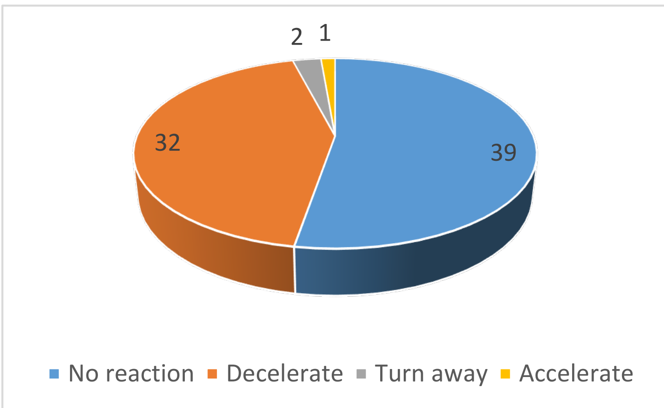

Figure 23. Drivers' typical reactions in conflict situations (Ess, et al., 2021).

The most common behaviour for pedestrians in a conflict at uncontrolled crossing was deceleration (74.3%), while 6.8% started accelerating (see Figure 24). However, it does not seem logical behaviour in dangerous situation, 18.9% of pedestrian who found themselves in a conflict did not take any action at all.

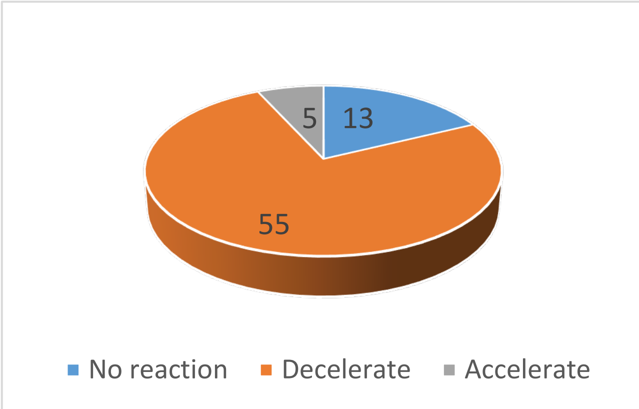

Figure 24. Pedestrians' typical reactions in conflict situations (Ess, et al., 2021).

During the pilot study, which took place in winter, there were detected 33 conflicts and during the main stage, which took place in summer, 41 conflicts. Taking into account the volume of video material collected there were observed ca 1.34 conflicts per 10 h in winter and ca 0.33 h per 10 h in summer. So, conflicts in winter were observed 4 times more frequently than in summer.

The analysis of the winter stage of the study shows that proportionally more conflicts happened in the dark – 63.3% of the conflicts took place in the dark, while the amount of video filmed in the dark was 54.4%. However, this disproportion is rather week and it should be mentioned that the disproportion is small the street illumination was on, and the crossings had additional illumination as well. During the summer stage of the study the amount of video filmed in the dark was 4.3% and no conflicts were detected in the darkness. This is explained by long daylights and lower traffic volume in the evenings. Other conditions such as precipitations did not play a significant role in the frequency of conflicts (see Table 6).

Table 6. The number of serious conflicts according to the light and weather conditions.

Conditions	Winter	Summer	Total
Daylight and dry	10	41	51
Daylight and precipitations	2	0	2
Dark and dry	17	0	17
Dark and precipitations	4	0	4

Source: (compiled by the author).

Much to the authors' regret, due to strict personal data protection legislation, it was impossible to get detailed description of pedestrian accidents from the police, which made conflict validation with real crash data complicated. Police provided only superficial accident descriptions, which contained little to no detail. There were analysed the descriptions of 40 accidents which took place in 2012–2018 at the same pedestrian crossings where the traffic conflict study has been conducted. Five vehicle-pedestrian collisions corresponded to the first type of conflicts, also five to the second, and two to the third type. Due to a lack of information, it was impossible to classify the remaining accidents, but analysis showed that conflicts of all three types end up with real traffic accidents.

For 33 of the 40 accidents there is data available describing the light and weather conditions (see Table 7). 11 accidents (or 33.3%) happened in the dark, while 7 accident (or 21.2%) took place at the during precipitation. These ratios do not coincide with the traffic conflict data, but it is explained by the fact that conflict study periods did not cover the whole year and the periods of darkness and precipitations during the calendar year and the study period were proportionally different.

Table 7. The number of vehicle-pedestrian accidents according to the light and weather conditions.

Conditions	**Number of accidents**
Daylight and dry	17
Daylight and precipitations	5
Dark and dry	9
Dark and precipitations	2
Total:	33

Source: compiled by the author.

To sum up, there were determined three types of serious vehicle-pedestrian conflicts. Validation with accident data showed that all these conflict types ended up with real traffic accidents, but detailed and more precise validation was not possible. In the dark conflicts were detected the more frequently than in the daylight, but accident statistics did not prove any connection between the risk of vehicle-pedestrian accidents and the light and weather conditions. Most of the drivers and many pedestrians having found themselves in a traffic conflict remain passive and take no action. The most common action taken by pedestrians (and many drivers) is deceleration.

3.3.2 Microsimulation and analysis

For every conflict type, researchers selected the most serious conflict and analysed it in T-Analyst and PC-Crash. T-Analyst was used to determine road users' trajectories, speeds and accelerations as well as TTC_{min} and T2. This data was imported to PC-Crash to create conflicts' models which were used for situation analysis.

The type 1 conflict is presented on Figure 25. The vehicle initially moved at a speed of 36.4 km/h and the pedestrian at a speed of 7.9 km/h. This situation is interesting because of its dynamics. Analysis showed that the dense traffic flow caused visual distraction (see Figures 26 and 27). Pedestrian turned his head to look left exactly at the moment when the conflicting car would be visible for him from the right and turned his head back right at the moment, when the car was behind another car in the second lane. When road users saw each other, the situation has become critical. The driver started decelerating while the pedestrian started running and jumped away from the approaching vehicle. TTC_{min} was 1.0 s. In case of a collision, the vehicle would have hit the pedestrian at a speed of 34.2 km/h.

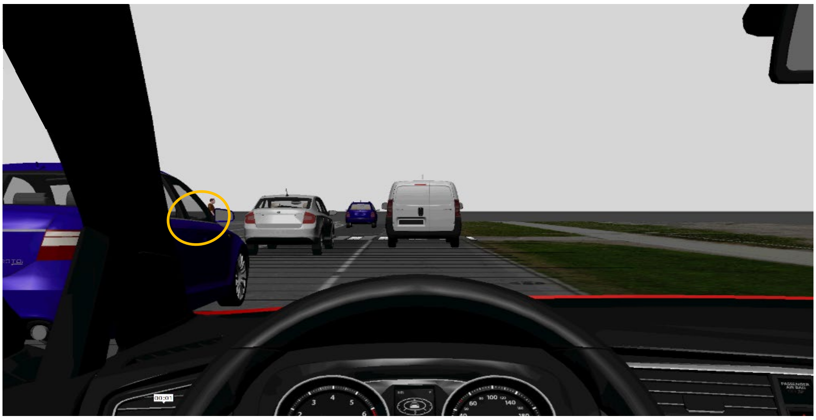

Figure 25. Model of the type 1 conflict (Ess, et al., 2021).

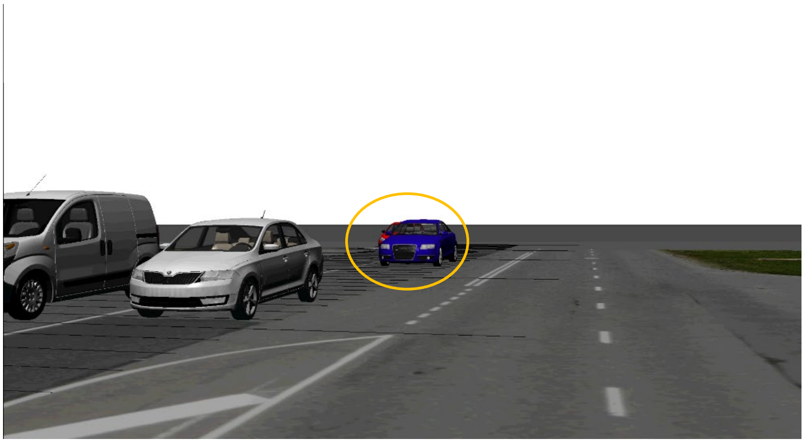

Figure 26. Pedestrians' visual distraction within the type 1 conflict (Ess, et al., 2021).

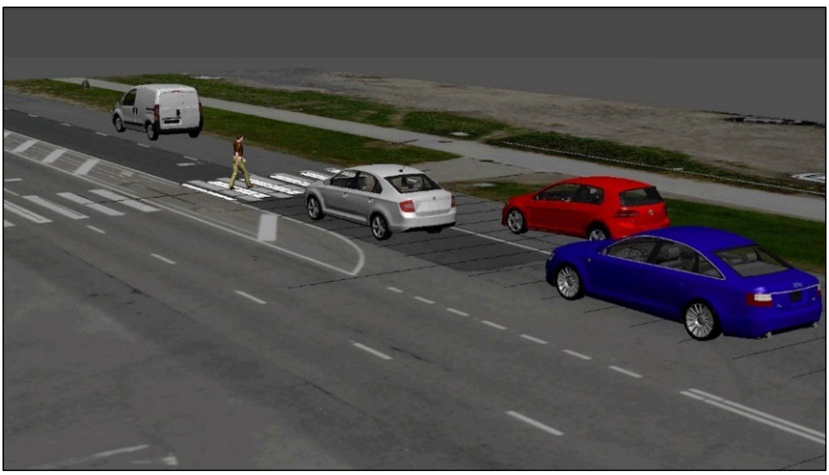

Figure 27. Drivers' visual distraction within the type 1 conflict (Ess, et al., 2021).

Taking into account the speed and road conditions, the stopping distance would be 22.1 m. This means that, to warn the driver, the SPC should give the warning signal when the distance to the pedestrian is at least 22.1 m. It should be mentioned that this is the minimum possible distance to send give the warning system. At the same time the SPC would detect the pedestrian well in advance and can give the warning signal earlier.

In any case, the distance to the crossing would be relatively small, and one can admit that the driver would notice the warning signal at the crossing even when moving in a dense traffic flow. However, it should be taken into account that the driver might not see the pedestrian at the moment when the warning signal is activated, and the question arises whether the driver reacts in an expected manner (brakes with maximum deceleration)?

To warn the AEB-equipped vehicle, the SPC should send the warning signal when the distance to the pedestrian is at least 12.0 m. This interval is smaller than in case of warning the driver, because the latter needs time to react. So, warning the vehicle is more reliable, as the warning signal can be sent to the car when there are only two car bogy length remaining until it hits the pedestrian. It is interesting to note that this conflict scenario is very inconvenient for an on-board pedestrian detection system. Vehicles' sensors would detect the pedestrian approximately 1 s before the collision, which would make it inevitable. At the same time additional input from the SPC would prevent the accident.

The type 2 conflict is presented on Figure 28. The vehicle moved initially at a speed of 57.6 km/h (while the speed limit is 50 km/h) and the pedestrian at a speed of 5.4 km/h. It was snowing and the road was slippery. The conflict took place in the dark, but the road lighting was on and the pedestrian crossing had additional illumination. There were no obstacles that could limit the driver's field of vision. The driver was distracted or assessed the situation incorrectly. When it was too late for braking, the driver took the decision to accelerate and pass the crossing before the pedestrian. The pedestrian noticed the vehicle just before stepping to the carriageway from the safety island. He stopped abruptly, slipped, and nearly fell down. $T2_{min}$ was 1.24 s. In case of a collision (for instance, if the pedestrian assessed the situation incorrectly and started accelerating), the vehicle would hit the pedestrian at a speed of 57.6 km/h.

Figure 28. Model of the type 2 conflict (Ess, et al., 2021).

Taking into account the speed and road conditions, the SPC should warn the driver when the distance to the pedestrian was at least 43.0 m. This raises a number of questions. Would the driver notice a warning signal located at the crossing, i.e ca 40 m ahead? Would the speeding driver realise the danger and react to this warning signal? Would the driver assess the road conditions correctly while deciding when to start braking? To sum up, there is certain doubt that warning the driver would have the desired effect in this situation.

In the case of the AEB system, the warning signal should be given when the distance to the pedestrian is at least 27.0 m. Despite the precipitations there is little doubt that an on-board pedestrian detection system would need input from the SPC, as the field of vision is not limited.

The type 3 conflict is presented on Figure 29. The vehicle initially moved at a speed of 41.4 km/h and the pedestrian at a speed of 6.5 km/h. It was snowing and the road was slippery. The pedestrian moved along the road off the pavement (the trajectory is shown on figure with the blue line). He did not turn his head before crossing the road and because of his hood, he did not see the approaching vehicle in his peripheral vision. The driver started decelerating after the pedestrian had stepped to the crossing. Due to the late reaction, the car passed just in front of the pedestrian. $T2_{min}$ was 0.27 s. In case of a collision, the vehicle would have hit the pedestrian at a speed of 42.5 km/h.

Figure 29. Model of the type 3 conflict (Ess, et al., 2021)

Taking into account the speed and road conditions, the SPC should warn the driver when the distance to the pedestrian was at least 26.5 m. In the case of the AEB system, the warning signal should have been given at least 15.0 m before the crossing. In both cases, the warning should be given before the pedestrian changes direction to cross the road, i.e. before it is clear that he intends to step on the crossing.

This case shows that in some situations, the SPC should give false positive warnings, especially in locations where the pavement is situated just next to the carriageway and the pedestrian can either cross the street or proceed walking parallel to it. Both for drivers and for AEB-equipped vehicles false positive signals would mean that sometimes they will have to brake ‘just in case’. However, this speed behaviour is typical for defensive driving style and many drivers are doing it in real traffic every day. This also means that the SPC should be ‘smart’ enough to predict the trajectories of pedestrians and to assess possible risks.

Coming back to the potential efficiency of SPC, in this situation it is likely to prevent collision by warning the driver, as he or she sees the pedestrian, but postpones braking for the moment when it is too late. A warning signal would help to take a decision in time.

In this particular case, one cannot expect the on-board pedestrian detection system to react in time without a warning signal from the SPC. As the pedestrian changes his direction suddenly and is very close to the crossing, the system will not consider him a conflicting object, before he actually turns and starts crossing the road. As a result, the vehicle will start decelerating later than needed and collision would be inevitable.

Analysis of traffic conflicts showed that road users behave in pre-crash situations differently. To assess the possible situation development, the most typical behaviour patterns were added to traffic conflict models, and it was checked if these patterns increase collision risks. Results are presented in Table 8. Impossible scenarios are marked with ‘-‘. The estimation ‘High collision risk’ means that in the simulated situation road users did not collide but were very near to a collision. Respective estimation was given according to road users’ trajectories.

Table 8. Potential probability for preventing collisions by type.

Driver	Pedestrian	Type 1	Type 2	Type 3
Takes no action	Accelerates	No collision	Collision	Collision
Accelerates	Takes no action	Collision	No collision	High collision risk
Accelerates	Accelerates	Collision	High collision risk	Collision
Turns away	Takes no action	-	No collision	-
Turns away	Accelerates	-	No collision	-
Turns away and accelerates	Takes no action	-	No collision	-
Turns away and accelerates	Accelerates	-	No collision	-
Turns away and decelerates	Takes no action	-	No collision	-
Turns away and decelerates	Accelerates	-	High collision risk	-

Source: (Ess, et al., 2021)

The outcomes show that in most simulated cases, the acceleration of a conflicting vehicle and/or pedestrian leads to collision or high collision risk. At the same time there are also some specific scenarios which can increase the risk of collision. For instance, for the Type 2 conflict if the pedestrian starts running and at the same time the driver brakes and tries to turn away by going to the adjacent lane, the collision risk would be high.

So, simulating typical behaviour patterns of road users indicated that to prevent collisions effectively the SPC should also predict possible acceleration of the vehicle and the pedestrian as well as their trajectories.

3.3.3 Outcomes

According to analysis performed within microsimulation for all the situations studied, researchers answered the question ‘Would an SPC help prevent a collision?’ Results are presented in Table 9. It should be noted that research concentrated at accident prevention. For instance, there were not handled cases then vehicle still collides with pedestrian, but the risk of injury is small. There were concerned scenarios, when driver has to stop the car fully to avoid the collision.

Table 9. Ability for preventing collisions by type.

Type of warning	Type 1	Type 2	Type 3
Warning the driver	likely	doubtful	likely
Warning the AEB-equipped vehicle	yes	yes	yes

Source: (Ess, et al., 2021)

Results show that the SPC will work most efficiently by warning AEB-equipped vehicles as their pre-braking time is shorter. So, if the vehicle is feasible to receive signals from the C-ITS and brake automatically, typical vehicle-pedestrian collisions at uncontrolled crossings would be prevented.

For two of the three conflict types warning the driver is likely to prevent the collision and for one conflict type it is assessed as doubtful. These estimations should be treated as follows – if the driver notices the warning signal and brakes, the collision will be prevented; but if the driver does not notice the warning or fails to react properly, the collision may happen, and its prevention would depend on the interaction between the conflicting driver and pedestrian.

The estimations of SPC efficiency when warning the driver are based at the fact that with our current knowledge, we cannot be sure that the driver will react at the warning signal as expected. On the other hand, the conflict study showed that 53% of drivers involved in serious conflicts did not react at all, i.e. proceeded driving at the initial speed. They have assessed situation incorrectly or were distracted, so, the warning signal might be useful. The recent case study held by TalTech in 2021 indicated that application of the SPC prototype, which corresponds to Level 5 and uses pedestrian crossings’ illumination as a warning signal for drivers and pedestrians, decreased the number of potential conflicts by 37% (TalTech, Stratum, 2021). In this context the estimations highlighted in this thesis might be too conservative.

In any case, the efficiency of the SPC will highly depend on the efficiency of warning signals, first of all, on their type and location, and this is the topic for further research.

The same can be said about warning signals for pedestrians. If driver fails to react at the warning signal in time, the outcomes would depend on the interaction with the pedestrian. In many cases collision will be prevented (for instance, the pedestrian stops). In some cases, the vehicle will hit the pedestrian at a low speed and the injury will be insignificant. Only the very critical situation when the pedestrian fells down at the crossing or takes a wrong decision (starts accelerating, when it would be safe to stop), the collision will end up with serious injury or fatality. It means that the estimations 'likely' or 'doubtful' in the Table 9 do not indicate that the SPC would not contribute to improvement of road safety.

An important finding is connected to on-board pedestrian detection system. In two of the three conflicts studied, the vehicle equipped with such a system would need additional input for the SPC. In one case it is connected to limited field of detection of vehicles' sensors (type 1 conflict) and in another case the pedestrians' trajectory should be predicted before he turns to cross the street and becomes a conflicting object (type 3 conflict).

To sum up, SPCs a promising solution for pedestrian safety improvement. Warning the AEB-equipped vehicles would be most efficient and could prevent the typical vehicle-pedestrian collisions at uncontrolled crossings. It means that Level 6 SPCs would be more efficient than Level 4 and 5 SPCs provided that the share of vehicles capable of receiving signals from C-ITS is significant. Warning the drivers also has strong potential, but the efficiency of SPCs will to a large extent depend on the quality of warning signals. An on-board pedestrian detection system cannot replace the SPC and in many cases would need its input to prevent collision. Thus, to ensure rapid and sustainable development in this field, it makes sense to equip the new vehicles with V2I or V2X communication modules in the standard vehicle configuration.

3.3.4 Features to provide efficiency of the Smart Pedestrian Crossing

Efficiency of the SPC would depend on the following factors:

- the number of accidents prevented;
- the number of false-positive warnings;
- public acceptance;
- the drivers' speed behaviour.

To be effective, the SPC should be able to prevent as many serious vehicle-pedestrian conflicts as possible and the percentage of prevented accidents should be as high as possible. The warning should guarantee that drivers choose safe speeds and brake if needed. But it should be given only in case of potential danger, and the number of false-positive warnings should be as low as possible. The warning signals should be understandable, so that drivers react at them in expected manner. Drivers and pedestrians should treat the SPC well – the higher is public acceptance, the more efficient is the SPC.

Drivers speed behaviour can be estimated using methodology developed in the scope of this study. Taking into advance technological level of the SPC, determining the 85^{th} percentile location speed and mean location speed can be done automatically. The SPC could be also feasible of detecting false positive warnings and the number of prevented and not prevented accidents. This would make it possible to assess the SPC efficiency constantly and to improve the warning algorithms. Measuring public acceptance (for instance, by means of online surveys) would finalize the efficiency estimation.

To maximize the SPC efficiency it should have certain ‘must have’ features. First, it is important that the SPC calculates the stopping distances precisely. If the road is dry and the vehicle’s speed is 50 km/h, the SPC should warn the driver at least 27.3 m before the crossing, but in case of snow on the carriageway, 64.9 m before the crossing. The system should be smart enough to know the coefficient of static friction and to warn road users and vehicles in time. This data can be collected by means of sensors or by a wireless signal from the closest road weather station.

Secondly, the SPC should predict possible acceleration of the vehicle and the pedestrian as well as their trajectories. It sets high standards to the SPCs software and processing power. Most probably the system should be based on machine learning, i.e. it should ‘learn’ the behaviour of road users from real traffic. To prevent probable collision in some scenarios (like the Type 3 conflict) the SPC should give false positive warnings, which would mean that drivers or AEB-equipped vehicles will have to brake ‘just in case’. The number of such warning should be as low as possible.

In the third place, the SPC should be orientated not only to the vehicles, but also to the road users. The system will be most efficient for the AEB-equipped vehicles, but their share in traffic during the next decade will be relatively low. For instance, according to Estonian Transport Administration the average age of a passenger car in Estonia is 12.9 years. The total number of passenger cars is approximately 910,000, while the number of annually sold new cars is approximately 26,000. So, it is not realistic that the new technologically advanced cars will not replace the old ones within the next 10-20 years. It means that the SPC should warn not only vehicles, but also drivers and its efficiency will largely depend on the warning signals.

3.3.5 The operational concept of Smart Pedestrian Crossing

The aim of the SPC is to prevent vehicle-pedestrian conflicts at uncontrolled crossing as well as in its close proximity. The system should detect potential conflicts and warn the road users and the vehicles. Leaving aside the technical part such as hardware and software, efficiency of the SPC will largely depend on the warning signals.

This study proved that warning the AEB-equipped vehicles would be very effective, but currently there are not many vehicles at the EU roads capable of receiving signals from roadside C-ITS. Therefore, the warning patterns of the SPC should consider different addressees such as drivers, pedestrians, and vehicles with different level of equipment. This makes it reasonable to use the Safe System approach, which assumes implementing safety measures at multiple levels – if one element fails, the next level brings the situation back to safety. Therefore, the author proposes to perform the warning on two stages (see Figure 30). Hereafter, there will be discussed the basics of this concept without considering the details connected to the warning signals.

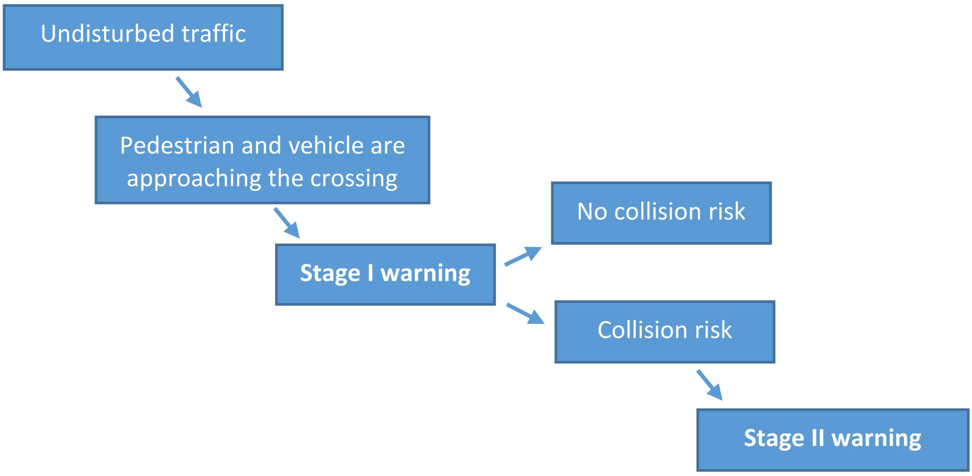

Figure 30. Scheme of warning given by Smart Pedestrian Crossing (compiled by the author).

The first stage is rather basic – when device detects a pedestrian and a vehicle approaching to the crossing, it applies a gentle warning. For instance, activates additional illumination of the crossing or changes the colour of the VMS traffic signs 'Pedestrian crosswalk'. Depending on the quality of the warning signals, at this stage many of potential collisions can be prevented. The resent case study by TalTech indicates that this warning can prevent one third of potential conflicts (TalTech, Stratum, 2021).

The second stage of warning is more specific and consists of different signals. Some of them are universal, while others are specific and addressed to vehicles which are capable of receiving signals from C-ITS. The universal signals are, for instance, activating intensive illumination at the crossing and/or changing the colour of the traffic signs 'Pedestrian crosswalk'. The specific warning is a signal sent to the vehicle which warns of high collision risk. Having received the signal, the vehicle can perform according to its software and equipment. It can show a warning sign at the dashboard or brake automatically, turn emergency lamps on and automatically honk the horn. These actions can be taken by the vehicle all together or selectively.

Most of the systems listed above are used on the vehicles nowadays, but some of them are less widespread that others. Dashboard warnings are a standard option of any car and contemporary active safety systems such as front assist display big warning signals at the dashboard and emits a loud single beep to warn about a possible collision. Emergency lamps signalize of a sharp braking and many contemporary vehicles turn them on automatically when 'feel' an intensive deceleration. The automatic horn honking is currently not used at the cars, but it has a good potential to prevent vehicle-pedestrian collisions. When hearing a horn, pedestrian will instinctively look in its direction, i.e. in the direction of danger, and as a result he or she will react rapidly. However, this type of warning should be thoroughly studied before application, as theoretically some pedestrians may react at the horn sound by stopping in the middle of the lane, which is potentially very dangerous.

Since the current level of automatization of car fleet is relatively low, the first versions of the SPC can use alternative options of the stage II warnings. For instance, audible warning signal can be given by a column speaker mounted at the crossing (not by automatically applied vehicle horns). As older vehicles cannot display the warning sign at the dashboard, this warning can be replaced by (or complemented with) VMS signs placed at the crossing.

The concept described assumes using the gentle and the aggressive warning. This approach helps to decrease the number of sharp braking and other evasive actions, which makes the traffic smoother and more predictable. If the SPC works properly, the road users will feel that it improves their safety and will treat it well. Ideally, the SPC should self-evaluate itself by determining the efficiency parameters discussed previously. It will help to ensure the high level of SPC effectiveness.

The study results were used in software development for the first prototypes of the SPC. The latest prototype corresponds to Level 5 SPC. It uses narrow artificial intelligence algorithms, which are capable of predicting the road users' trajectories. It uses only stage I warnings – pedestrians are warned with audio signal and vehicle drivers with illumination and blinking LED lights at the crossing. At the moment of writing this thesis, the prototypes are being tested in Tallinn, Viimsi, and Tartu.

3.3.6 Future research and discussion

Study showed that the SPC is a promising technology, but there is a number of questions which must be answered in the scope of future research.

The most important issue is connected to cost-effectiveness. The study showed that SPC should be smart enough to consider possible behaviour of road users. Most likely, that means that it should have software based on artificial intelligence. Will it be affordable and will it be repaid by lowering the number of collisions? Taking into account that the median value of a serious injury in Europe is 254,777 euros (Schoeters, et al., 2017), one can admit that the SPC price will be repaid. For instance, at the pedestrian crossings observed in the scope of this study there are happening on average 4 pedestrian accidents per year. If installing SPCs to all these pedestrian crossings prevents all the serious accidents with the median value of a serious injury, the repaid value in one year will be over 1 million euros. So, with high probability the SPC would be economically feasible. However, final conclusions can be done only when we know the price and maintenance cost of the SPC and its actual efficiency.

Another important question is connected to the warning signals meant for drivers and pedestrians. The study showed that 52.7% of drivers and 18.9% of pedestrians did not take any action when they found themselves in a dangerous situation. It raises a question of whether they would react to a warning signal. As proposed before, that largely depends on the efficiency of warning signals and this issue is actual for SPCs of Level 3 and above. In this context, it is important to understand how to warn pedestrians and drivers in the best possible way and at the same time not to 'spoil' the urban environment. For instance, aggressive blinking LEDs and strong audible signals could attract more attention, but, from the other hand, be annoying to road users and other people close to the SPC. Unexpected strong audible signals are also potentially dangerous for elder people and people with health problems.

Another issue is what happens when road users see or hear the warning. What will they do and more importantly – where will they look? In this context the author made an assumption that warning pedestrians by means of automatic activation of vehicles' horn would be more effective than using loudspeaker at the crossing, as the horn would indicate pedestrian the direction of danger. However, this hypothesis which needs to be checked. At the example of the Type 2 conflict one can see that the SPC should warn the driver when the distance to the pedestrian was at least 43.0 m. It should be outlined that the carriageway was wet, and the driver exceeded the speed limit. However, the situation could have been even worse, for instance, if there was ice on the road. In such a case, due to lower coefficient of static friction the stopping distance of the vehicle would be longer, and the driver should see the warning earlier. Would the driver react at a warning signal if it is located so far away? This question should be also answered in the scope of future studies.

The future developments the SPC should consider not only pedestrians who are crossing the street, but also cyclists and drivers of electric scooters and other contemporary technological means of transport. This assumes monitoring traffic with sensors and radars with broader field of detection and software capable of predicting possible acceleration and trajectories of different the means of light transport moving in the same street space as pedestrians. This ads to the complexity of the SPC technological level and should be also considered in the future research connected to cost-effectiveness and the warning signals. It is not excluded that after these studies the classification of SPCs should be reviewed and supplemented with another Levels, which consider cyclists and drivers of electric scooters.

4 Conclusion

The aim of this doctoral thesis is to find a perspective direction for future road safety developments, to propose a solution to the problems determined and to estimate its effectiveness. This topic is actual, because road safety improvement in the EU has stagnated and old approaches do not give the desired results anymore.

The research outcomes and conclusions are listed below:

- The analysis of changes in the behaviour of road users showed that not yielding to pedestrians at uncontrolled crossings is the most critical road safety problem which remains unsolved.
- As a solution to this problem, the concept of state-of-the art Smart Pedestrian Crossing was proposed. This is a C-ITS traffic calming device, which is installed at uncontrolled crossings to monitor the traffic situation and to warn drivers, pedestrians, and vehicles of potential danger.
- The general TCM efficiency parameters are closeness of the 85th percentile location speed to safe speed, change in mean location speed when passing a TCM and public acceptance. An effective TCM should 'force' drivers to reduce their speed only to the needed extent; excessive braking is not welcomed. The better actual road users treat the TCM, the more efficient it is. Based on these parameters, a new methodology for estimating TCM effectiveness was designed and tested, which is suitable both for classical and new-generation TCMs, such as the SCP.
- A new methodology was designed for estimating the effectiveness of an SPC under typical vehicle-pedestrian collision scenarios at uncontrolled crossings. It is based on the traffic conflict technique and the microsimulation of the most critical conflicts. The study conducted in accordance with this methodology showed that there are three typical scenarios of vehicle-pedestrian collisions. Microsimulation analysis showed that an SPC can prevent all of these collisions by warning AEB-equipped vehicles which are able to receive signals from the C-ITS and brake automatically. Warning the driver was estimated to have strong potential to prevent typical collisions, however, SPC efficiency depends on the quality of the warning signals. If the driver notices the warning signal and brakes, a collision will be prevented; but if the driver does not notice the warning or fails to react properly, a collision may happen, and its prevention would depend on the interaction between the conflicting driver and pedestrian.
- To be effective, an SPC needs certain features. It should 'know' the coefficient of static friction and predict the possible acceleration of the vehicle and the pedestrian as well as their trajectories. In some cases, the SPC will give false-positive warnings, but the share of such warnings should be as low as possible. An SPC should warn not only the vehicles, but also the drivers. To support this approach, a respective operational concept of an SPC was developed.

The general outcome is that SPCs are a promising solution for pedestrian safety improvement. It makes sense to proceed with the development of SPCs and to equip new vehicles with V2I or V2X communication modules in the standard vehicle configuration.

The input and outcomes of this thesis were used for software development of an SPC prototype which has narrow artificial intelligence algorithms capable of predicting the trajectories of road users. It is being tested in Tallinn and several other cities. Currently, its functionality is limited to warning road users.

Although SPCs are a promising technology, there is a number of questions which must be answered in the scope of future research. These are connected to efficiency of the warning signals and the ability of an SPC to prevent collisions between vehicles and cyclists as well as between vehicles and drivers of electric scooters and other contemporary technological means of transport.

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Abstract

Looking for a solution to enhance pedestrian safety and estimating its potential effectiveness

The EU has set an ambitious goal to reduce the number of road fatalities close to zero by 2050. Respective work on the issue used to be productive, but starting from 2013, positive trends nearly stagnated and further improvement of road traffic safety has become challenging. As old approaches do not give the desired result, it is important to find new effective solutions to reduce the number of traffic accidents. The aim of this doctoral thesis is to find a perspective direction for future road safety developments, to propose a solution to the problems determined and to estimate its effectiveness.

An analysis of changes in the behaviour of road users combined with available road safety data showed that solving the problem of pedestrian safety at uncontrolled crossings would correspond to the general road safety improvement. In this respect, the concept of a state-of-the art Smart Pedestrian Crossing (SPC) was proposed. This is a C-ITS traffic calming device which is installed at uncontrolled crossing to monitor the traffic situation and to warn drivers, pedestrians, and vehicles of potential danger.

To understand the general efficiency features of an SPC, a unified methodology suitable for estimating the efficiency of traffic calming measures (TCMs) was designed. It does not require conducting before-and-after studies and uses efficiency parameters such as the 85th percentile speed, mean speed, and public acceptance. It was found that an effective TCM should 'force' drivers to reduce their speed only to the required extent and prevent excessive braking. At the same time, public acceptance is also important — the better the actual road users treat the TCM, the more efficient it is considered to be. The new methodology was successfully tested and validated in the scope of a pilot study. Next, the research estimated whether an SPC can prevent typical vehicle-pedestrian collisions at uncontrolled crossings. Typical collisions were determined using the traffic conflicts' approach. A large-scale conflict study was held, which resulted in 1,512 hours of video material. Serious conflicts were classified into three types according to the similarity of the scenarios. The most critical conflict of each type was modelled with software used for traffic accident investigation to analyse the situation dynamics as well as other factors, such as field of vision and visual distraction. Based on the stopping distance and on the circumstances of the situation, in was estimated whether a warning signal can be given early enough to prevent collision. It was found that the proposed SPC would be able to prevent the typical collisions by warning AEB-equipped vehicles which are able to receive signals from the C-ITS and brake automatically. Warning the driver has also strong potential to prevent typical collisions, but the proposed SPC efficiency depends on the quality of the warning signals.

Taking previous findings into account, certain 'must-have' features of an effective SPC were determined. Its efficiency directly depends on the ability to adapt to the real traffic situation. It means that an effective SPC should warn road users and vehicles only in case of danger, using understandable warning signals which are given at the right moment. To ensure high level of efficiency, the system needs to 'know' the coefficient of the static friction of the carriageway and to be able to consider possible trajectories and the acceleration of the vehicle and the pedestrian.

The scientific novelty of this doctoral thesis is in designing new methodologies for estimating the effectiveness of TCMs, including intelligent and non-existent measures.

These methodologies do not require conducting before-and-after studies and use surrogate safety indicators. The thesis provided important input for the development of state-of-the-art C-ITS technologies, showing that SPCs will be more effective than on-board pedestrian detection systems. The results of this doctoral thesis were implemented in a prototype SPC that was developed in Estonia. At the moment of defending this doctoral thesis, the first SPCs are being tested in Tallinn, Viimsi, and Tartu.

Lühikokkuvõte

Liikluskäitumise analüüs ja targa ülekäiguraja tõhususe hindamine jätkusuutliku liiklusohutuse parandamiseks

Euroopa Liit seadis ambitsioonika eesmärgi 2025. aastaks vähendada liikluses hukkunute arvu nullilähedasele tasemele. Vastav töö oli produktiivne, kuid alates 2013. aastast positiivne trend peaaegu katkes ja edaspidine liiklusohutuse parandamine muutus keeruliseks. Vanad lähenemised soovitud tulemust enam ei anna, mistõttu peab otsima uusi ja tõhusamaid lahendusi. Selle doktoritöö eesmärk on leida perspektiivne suund liiklusohutuse arendamiseks, pakkuda lahendus tuvastatud probleemidele ja hinnata selle tõhusust.

Liikluskäitumise analüüs kombineerituna olemasolevate liiklusohutuse andmetega näitas, et liiklusohutust aitab parandada jalakäijate ohutuse probleemi lahendamine reguleerimata ülekäiguradadel. Seoses sellega pakuti välja kaasaegse nutika ülekäiguraja (NÜR) kontseptsioon. Tegemist on intelligentse liiklust rahustava transpordi sidussüsteemiga (C-ITS), mis paigaldatakse ülekäigurajale, et jälgida liiklust ning potentsiaalse ohu korral hoiatada sõidukijuhte, jalakäijaid ja sõidukeid.

NÜR-i tõhususe põhiparameetrite määramiseks töötati välja uus metodoloogia, mis sobib liikluse rahustamise meetmete (LRM) efektiivsuse hindamiseks. See ei eelda enne-ja-pärast uuringute korraldamist ja kasutab selliseid efektiivsuse parameetreid nagu 85. protsentiili kiirus, keskmine kiirus ja liiklejate heakskiit. Töö käigus jõuti järeldusele, et efektiivne LRM peab „sundima“ juhte vähendama kiirust vajaliku tasemeni ning liigne aeglustamine ei ole teretulnud. Samal ajal on tähtis liiklejate suhtumine LRM-idesse – mida parem on see suhtumine, seda efektiivsem on LRM. Uut metodoloogiat katsetati edukalt ja valideeriti pilootuuringu raames. Edaspidi hinnati, kas NÜR saab ennetada tüüpilisi sõidukite ja jalakäijate kokkupõrkeid reguleerimata ülekäiguradadel. Tüüpõnnetused määratleti liikluskonfliktide lähenemise abil. Selleks korraldati suuremahuline konfliktuuring, mille raames koguti 1512 tundi videomaterjali. Tõsised konfliktid liigitati vastavalt nende stsenaariumitele kolmeks tüübiks. Iga tüübi ohtlikuim konflikt modelleeriti tarkvara abil, mida kasutatakse liiklusõnnetuste uurimiseks, ning loodud mudelite abil analüüsiti situatsiooni dünaamikat ja teisi faktoreid, nagu vaateväli ja piiratud nähtavus. Sõidukite peatumisteekonna ja liiklusolukorra asjaolude alusel hinnati, kas kokkupõrke ennetamiseks on võimalik hoiatussignaal piisavalt vara anda. Tulemused näitasid, et välja pakutud NÜR hoiaks ära kõiki tüüpõnnetusi, kus see saadaks hoiatussignaali autole, mis on varustatud autonoomse hädapidurdussüsteemiga (AEB) ja on võimeline vastu võtma C-ITS-signaale. Juhtide hoiatamisel on samuti tugev potentsiaal, kuid NÜR-i tõhusus sõltub hoiatusmärguannete efektiivsusest.

Eeltoodud uuringute tulemuste põhjal määratleti hädavajalikud NÜR-i omadused. NÜR-i tõhusus sõltub otseselt selle võimekusest kohaneda konkreetse liiklusolukorraga. See tähendab, et efektiivne NÜR peab hoiatama liiklejaid ja sõidukeid ainult ohu korral ning kasutama selleks arusaadavaid ja õigeaegselt antavaid hoiatusmärguandeid. Süsteem peab „teadma“ sõidutee haardetegurit ja olema võimeline prognoosima võimalikke trajektooride muudatusi ning jalakäijate ja autode võimalikke kiirendusi.

Selle doktoritöö teaduslik uudsus seisneb uute metodoloogiate väljatöötamises LRM-ide, s.h tarkade ja mitteeksisteerivate LRM-ide, efektiivsuse hindamiseks. Need metodoloogiad ei eelda enne-ja-pärast uuringute korraldamist ja kasutavad alternatiivseid ohutuse parameetreid. See doktoritöö tagas tähtsa sisendi kaasaegsete

C-ITS-tehnoloogiate arendamiseks näidates, et NÜR-id on tõhusamad kui autodele paigaldatud jalakäijate tuvastamise süsteemid. Doktoritöö tulemusi kasutati Eestis loodud NÜR-i prototüübi väljatöötamisel. Doktoritöö kaitsmise ajal katsetati esimesi NÜR-e Tallinnas, Viimsis ja Tartus.

Appendix

Publication I

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UNIFIED METHODOLOGY FOR ESTIMATING EFFICIENCY OF TRAFFIC CALMING MEASURES – EXAMPLE OF ESTONIA

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Abstract. Traffic calming is an integral part of contemporary traffic planning and traffic management being used for fulfilling different tasks such as reducing vehicle speed and traffic volume, and in final terms reducing number of accidents. Traffic calming measures are notstandardized internationally and have significant differences in geometric shape and layout in different countries, as well as in Estonia. At the same time impacts of different calming measures are unstudied well, and often the surveys are incomparable to each other. There are also no certain recommendation which measures should be implemented under different conditions. One of the reasons for that is lack of tested methodology for estimating the effectiveness of calming measures. This paper describes research that aimed at developing such a methodology and conducting a pilot study to test it. Effectiveness of traffic calming measures is estimated from the perspectives of vehicle speed and public acceptance. The new methodology assumes conducting an experiment. It allows comparing efficiency of two or more measures of the same type. The pilot study was conducted in Tallinn with a sample of 30 drivers. Results of this study proved that the new methodology is suitable for estimating effectiveness of traffic calming measures.

Keywords: efficiency, Estonia, Global Navigation Satellite System, methodology, traffic calming, traffic calming measures, traffic safety, traffic study.

1. Introduction

During the last decade different traffic calming measures (TCM) have been implemented in Estonian cities and built-up areas. Today there are plenty of different measures being introduced, however it is unknown which of them are more efficient. Respective studies are complicated due to significant differences in geometrical characteristics and layout of TCM of the same type. It means that the same TCM implemented in similar conditions potentially have different impact and efficiency. As a result, estimated efficiency is applicable only to the exact TCM studied. For the same reason results of surveys held abroad could not be applicable to Estonian conditions or the impacts might be different from the originals. Authors of this paper set a goal to develop and to test methodology for estimating efficiency of TCM, which could be used as a unified methodology for respective studies in Estonia. This could be taken as a first step to understand efficiency of TCM of different shape, size and layout, standardizing TCM and drawing recommendations to use the most effective TCM under certain conditions. Respective interest groups are local authorities and traffic management specialists.

2. Literature analysis

The Institute of Transportation Engineers (USA) in *Guide for Achieving Flexibility in Highway Design* defines traffic calming as the combination of mainly physical measures that reduce the negative effects of motor vehicle use, alter driver behaviour and improve conditions for non-motorized street users. According to Estonian standard *EVS 843:2003 Town Streets* traffic calming assumes that drivers should feel themselves being in an area where safe speed limit is 50 km/h and where is a higher probability to meet a pedestrian. Sometimes it is said that traffic calming measures are used to replace enforcement. They place physical rather than legal restrictions on the actions of citizens and can be argued to provide a more socially equitable and efficient solution than regulation (Garrod *et al.* 2002).

There are various types of TCM depending on their character. For instance, there are distinguished vertical and horizontal TCM. Vertical TCM include any measure that alters the vertical profile of the carriageway such as road humps and speed cushions. Horizontal TCM include measures that alter the horizontal alignment of the carriageway such as mini-roundabouts, build outs and chicanes (Mountain *et al.* 2005).

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How can one understand TCM efficiency? Literature analysis shows that there is no widespread or commonly accepted definition of TCM efficiency. However, many sources connect efficiency to the goals of the traffic calming project. For instance, Corkle *et al.* (2002) state that to estimate efficiency of traffic calming measures one should set exact and measurable goals and base oneself on the fact whether these goals have been achieved or not.

There are many efficiency parameters being used in studies aimed at estimating TCM impacts. Among the different speed-related parameters known in the literature, mean speed is very often used as measure for safe driving, mainly because elevated crash risk and severity have been related to an increase in mean speed (Ariën *et al.* 2013). Other speed related efficiency parameters are 85th percentile speed, standard deviation of longitudinal acceleration and deceleration, percentage of drivers exceeding the speed limit, the highest speeds, 10 mph pace (Ariën *et al.* 2013, 2014; Corkle *et al.* 2002; Mountain *et al.* 2005). Among other commonly used TCM efficiency parameters are reduction of traffic volume, change in the number of fatal and injury accidents, traffic noise level, vehicle emission and public health impact (Čygaitė *et al.* 2014; Huang, Cynecki 2001; Lee *et al.* 2013). Some authors measure TCM efficiency as a delay per TCM during emergency transport (Berthod 2011), or delay time for crossing the road (Garrod *et al.* 2002), cost of traffic calming project and maintenance costs (Garrod *et al.* 2002, Langdon 2003). Other authors estimate such effeciency parameters as private expenditures in fuel and vehicle maintenance (Jazcilevich *et al.* 2015), impact on public transport (Banister 2009) and cyclists (Pinkerton *et al.* 2013). Literature analysis shows that public acceptance has become an important TCM efficiency component (Čygaitė *et al.* 2014; El-Basyouny, El-Bassiouni 2013; Garrod *et al.* 2002). Nevertheless the most common efficiency parameters of TCM are connected to speed, traffic volume and number of accidents.

Analysis shows that the most common method used to determine efficiency of TCM is a before-and-after study. It assumes that a road is divided into road sections each of them having a TCM implemented on it. Selected efficiency parameters are measured on each road section before implementing TCM and after that. Afterwards these parameters for each road sections are compared to each other and respective conclusions are made. However, despite its popularity, a before-and-after study can give misleading conclusions. It happens because of lack in control for regression-to-the-mean (or long-term trends in accident occurrence) or because of ignoring the presence of potentially important confounding factors such as change in traffic volume and modifications in land use (Granà *et al.* 2010).

Among the other common TCM efficiency research methods are interviews, microscopic traffic simulation as well as comparison analysis. Another research method is the meta-analysis method. It assumes collecting and examining data from different studies on a specific theme in order to identify the common effect of a treatment, when this is consistent from one study to the next. On the contrary, the meta-analysis can be applied to explain the variation when the effect size is a little bit different in all the studies (Granà *et al.* 2010).

TCM efficiency study methods assume acquisition of different efficiency parameters. Some of them can be gathered from databases, for instance the statistic of accidents, while other parameters such traffic volume and vehicle speed should be measured by researchers. In respect of the latter parameter, it is recommended to hide the presence of the data acquisition devices and to avoid possible alterations of natural behaviour of drivers (i.e. reductions of speed), which often occur when devices (such as pneumatic tubes or radar placed on a tripod, etc.) are clearly visible at the side of the street or on it (Pau, Angius 2001). In this context a good option is using GPS trackers placed in the car, but it assumes working conducting experiments with focus groups.

To sum up, according to literature the main goals of traffic calming can be set as improvement of safety of street users and reduction of negative effects of motor vehicles. There is unclear definition of traffic calming efficiency. The latter is mostly measured by means of parameters connected to speeds, traffic volumes and number of accidents. The most widespread method of measuring traffic calming efficiency is before-and-after study, but it sometimes give untruthful results. Other common TCM efficiency research methods are interviews, microscopic traffic simulation and comparison analysis.

3. The new methodology for studies in Estonia

Authors of this paper set a goal to develop and to test a unified methodology that would be suitable for estimating efficiency of TCM implemented in Estonia. Under the term efficiency authors understand practical value of the implemented TCM, i.e. whether they perform their task (for example, reduce speed to desired limit) or not. It should be noted that the goal of researchers was to introduce methodology for studying isolated TCM, not their combinations or traffic calming schemes.

In Estonia TCM are unstandardized. For instance, a speed hump can consist of thermoplastic as well as of asphalt concrete. It can have a height of 10 cm up to 20 cm. It can be marked with white pavement marking, special road posts or road signs, or it can be unmarket at all. Thus it is obvious that even the TCM of the same type have different impact. The new methodology allows comparing efficiency of two or more TCM of the same type (for instance, a horizontal calming measure can be compared to another horizontal measure and a vertical measure can be compared to another vertical measure). At the same time, methodology allows comparing efficiency of two or more TCM of the same type, but with various design parameters (for instance, can be compared to speed hump with a height of 10 cm and speed hump with a height of 20 cm).

In their work authors based on international practice, particularities of traffic management in Estonia and availability of data. These facts were also considered when choosing TCM efficiency parameters. Further the developed methodology is described in detail, starting with efficiency parameters to be measured, proceeding with description of the study method and finishing with the pilot study held in Tallinn to test the methodology.

3.1. Efficiency parameters

Efficiency parameters have been chosen based on results of literature analysis as well as on availability of data. Analysis has shown that the most common TCM efficiency parameters are connected to vehicle speed, traffic volume and accident. Another important parameter is public acceptance. However, incomplete data is available for researchers. For instance, in Estonia there is unreliable traffic incident data for calmed roads. At the same time some parameters such as traffic calming impact on traffic volume can be adequately measured only by means of before-and-after studies. Unfortunately, such studies are untaken in Estonia and as a result there is no "before" data for existing TCM. Unlike the other parameters, researchers can successfully estimate drivers' speed behaviour and public acceptance. The chosen efficiency parameters are described in deeper detail further on.

85th percentile location speed. When estimating drivers' speed behaviour, it makes sense to proceed from the fact that traffic calming aims at choosing safe speed. Safe speed is usually shown by respective traffic signs. Wherein, it is assumed that drivers choose safe speed inparticular when crossing a TCM, but on the whole calmed road section. Therefore, drivers' speed behaviour is estimated in different locations (points). These points have been selected on the basis of based pre-study experiments and are shown on Fig. 1. In Point 1 drivers are approaching the TCM; at this point they have not jet started reacting at it. Speed in Point 3 shows how quickly the first axle of the vehicle runs on the TCM. Speed in the Point 4 shows how quickly the rear axle of the vehicle drives down the obstacle. In Point 6 drives have finished interacting with the TCM. Speeds in Points 2 to 5 are transitional and are used for better understanding of drivers' speed behavior when crossing TCM. 85th percentile location speeds at the Points 1 and 6 are compared to the established speed limit on particular road section. The closer these speeds are to the speed limit, the more efficient TCM is considered to be. 85th percentile speed is chosen as an efficiency parameter, as it is inaffected by extremes and characterizes drivers' speed behaviour in the most objective way. Therefore, this speed parameter suits the set purposes the best.

Location speeds can be measured using contemporary GNSS (Global Navigation Satellite System) equipment. Contemporary GNSS devices work with frequency of 10–20 Hz and allow determining position of vehicle with high accuracy. For instance, *Vbox*-type equipment allows determining position of vehicle with accuracy of 10 cm and determining speed with accuracy of 0.01 km/h.

Change in mean location speed. When speaking about speed, there should be considered not only compliance with speed limit, but also such parameter as smoothness of traffic flow. Drivers should drive without reducing operating speed considerably in front of TCM, as it is connected to increased risk of rear-end collision, difficulties for emergency vehicles as well as excess air pollution and noise level. Therefore, authors propose to estimate change in mean location speeds when running TCM. For these purpose mean speeds are calculated for Points 1–6 (Fig. 1). After that there is calculated change in mean location speeds in relation to mean speed in Points 1 (Fig. 2). The higher is percentage ratio of mean speed in Point 3 to mean speed in Point 1, the more efficient is the TCM. It means that drivers are unnecessary to decelerate operating speed considerably in front on the TCM. Mean speeds in Points 2, 4, 5 and 6 are used for better understanding of drivers' speed behavior when crossing TCM.

Mean speed is chosen here as an efficiency parameter, as it is more informative for the chosen locations than 85th percentile speed. Pre-study showed that extremes undeform results significantly, as the majority of drivers cross TCM with similar speed.

Public acceptance. Literature analysis has shown that along with other parameters public acceptance is also widely used for estimating efficiency of traffic calming. Under public acceptance authors understand attitude of road users towards the TCM. By its nature traffic calming is connected to certain limitations. Therefore, acceptance of a TCM assumes that people are aware of traffic calming goals and are ready to scarify their comfort to some extent

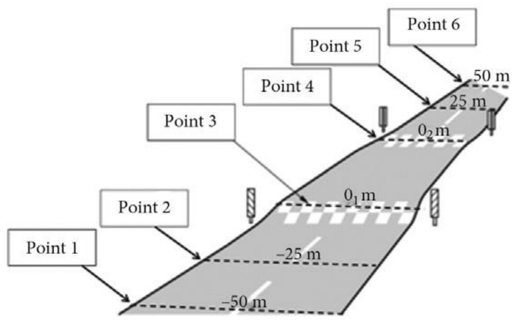

Fig. 1. Scheme of the speed measurement points

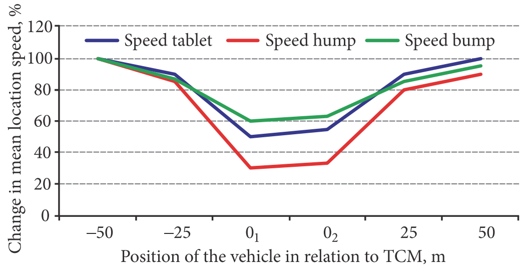

Fig. 2. Change in mean speed when running traffic calming measures (example)

to help these goals achieved. Estimating public acceptance seems to be logical as opinion of the actual road users (although it is very subjective) could be also considered along with the other more objective parameters. The authors propose to make a connection between efficiency of TCM and attitude of road users towards them – the better is public attitude, the more efficient the TCM is considered to be.

Public acceptance is estimated by means of survey with multiple choice questions. Respondents should assess their attitude towards TCMs on bases of five point scale (very poor, poor, fair, good, very good). For each TCM there is calculated the total number of voices for "good" and "very good" and respective rankings is made. The higher is place in this ranking, the more efficient the TCM is. In order to get reliable results, it is highly recommended to accompany questions with pictures of the TCM being studied. The easiest way to get reliable results is to conduct the survey among drivers who participate in the experiment. In such case for logical reasons survey should be conducted after the route is passed.

3.2. Test survey

The proposed method for estimating efficiency of traffic calming measures was tested in an experiment. The experiment was conducted with a sample of drivers, which gender and age structure corresponds to gender and age structure of all the Estonian drivers. The bigger is sample size, the more precise are the results of the experiment. Selected drivers pass a certain route, which has calmed road sections on it. Each section is being dealt with separately representing one TCM being situated on it. It is essential that drivers should not know the real aim of the experiment.

Table 1. Example of ranking efficiency of traffic calming measures

Traffic calming measure	85th percentile location speed	Change in mean speed	Public acceptance	Ranks in total
Speed bump	1	1	2	4
Speed hump	2	3	1	6
Speed tablet	3	2	3	8

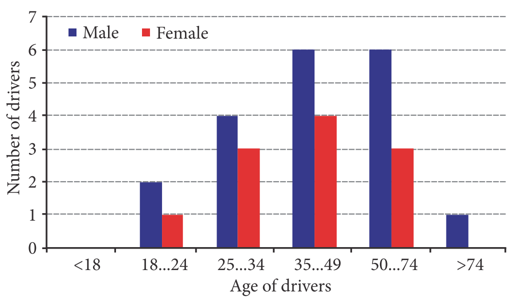

Fig. 3. Age and gender of the drivers who participated in the pilot study

Experiment is conducted in free-flow traffic conditions, i.e. no obstacles like slower moving vehicles or pedestrians crossing the road should influence choice of speed. Ideally, there should be no other vehicles on the route at all. In case of any conditions that affect purity of the experiment, respective data is ignored.

Efficiency of TCM is estimated on the bases of three parameters:

– 85th percentile location speed,
– change in mean location speed,
– public acceptance.

The study method assumes that efficiency parameters are being collected on each road section. For each parameter the TCM are ranked according to their efficiency. If there are three TCM studied like its shown in Table 1, they are ranked by efficiency from 1 to 3 where "1" is the most efficient TCM and "3" is the least efficient TCM. If there are four TCM studied, there would be four ranks where "1" is the most efficient TCM and "4" is the least efficient TCM and so on.

Ranks are summarized. As "1" stays for the most efficient TCM, the TCM should get as less points in total as possible. In the example given in Table 1 the most efficient TCM would be the speed bump. However, one should take into consideration that ranks are given on an interval scale and, therefore, they do not show, but rather indicate the leaders. Sometimes these leaders should be thoroughly compared to reveal the most effective measure. If effectivness of two or more measures is practically the same, an additional efficiency parameter can be applied such as cost of implementing the TCM. It should be noted, that as TCM are unstandardized respective conclusions are applicable only to the TCM studied and to the TCM similar in size, shape and markings.

The experiment for testing the new methodology (pilot study) took place in Tallinn in March 2014 and lasted for one month. During a study there was formed a sample of 30 drivers whose age and gender are shown on Fig. 3. As it comes from the methodology the age and gender structure of the sample corresponds to the age and gender structure of all the Estonian drivers.

During the study TCM were grouped by types (number of studied TCMs in each group is given in brackets) – speed bumps (3), raised pedestrian crossings (3), junctions with priority-to-the-right rule (4) and raised junctions with priority-to-the-right rule (6). All the TCM of the same type have the same parameters and markings. As the TCMs were considered in groups, efficiency parameters for the TCM inside each group were averaged.

In order to exclude factors that could affect behaviour of drivers such as slower moving cars, test trips were held outside rash hours, mainly on the weekends. Speed limit on the calmed road sections studied was 30 km/h. All the drivers were driving one and the same car. They were told that the aim of the experiment is to estimate mean speeds of male and female drivers of different age in different road conditions, so they misunderstand the real aim of the experiment.

Table 2. Mean 85th percentile location speed, km/h

Traffic calming measures	–50 m	–25 m	0_1 m	0_2 m	25 m	50 m
Speed bumps	32.44	29.25	16.98	16.47	30.89	32.60
Raised pedestrian crossings	43.14	37.56	19.90	20.30	33.43	36.70
Junctions with priority-to-the-right rule	46.15	42.18	38.30	39.37	38.76	40.99
Raised junctions with priority-to-the-right rule	37.32	35.94	23.01	23.35	34.01	36.26

Table 3. Mean location speed, km/h

Traffic calming measures	–50 m	–25 m	0_1 m	0_2 m	25 m	50 m
Speed bumps	26.18	24.75	13.11	12.75	26.85	29.77
Raised pedestrian crossings	36.62	32.65	14.76	15.63	27.86	31.07
Junctions with priority-to-the-right rule	38.75	34.75	25.97	29.63	32.62	33.98
Raised junctions with priority-to-the-right rule	32.39	30.86	16.97	19.85	29.87	32.22

Table 4. Public acceptance

Traffic calming measure	Very good	Good	Fair	Poor	Very poor	Do not know
Speed bumps	1	7	12	7	2	1
Raised pedestrian crossings	3	12	12	0	1	2
Junctions with priority-to-the-right rule	1	6	7	8	6	2
Raised junctions with priority-to-the-right rule	2	15	12	2	1	1

Note: numbers correspond to the number of drivers who gave the respective estimations.

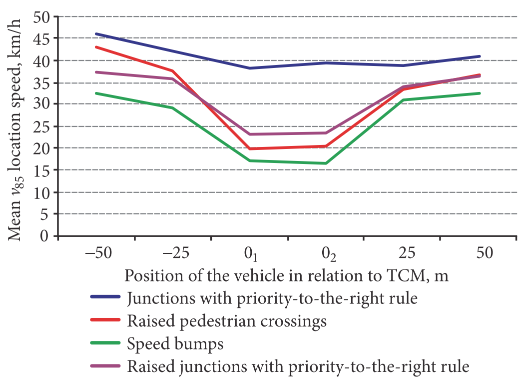

Fig. 4. Mean 85th percentile location speed (speed limit 30 km/h)

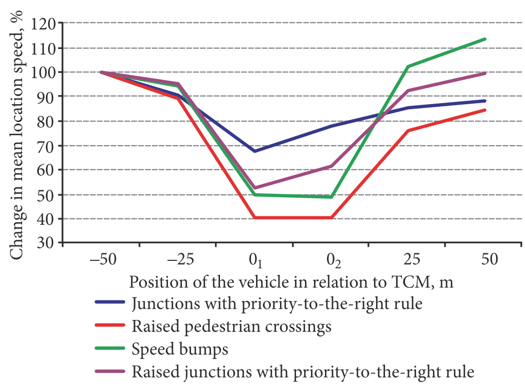

Fig. 5. Change in mean location speed in relation to location speed in Point 1

Speeds were measured by means of *Video Vbox* device. Public acceptance was estimated by means of survey held with all the drivers after each trip. Respective efficiency parameters for each TCM group are shown on Figs 4–6 and are summed up in Table 2.

Study results are given in Table 5. The best total rank that is possible to get is 3 and raised junction with priority-to-the-right rule has 4. Other TCM are far behind with ranks 7 to 9.

Raised junction with priority-to-the-right rule has the best total rank. However, as it was mentioned before, ranks are given on an interval scale and one cannot make single valued conclusions, but has to pay attention to other circumstances besides the total rank.

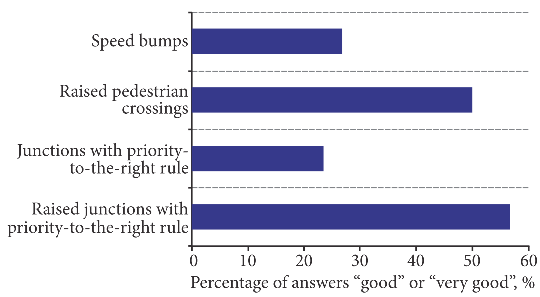

Fig. 6. Percentage of drivers who estimated their attitude towards the TCM as "good" or "very good"

Table 5. Results of the pilot study

Traffic calming measure	85^{th} percentile location speed	Change in mean speed	Public acceptance	Ranks in total
Speed bumps	1	3	3	7
Raised pedestrian crossings	3	4	2	9
Junctions with priority-to-the-right rule	4	2	4	8
Raised junctions with priority-to-the-right rule	2	1	1	4

The study revealed that using raised junction with priority-to-the-right rule and junction with priority-to-the-right rule is connected to traffic hazards. At such junctions drivers have to give way to vehicles approaching from the right. However, vertical visibility before these junctions is severely limited by buildings and fences, so drivers are able to see vehicles on the intersected road only entering the junction (if applied to Fig. 1 drivers start seeing vehicles approaching from the right in point 3). Such junctions are used to calm traffic, because it is assumed that drivers choose low speed when approaching them, otherwise they will not be able to give way. However, study showed that in Point 3 mean speed for junctions with priority-to-the-right rule is 25.97 km/h and mean speed for raised junctions with priority-to-the-right rule is 16.97 km/h. In the first case, stopping distance would be 12.3 m and for the second case, stopping distance would be 7.2 m. If driver enters a junction with such a speed and there is a vehicle approaching from the right, he will not have enough room to stop and will not be able to give way. It means that using junctions with priority-to-the-right rule is potentially connected to hazards.

So, taking into account conclusion made above, study results should be specified. Raised junction could be considered to be the most efficient TCM among the other TCMs studied, but it is recommended to step aside from priority-to-the-right rule and to use rather priority signs ("Main road" and "Give way") or make it a stop-controlled intersection with four-way stops (with "Stop" signs from each direction).

In conclusion, one can state that the pilot study gave trustful results and confirmed that the developed methodology is suitable for estimating TCM efficiency in contemporary Estonian conditions. Although the pilot study aimed at comparing types of TCM, the same method can be used for comparing TCM of the same type. Such a comparison makes sense, if TCM of the same type have different parameters and markings.

4. Conclusions

1. The aim of this study was to develop and to test a unified methodology, which could be used for estimation of efficiency of traffic calming measures in Estonia. Authors see the unified methodology as the first step to understanding efficiency of traffic calming measures of different shape, size and markings, standardizing traffic calming measures and drawing recommendations to using the most effective traffic calming measures under certain conditions.

2. The developed methodology assumes conducting an experiment. It suits for studying isolated traffic calming measures, not their combinations or traffic calming schemes. The experiment was conducted with a sample of drivers who pass a certain road section, which has traffic calming measure. Each road section is being dealt with separately representing one traffic calming measure being situated on it.

3. Effectiveness of traffic calming measures is estimated from the perspectives of vehicles speed and public acceptance. These parameters have been chosen based on results of literature analysis as well as on availability of data. Speeds are determined by means of Global Navigation Satellite System equipment such as *Video Vbox* device situated in the car. Speeds are measured in certain locations and are used to understand how traffic calming measures contribute to compliance with speed limits and to smoothness of traffic flow. The closer is a vehicle speed to the speed limit and the smoother is change in speeds when running a traffic calming measure, the more efficient it is considered to be. Public acceptance, i.e. road user's attitude towards the TCM, is estimated by means of survey held with all the drivers after each trip. The higher is rating of traffic calming measures, the more efficient it is considered to be.

4. The traffic calming measures being studied are ranked according to the efficiency parameters. Ranks indicate the "leaders" and researchers have to study the results of experiments thoroughly in order to make conclusions. These conclusions are valid only for the traffic calming measures studied and for traffic calming measures having the same shape and markings.

5. In order to test the new methodology, a pilot study with a sample of 30 drivers was conducted in Tallinn. The study gave trustful results and proved that the new methodology is suitable for estimating effectiveness of traffic calming measures in Estonia.

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ESTONIAN TRAFFIC BEHAVIOUR MONITORING STUDIES 2001–2016: OVERVIEW AND RESULTS

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Abstract. One of the most significant factors affecting road safety is human. Estonia has improved road safety dramatically since its re-independence in 1991, and among the other reasons, this has happened due to changes in behaviour of road users. Likely, at the same time, there have been annual studies conducted, aimed at measuring specific indicators connected to compliance with road traffic law. As a result, one gets long-term trends in such indicators as compliance with traffic signals, usage of seat belts, yielding to pedestrians at uncontrolled crossings. This paper aims to describe Estonian traffic behaviour studies, analysing their results and pointing out actual problems in traffic behaviour. According to the results of studies, all aspects of traffic behaviour showed positive trends, but these trends are different. Certain indicators such as usage of seat belts have changed dramatically, while others like compliance with traffic signals showed only moderate changes. The foremost problem in traffic behaviour is found out to be ignorance to yield at uncontrolled pedestrian crossings. It is certainly one of the issues to deal with in the context of achieving Estonian strategic goals in road safety.

Keywords: Estonia, behaviour of road users, road safety, safety performance indicators, traffic behaviour, traffic behaviour monitoring, traffic study.

1. Introduction

The road-transport system serves a vital role in the well-being and prosperity of modern societies, yet according to statistics from World Health Organization by 2016, this system is a major source of trauma with more than 1.25 million people killed worldwide. The latter number is comparable to the population of Estonia, which is 1.3 million inhabitants.

Road safety has been amongst the most important topics in Estonia since the 1990s. The first road safety social campaign was held in 1995, and since then similar campaigns have become standard practice. In 2003, the Estonian National Road Safety Program (hereafter ENRSP) was launched, which aimed at reducing the number of fatal accidents from 264 in 2002 to 100 in 2015. This goal was achieved much earlier – already in 2009 – and by 2015 the number of fatal accidents reduced to 67. At the same time, the Annual Average Daily Traffic on Estonian highways increased 1.5 times, and motorization level increased 1.6 times. It indicates that the number of fatal accidents decreased in spite of the rapid development of the Estonian transport sector.

Compared to European statistics, the reduction of fatal accidents in Estonia was happening faster. Figure 1 gives numbers of road accident fatalities per million population, provided by Estonian Road Administration. The number of road accident fatalities in Estonia decreased faster than across the the European Union (hereafter EU) in general. In fact, in 1991 the number of road accident fatalities in Estonia was almost twice as high as on average in the EU, then in 2015, it was 2% less than the EU average. Much smaller sample sizes explain why the Estonian graph is more uneven (correlation coefficient R-squared is 0.846) compared to those for the EU.

Amongst the reasons for rapid improvements in road safety, there is a combination of different factors named. Some of them are on a global scale – such as the development of the car industry and safer fleet as well as economic factors (especially the recession in 2007, which favoured the reduction of fatal accidents nearly twice). Other factors refer to ENRSP 2003–2015, which assumed conducting social campaigns, rebuilding major roads and dangerous road sections, enforcement and lots of other activities. While it is impossible to access the effectiveness of each road safety improvement measure separately, one still gets the general results. In Estonia changes in behaviour of road users are accessed using annual state-wide studies conducted since 2001. By analysing respective data,

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understanding trends and comparing them to other information that is available, it is possible to establish the behavioural problems to concentrate on in future work.

This paper aims to make the analysis mentioned above. The literature review helps to understand the connection of behaviour of road users to road safety and provides a general overview of road safety studies. In the main part of this paper, there is a description of Estonian traffic behaviour studies, and the results of these studies are provided and analysed.

2. Literature analysis

The term "road safety" is considered as the absence of unintended harm to living creatures or inanimate objects (Evans 2004). There are different options for measuring road safety using various parameters connected to road accident fatalities, injuries and crashes (Abbas 2004; Madsen *et al.* 2017; Rundmo *et al.* 2004). Regardless of the variety of respective indicators, road safety research and practice focus on accident prevention. Thus the number of accidents is being considered the main criterion (Gehlert *et al.* 2014). At the same time when speaking about road safety, the accent is being done at the personal damage (accidents resulting in injuries and deaths) rather than at material damage. For instance, a popular safety paradigm, Vision Zero, focuses on incidents, which lead to a person being killed or seriously injured (Johansson, 2009).

A key factor in crash risk is road user behaviour (Rowe *et al.* 2015). Some studies estimate human error to account

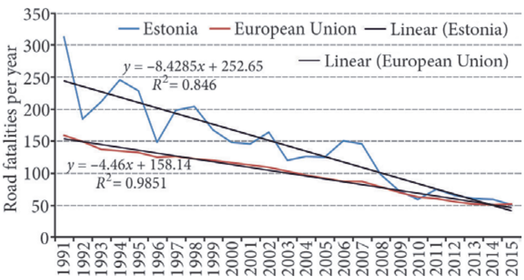

Fig. 1. Road accident fatalities per million population in Estonia and the European Union (1991–2015)

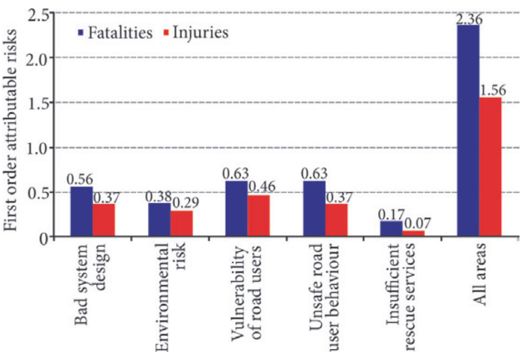

Fig. 2. Importance of risk factors in contributing to traffic accidents and injuries (Elvik *et al.* 2009)

for about 90% of all traffic accidents (Finley *et al.* 2015; Lund *et al.* 2009). If violations of road traffic law did not occur, the number of fatalities could be reduced by 63% (Elvik *et al.* 2009), and in this context, behaviour of road users is one of the most important aspects of road safety (Fig. 2). Drinking and driving, speeding and failing to wear a seat belt are named as major contributing factors to roadway fatalities (Adminaitė *et al.* 2016; Finley *et al.* 2015).

Latest approaches to road safety assume improving road safety climate (Gehlert *et al.* 2014). Road safety climate is understood as the attitudes of road users and perceptions of the traffic in a context (e.g., country) at a given point in time (Özkan, Lajunen 2011). It is assumed that the much positive a road safety climate is perceived, the more behavioural control is be seen, and the fewer traffic violations are indented and committed (Gehlert *et al.* 2014). Unfortunately, empirical research on road safety climate is still in its infancy (Ostroff *et al.* 2013; Zohar 2010). At the same time, there are numerous studies on behaviour of road users.

Studies on pedestrian behaviour mostly focus on safety on zebra crossings. Among the study methods being used, there are field observation, interviews and self-report surveys (Koekemoer *et al.* 2017; Porter *et al.* 2017). Observation often includes pedestrian-vehicle conflict counts on zebra crossings and intersections (Fu *et al.* 2016; Gitelman *et al.* 2017). Ontario Traffic Manual defines a conflict as a traffic event involving the interaction of two or more road users, where an evasive action such as braking or swerving occurs to avoid a collision. Conflicts are used because they are considered as good surrogates for pedestrian collisions (Fu *et al.* 2016).

The literature analysis shows that there are two general approaches to estimating behaviour of drivers, which are self-report survey studies and observation studies. One of the most popular tools for survey studies is the Driver Behaviour Questionnaire (hereafter DBQ), in which respondents indicate how often they commit particular types of aberrations in traffic. Driver Behaviour Questionnaire investigates such components as involuntary errors, involuntary lapses, intentional rule violations and intentional aggressive violations. Intentional rule violations and aggressive violations are considered to be dangerous, errors are judged as "potentially dangerous", and lapses are characterised as "not dangerous" or "silly" (Lawton *et al.* 1997; Mattsson *et al.* 2015). Over the other options, DBQ is used to investigate differences in traffic behaviour between countries (de Winter *et al.* 2016). Among popular observation study methods, there is naturalistic driving, which is considered to reflect more realistic driver behaviour than other alternatives (Bao *et al.* 2015). However, at the same time, this fails to provide information whether aberrations in traffic are intentional or not. In such studies, specialized research vehicles are used to record a significant amount of data continuously from the driver, the car and the surroundings (Valero-Moraa *et al.* 2013). The naturalistic driving method is used for studying different aspects of risky driving behaviours such as speeding, secondary task engagement (for instance, cell telephone dialling), as well as seat belt usage (Bao *et al.* 2015; Simons-Morton *et al.* 2015). As with every study method, both DBQ and naturalistic driving have some restrictions. Weaknesses of DBQ are connected to the subjectivity of answers and issues with sampling methods (Mattsson *et al.* 2015). Limitations of naturalistic driving studies are linked to behavioural modification as drivers know they are under observation, issues with large amounts of data and high costs (Valero-Moraa *et al.* 2013).

As a rule, studies on behaviour of road users are done within short periods and fail to reveal long-term trends. The only exception known to Authors of this paper is Finnish traffic behaviour monitoring, which has been held annually since 1992. The main objective of this observation study is monitoring the behavioural changes taking place in Finland. The idea of Estonian studies on behaviour of road users was taken over from Finland, so these studies have much in common. However, interviews with Finnish researchers dealing with traffic behaviour monitoring revealed certain differences in the methods being used in field observation. As a result, it is impossible to compare Estonian and Finnish data directly, but trends in traffic behaviour in the two countries are still comparable.

To conclude, traffic behaviour is an important part of the road safety paradigm. There are numerous studies on behaviour of road users, which are done mostly using surveys or observation. Most of the parameters being used for assessing traffic behaviour are connected to violations of road traffic law. Literature analysis showed that the absolute majority of traffic behaviour studies are done on an irregular basis and fail to provide long-term trends in behaviour of road users.

3. Traffic behaviour monitoring in Estonia

In Estonia behaviour of road users is assessed using annual studies aimed at revealing trends. Between 2001 and 2005, both survey and observation methods were used, but later survey studies were separated from observation and concentrated on estimating attitude of road users towards the observance of traffic regulations.

Estonian monitoring on behaviour of road users is done within an annual state-wide observation study. There are over 100 fixed observation places on urban and rural roads where data is collected using standardised observation methods. Traffic behaviour is estimated using definite Safety Performance Indicators (hereafter SPI-s) connected to compliance with road traffic law. Each indicator is an average share of violators among respective observation places. As indicators are measured regularly, they provide a good idea about behavioural trends of road users. Since 2001 there have been different SPI-s, and for five of them, there are 16 year-long data rows available. These indicators are compliance of drivers with traffic signals, compliance of pedestrians with traffic signals, yielding to pedestrians at uncontrolled crossings, using turn indicators and using seat belts. There have been other safety indicators used, such as speeds, compliance with traffic signals at railroad crossings and use of safety reflectors by pedestrians, but for different reasons, observations were terminated. For instance, speed monitoring was made using Global Positioning System, and researchers had to drive in a traffic flow with the speed of the flow. This speed was higher than the speed limit, and at some point, Estonian Road Administration decided that they do not have the right to ask researchers break the speed limit and this research was terminated.

Compliance of drivers and pedestrians with traffic signals is observed on intersections, and zebra crossings controlled by traffic lights. Adequate safety indicators are calculated by dividing the number of violators by the total number of drivers or pedestrians observed. Yielding to pedestrians at uncontrolled, crossings is estimated using episodes. An episode is a situation when a driver has to yield to a pedestrian or pedestrians at an uncontrolled crossing. The share of violators is calculated by dividing the number of violators, by the total number of drivers who participated in episodes. Usage of seat belts is observed both on the front and rear seats of passenger vehicles. Data is collected into four categories – driver, front passenger, rear passenger and child. The share of violators is calculated in each category separately (for instance, the number of drivers, who fail to wear a seat belt, is divided by the total number of drivers observed). Usage of turn indicators has been observed using different methods. Between 2014 and 2016, studies were done at roundabouts where the objects of observation were cars driving out from roundabouts. The share of violators was calculated by dividing the number of drivers, who left the roundabout without indicating a turn, by the total number of drivers who left the roundabout. Before 2014, usage of turn indicators was observed near bus stations, and at regular junctions, so one has to admit that respective data incomparable. Therefore, trends in the usage of turn indicators are excluded from the future analysis.

It is important to mention that according to the European Transport Safety Council, drinking and driving, speeding and failing to wear a seat belt are major contributing factors to fatal accidents. At some point in time, official reports of Estonian traffic behaviour studies contained data for all the above mentioned violations, but researchers never dealt with drinking and driving – the police did it. As data rows for drinking and driving and speeding behaviour are rather short, they are being excluded from the future analysis in the scope of this paper.

4. Analysis of the study results

Hereafter, the results of the analysis are based on data available from studies of road users behaviour conducted in Estonia during the period from 2001 until 2016. Authors of this paper are operating only with the available data and cannot calculate confidence intervals or estimate preciseness of the SPI-s in another way. Therefore, the data is taken "as is" and the accent is done rather at trends in behaviour of road users, than at single values.

There are four SPI-s, which is possible to analyse for the period from 2001 to 2016. This is the compliance of drivers and pedestrians with traffic signals, usage of seat belts and yielding to pedestrians at uncontrolled crossings. Trends for all of the four SPI-s are positive (share of violators was decreasing), but these trends are still different. There are there are two groups of SPI-s – those who have shown dramatic changes and those who showed only minor changes.

Usage of seat belts belongs to the first group of SPI-s – in 2001–2016, this indicator showed the very best improvement trend (Fig. 3). Both road administration and police contributed to this using numerous social campaigns and enforcement procedures. Figure 3 shows that the most rapid changes have taken place in categories of grown-ups on rear seats and children. Due to smaller sample sizes, these graphs are more uneven compared to the others (the biggest issue is with grown-ups on rear seats), despite that they show strong improvement trends. Such a rapid change in behaviour of drivers and passengers is explained among the other factors by a poor initial benchmark. General improvement of seat belt use rates happened before 2011 when these rates nearly reached the maximum, and afterwards, the positive trend stagnated. Seat belt use rate in the category of grown-ups on rear seats achieve lower level than the other categories. Taking into account the general trend and small sample sizes, there is a high probability that the decrease in the share of violators among grown-ups on rear seats in 2011–2013 was occasional and is in 2014, the graph just came back to the right place.

Another SPI, which showed a strong improvement trend is yielding to pedestrians at uncontrolled crossings.

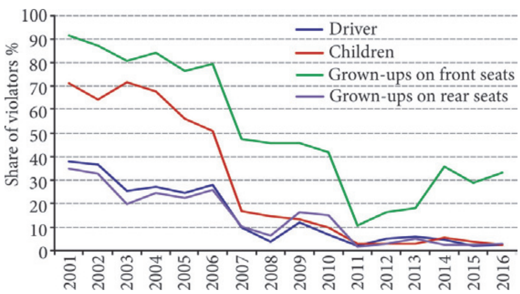

Fig. 3. Seat belt use rate in Estonia (2001–2016)

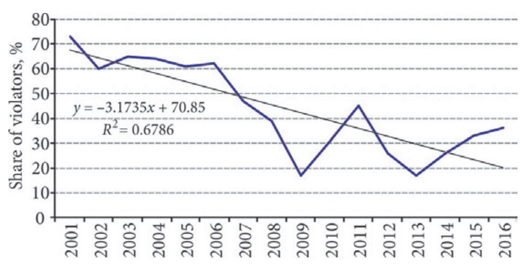

Fig. 4. Yielding to pedestrians at uncontrolled crossings in Estonia (2001–2016)

Respective data is presented in Fig. 4. Despite the fact that graph is uneven and has significant deviations, there is still a clear improvement trend. Deviations are explained by certain methodological issues as well as legislation issues (as for the traffic law 2011, the driver has to yield to a pedestrian who is about to step or has an intention to step at a zebra crossing. In many observational situations it is impossible to judge unambiguously whether the driver had to yield or not). The general improvement trend is very positive. Similarly to seat belt usage, the most rapid decrease in the share of violators took place in the first part of the observation period, but at the same time proportion of violations was far away from the minimum. Starting from 2010, the positive trend stagnated, and it is hard to forecast whether the SPI continues to improve or not.

What was done to improve this aspect of behaviour of drivers? Between 2001 and 2016, Estonian Road Administration regularly launched special social campaigns aimed at increasing safety at uncontrolled crossings, but one has to admit that enforcement failed to support these activities sufficiently. Traffic behaviour studies showed that between 2011 and 2015, the share of drivers who fail to yield to pedestrians was on average 29.4%. However, during the same period, only 0.5% of all the traffic fines were imposed on drivers who failed to yield to pedestrians.

The analysis shows that pedestrian safety is problem number one in road safety in Estonia. Between 2010 and 2016, the share of pedestrians in all the fatal accidents was between 18% and 36%. At the same time according to the European Commission, this proportion in the EU was 22% on average, and it is still considered to be too high. Despite all of the work done in the scope of ENRSP, pedestrian safety is still recognised as the main road safety problem of Estonia. According to Estonian Road Administration, more than 70% of all car-pedestrian collisions are happening on main streets of the four bigger cities (Tallinn, Tartu, Pärnu, and Narva) and most of them – at uncontrolled pedestrian crossings.

The SPI-s of the second group, which in 2001–2016 showed only that minor changes, are compliance of drivers and pedestrians with traffic lights. Figures 5 and 6 give respective data. Both graphs reveal slight improvement trends, but these are much weaker trends that those of the SPI-s discussed previously. To some extent, it is explained by a better initial benchmark – the danger from ignoring traffic signals seems to be very evident, and the situation when the majority of road users are ignoring traffic signals is complicated to imagine. Compared to seat belt usage and yielding at zebra crossings, there is no pronounced difference in behaviour trends before and after 2011 – changes were taking place slowly and gradually. It is worth mentioning that ENRSP did not foresee any particular measures for improving the behaviour drivers and pedestrians at controlled intersections. However, at the same time enforcement made more accent at these violations compared to yielding at pedestrian crossings. In 2011–2015, 7% of all the traffic fines were made to drivers ignoring traffic signals and 4% to pedestrians ignoring traffic signals. Taking into account that 48% of all the traffic fines in Estonia are made for speeding, these percentages are pretty high.

To summarize, trends of behaviour of road users for the period from 2001 to 2016 were analysed in the context of compliance of drivers and pedestrians with traffic signals, usage of seat belts and yielding to pedestrians at uncontrolled crossings. The last two SPI-s showed rapid improvement trends, which stagnated after 2010–2011. The share of drivers and pedestrians ignoring traffic signals also decreased, but positive changes were taking place slowly.

5. Discussion

In this paper, there were highlighted trends of behaviour of road users observed so far. The question arises, what aspects of behaviour of road users to be dealt with to continue improvement of road safety? To answer this question, one needs first of all to have a deeper look at road safety statistics.

In fact, in 1991–2016 road safety in Estonia had improved dramatically, but these judgements are based mostly of on statistics of road accident fatalities. Traditionally road safety research focuses on traffic accidents rather than on the number of fatalities. It is particularly important in the case of small sample sizes, which is an issue for Estonia. Unlike data of road accident fatalities instead, trustful accidents statistics are available only since 2003. Respective data provided by Estonian Road Administration is in Fig. 7. As a reference on this figure, there are also given traffic injuries and fatalities. Since 2011, the number of injuries is slowly increasing, while the number of accidents is not changing. Also, the most significant shifts in fatalities took place before 2010 and in 2016 the number of fatal accidents increased. Given the tiny sample sizes and growing number of injuries, there is a likelihood that the positive trend in traffic deaths, which took place in 2011–2015 will change to negative during the next years.

So, to summarise, reducing the number of traffic injuries is crucial for further road safety improvements in Estonia.

In this paper, the Authors show that behaviour of road users improved in all of the studied aspects, and this played a certain role in the overall improvement of road safety. It is probable that the biggest contribution to road safety improvement was made by changes in seat belt use rates. Major improvements in road safety in Estonia coincide with the improvement of seat belt use rates. At the same time, some studies claim that adoption of lap/shoulder seat belts reduces the risk of life threatening injuries for front seat vehicle occupants by 45%, and the risk of moderate to critical injury by 50% (Chen *et al.* 2016). In this respect, there is a definite potential for improvement of seat belt usage on rear seats (by grown-ups), which is still very far from ideal. However, this is unlikely to have a considerable effect as there are very few vehicles with grown-up passengers in the rear seats. At the same time, the main problem of Estonian traffic is the high number of accidents, especially vehicle-pedestrian collisions. Seat belts are a passive road safety measure that helps to soften consequences of traffic accidents but fails to contribute to decreasing the number of accidents. In this context, yielding to pedestrians plays a more important role. Starting from 2010, the number of accidents at uncontrolled crossings is increasing, and the share of drivers who fail to yield is rather high. Analysis showed that amongst the other reasons, this is due to insufficient enforcement, but at the same time, enforcement is rather difficult because of legislation issues.

Fixing the legislation and bringing more focus of enforcement to behaviour of road users at pedestrian crossings is likely to have a significant effect on road safety

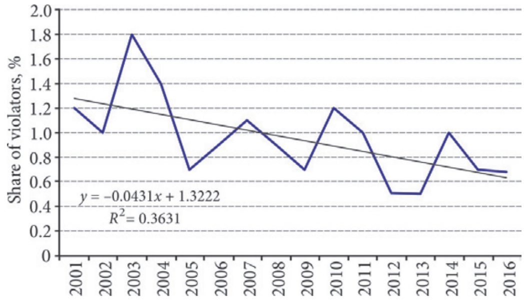

Fig. 5. Compliance of drivers with traffic lights in Estonia (2001–2016)

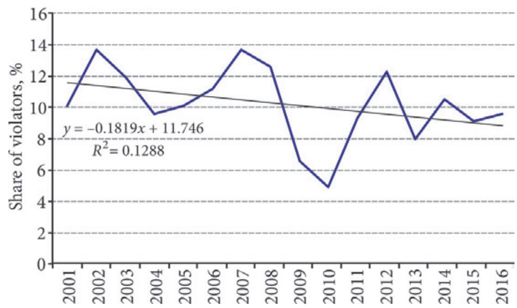

Fig. 6. Compliance of pedestrians with traffic lights in Estonia (2001–2016)

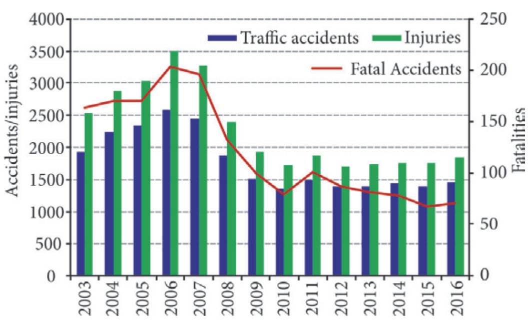

Fig. 7. Road accident fatalities and number of road accidents in Estonia(2003–2016)

statistics. However, in practice, it is rather difficult because of the bureaucracy machine and lack of police resources. One of the options is the application of alternative measures such as safer solutions for uncontrolled pedestrian crossings. The vision of the Authors of this paper for road safety improvement is rebuilding zebra crossings on main streets of bigger cities and applying contemporary Intelligent Transport System solutions to prevent vehicle-pedestrian conflicts. In this context, the question arises of how to assess the effectiveness of these measures in conditions where sample sizes are small, and traffic accident statistics are not sufficiently precise. Solving these issues helps the further improvement of traffic behaviour and with high probability the improvement of road safety.

6. Conclusions

1. Traffic behaviour is an important part of road safety paradigm and improving the behaviour of drivers and pedestrians favours the improvement of road safety.

2. Behaviour of road users is usually estimated in connection with violations of traffic regulations. The most common traffic behaviour study methods are survey and observation. Long-term traffic behaviour monitoring is performed only in Estonia and Finland.

3. Since 2001, Estonia has conducted annual statewide observation studies aimed at understanding trends in traffic behaviour. This behaviour is estimated through compliance with road traffic law. As for 2016, there are long-term trends available for compliance of drivers and pedestrians with traffic signals, usage of seat belts and yielding to pedestrians at uncontrolled crossings.

4. In 1991–2016, the usage of seat belts has improved dramatically. General improvement in seat belt usage happened before 2011, when most of the respective rates nearly achieved the maximum. At the same time usage of seat belts on rear seats has also significantly improved, but is still far from ideal.

5. Despite positive trend in yielding to pedestrians at the uncontrolled crossing, which took place between 2001 and 2009, the number of respective traffic accidents is increasing, and pedestrian safety is considered to be problem number one for road traffic in Estonia. One of the probable reasons for that is insufficient enforcement.

6. Behaviour of drivers and pedestrians at controlled intersections has shown minor improvements. Respective trends are slow, which can be explained besides the other things by specifics of violations at controlled intersections and absence of advocacy work.

7. It is crucial to reduce the number of traffic accidents, especially those, which lead to injuries, to continue improvement of road safety in Estonia. One of the options for achieving this goal is improving the behaviour of road users in the part of yielding to pedestrians at uncontrolled crossings.

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ORIGINAL PAPER

ESTIMATING THE POTENTIAL OF A WARNING SYSTEM PREVENTING ROAD ACCIDENTS AT PEDESTRIAN CROSSINGS

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ABSTRACT. **Background:** The safety of pedestrians is one of the main traffic safety issues today and despite measures being applied, the number of pedestrian deaths in traffic is not changing. According to the Pareto Rule, 80% of consequences come from 20% of the causes and here the question arises whether we have already used these 20% of the most efficient measures. Todaythe European Union (EU) puts big hopes are on contemporary technologies, such as Advanced Emergency Braking Systems (AEB) and cooperative intelligent transport systems (C-ITS). This decade, we can expect smarter vehicles with automatic brakes, and smarter infrastructure which can communicate with vehicles. Along this other profits technological development provides new opportunities for improving pedestrian safety. One of the most promising solutions is deployment of C-ITS systems at uncontrolled crossings. It would monitor the situation and warn the road users of potential dangers as well as make the vehicles brake automatically. However, before making large investments into this field, one has to be sure that this approach will work. The aim of this paper is to describe typical vehicle-pedestrian crash scenarios and to estimate whether a C-ITS warning system is able to prevent them. Research estimates the potential of this system and provides insights to its must-have features.

Methods: To understand the situations in which the warning system should function, researchers carried out traffic conflict studies at uncontrolled crossings with traffic filmed in both winter and summer. They determined and described serious conflicts and, based on their scenarios, classified them into three types. Then, researchers selected the most critical conflict of each type and analysed whether warning signals can be provided to the vehicle and the driver early enough to prevent collisions. For these purposes, researchers used a modelling software for traffic accident investigation. To access the efficiency of the C-ITS warning system, researchers estimated the probability of preventing collisions and used the efficiency parameters of classical traffic calming measures.

Results: The C-ITS warning system has good potential in preventing vehicle-pedestrian collisions at uncontrolled pedestrian crossings. It is remarkable and very promising that it would be able to prevent all types of conflicts analysed in the scope of this study by warning AEB-equipped vehicles. Warning the driver would be also effective, but the system work will largely depend on the quality of warning signals. An effective C-ITS warning system should be capable of predicting the trajectories and acceleration of road users as well as calculating the stopping distance of vehicles based on the coefficient of static friction. Study showed that in some cases, the system will have to give false positive alarms, but the fewer such alarms will be given, the more efficient the system will be. A disturbing or annoying C-ITS warning system cannot be considered effective.

Conclusions: Road accident statistics contain general data about vehicle-pedestrian collisions at uncontrolled crossing, but there is few information about behavioral patterns leading to accidents. Based on large-scaled traffic studies, researchers were able to determine these patterns and described how road users act when being involved in a dangerous situation. This knowledge helped to model typical vehicle-pedestrian collisions as well as their possible scenarios. Researchers used the conflict models totest the C-ITS warning system and to understand its efficiency. The study results were implementedin a prototype that has been developed in Estonia and is being tested it in real traffic conditions of a smart city in the scope of the Finnish-Estonian project "FinEst Twins".The next steps are to analyze the test resultsand to conduct research to understand how to warn drivers (and pedestrians) most effectively.

Key words: AEB, C-ITS, traffic conflict, traffic study, uncontrolled pedestrian crossing.

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INTRODUCTION

The safety of pedestrians and other vulnerable road users is one of the main traffic safety issues today. Modern vehicles offer a high level of protection to drivers and passengers, but pedestrians and cyclists are left with significantly lower chances to survive in a road accident. In Europe, 22% of all road fatalities are pedestrians [European Commission 2018].

Analysis of 16 years' long trends in the behaviour of road users indicated that pedestrian safety is the most crucial problem in road safety in Estonia [Ess and Antov 2017]. According to the Estonian Road Administration, 24.6% of traffic accidents registered in Estonia in 2011–2019 were vehicle-pedestrian collisions and 40.4% of them occurred at uncontrolled pedestrian crossings. Half of all the vehicle-pedestrian collisions happened in Tallinn.

Pedestrian safety is an important topic not only for Estonia, but for the entire EU. Figures show that the decrease in the number of vehicle-pedestrian crashes (as well as other crashes) stagnated in 2012 [European Commission 2019a], which made the achievement of Vision Zero targets for 2020 impossible. To overcome these difficulties, the EU puts big hopes on modern technologies, such as AEB, which can decelerate and stop the vehicle automatically, and C-ITS, which allows vehicles to communicate with each other, with the road infrastructure, and with other road users [European Commission 2019b]. From 2015, all new heavy-duty vehicles are equipped with AEB [European Commission 2016] and from 2022, all vehicles, including passenger cars, will also be equipped with AEB [Regulation (EU) 2018/858]. Euro NCAP has already included AEB systems to their tests, but it must be mentioned that these tests are done in almost ideal conditions – dry road, no precipitation, visibility at least 1 km [European New Car Assessment Programme 2017].

In real-life situations on uncontrolled pedestrian crossings, the efficiency of AEB is limited by the performance of the sensors of vehicles (radar, lidar, camera) and by the fact that they cannot 'see' behind the obstacles. However, a smart pedestrian crossing (SPC) can be applied. This is a C-ITS system that monitors the surroundings of pedestrian crossings from multiple locations and detects potential danger much earlier than the sensor of a vehicle. The system could warn both the vehicles and the drivers of potential danger. The AEB could use the signal received from the SPC as a trigger for automatic braking. This article aims at estimating the potential of such an SPC for preventing vehicle-pedestrian crashes at uncontrolled pedestrian crossings. For this purpose, researchers determine typical conflict situations at uncontrolled crossings in Tallinn, using a modelling software to 'convert' them to collisions and estimate whether a smart C-ITS device could prevent them or not.

TRAFFIC CONFLICTS AND SIMULATION

Crashes in traffic result from many objective factors operating together and in safety studies, it is essential to estimate the cause-effect relationship of a crash on a time scale [Elvik et al. 2009]. Crash reports from police databases do not provide precise information for analysis, but this can be done by means of traffic conflict studies. These studies assume that there are sufficient similarities between actual accidents and 'almost accidents' of the same type [Polders and Brijs 2018]. Traffic conflicts are observational situations in which two or more road users approach each other in space and time to such an extent that a collision is imminent if their movements remain unchanged [Svensson 1998]. Traffic conflict studies measure the number of conflicts and their severity, validate with traffic crash data, classify them, and find out precursors to crashes [Tarko 2012].

Conflicts are determined by means of special parameters or indicators which help to estimate the severity of a critical situation. The most common parameter in such studies is the time to collision (TTC) and its variations. TTC is the time until a collision between the vehicles would occur if they continued on their present course at their present rates [Laureshyn et al. 2016]. During the conflict, the TTC value varies over time, and therefore, a proper evaluation requires a continuous monitoring with the identification of the critical value. Usually, this is the lowest TTC value in the interaction – the minimal time to collision (TTCmin). As a rule, time TTCmin under 1.5 s is considered critical. However, for conflicts between vehicles and vulnerable road users, the proximity to a collision is only one dimension of its severity; the potential consequences (nearness to a serious personal injury) should be also taken into account [Polders and Brijs 2018]. These consequences can be estimated in relation to impact speed and a probability of death or injury [Astarita et al. 2019].

TTC can be used only if the trajectories of the road users are crossing and therefore do not take into account potentially dangerous ‘near misses’. For this reason, some studies use a variation of TTC, placing emphasis on the second (later) road user. The respective conflict parameter is called T2. It shows the expected arrival time of the second road user to the potential collision point. T2 can be calculated also in the case of a non-collision course, which is an advantage compared to TTC [Laureshyn et al. 2016]. One more conflict parameter used in some studies is the deceleration to safety time. It shows the nearness to a collision through the minimal necessary deceleration for a driver to avoid the collision [Hupfer 1997]. Some parameters take into account not only deceleration, but also the potential impact speed, i.e. the speed at the moment of the collision supposing a braking deceleration [Johnsson et al. 2018].

Traditionally, traffic conflict studies were carried out using trained observers in the field. As this approach involves a risk of missing or misjudging conflicts without providing an option to look through them again, video recordings of the sites are often collected. However, a manual analysis of the video footage is often very time-consuming. Researchers have thus developed video analysis software for the automated tracking of road users to identify traffic conflicts automatically to reduce the time spent on analysing the video footage. The tool is a so-called watchdog system that detects events that should be investigated further while discarding the parts of the video with no activity of interest [Madsen and Lahrmann 2017]. One example of such software is Road User Behaviour Analysis (or RUBA) developed at Aalborg University. The performance of such systems depends on weather and light conditions, occlusion, shadows, and complex traffic scenes with multiple road user groups sharing the same space. Hence, a human-in-the-loop is therefore still necessary [Madsen and Lahrmann 2017]. To calculate conflict parameters (TTC and others), researchers use software which allows the extraction of road user positions frame by frame and calculating their speeds, accelerations, and a number of surrogate indicators of safety, such as TTC. An example of such software is the video analysis tool T-Analyst developed by the University of Lund [Bulla-Cruz 2020].

Classical conflict studies investigate the cause-effect relationship of a crash, but do not consider possible scenarios provoked by errors of conflicting road users and crash consequences. This can be done by means of microsimulation, which is a traffic simulation approach to reproduce all dynamic interactions among vehicles in fine detail. The state-of-the-art microsimulation converts conflicts traffic conflicts to crashes, simulates potential human errors and crash consequences [Astarita et al. 2019].

DEVELOPED METHODOLOGY

To assess the potential efficiency of SPCs in preventing vehicle-pedestrian collisions, a large-scale traffic conflict study was held. Traffic at uncontrolled crossings was filmed with high-resolution cameras and the video material was analysed to detect serious vehicle-pedestrian conflicts. Observation places have been selected according to crash statistics and these were the most dangerous crossings in Tallinn. The selection following criteria was:

- number of vehicle-pedestrian collisions in 2012–2018: not less than three;

- no significant changes in traffic management from 2012;
- different types of crossings (number of lanes, refuge island);
- suitability for camera placement (a pole or building near the crossing where it is possible to place the camera).

As a result, for the purposes of the study, ten uncontrolled crossings of the following types have been selected:

- three crossings on 1 + 1 roads without a refuge island;
- four crossings on 2 + 2 roads with a refuge island;
- three crossings with 3 lanes in one direction with a refuge island.

The traffic study consisted of two parts – the pilot study (held in winter 2017–2018) and the main study (held in summer 2018). The pilot study revealed several issues with cameras and batteries. Action cameras with power banks were used, but this approach did not justify itself, as the workload of changing power banks and memory cards did not correspond to the number of conflicts detected. During the main study, researchers used upgraded systems, which consisted of a security camera with a Wi-Fi connection and a vehicle battery stored in a box placed on the street pole. Cameras were placed at the height of approximately five metres and a Wi-Fi connection was used to tune the filming angle.

In each location, traffic was filmed for two weeks during the working days, making up 10 days for each location in total. The video material was analysed both using the semi-automatic software RUBA and by manual review performed by a team of trained staff. However, the share of semi-automatic analysis was very low due to the fact that the software produced too much 'noise' in the timestamps, because it was impossible to place cameras at a height that would provide a filming angle optimal for the software.

The research highlighted and described serious conflicts. In most cases, the severity of conflicts was determined by a team of researchers visually, taking into account nearness to serious injury for the pedestrian. In case of doubt, researchers proceeded from the possible impact speed – a conflict was classified as serious if the impact speed was 20 km/h or higher. This threshold was chosen because respective studies [Roséna et al. 2011] show that starting from this impact speed, the health risk for pedestrians starts increasing. The impact speed was calculated according to the formula below [Bosch automotive engineering 2007].

$$V_{impact} = V_{vehicle} - (TTC_{min} - t_r - t_a - 0{,}5 \cdot t_s) \cdot \varphi_x \cdot g \quad (1)$$

where:

t_r is reaction time (1 s)

t_a is response time (0,15 s for passenger cars)

t_s is pressure build-up time (0,36 s for passenger cars)

φ_x is coefficient on static friction

g is gravity constant

Parameters for the calculations were collected with the help of T-Analyst. This software allows combining orthophotos and a camera view to create a system of coordinates and calculate the speed of road users, TTC, T2, and other conflict parameters (see Figure 1). In case of 'near-misses' when there was no collision course and therefore it was impossible to calculate the TTC, researchers used T2 as the closest possible value to TTC.

Fig. 1. Determining conflict parameters with T-Analyst

All the serious conflicts determined were classified into types based on the similarity of their circumstances. For each conflict type, researchers determined the most serious conflict. This was done by means of TTC_{min} and impact speed as well as the risk of serious injuries. These conflicts were modelled using the PC-Crash software, which is used for traffic accident analyses. It allows animating pre-accident situations and 'see' it from different perspectives (see Figure 2). To create PC-Crash models, researchers used data retrieved from T-Analyst (the trajectories, speeds, and accelerations of road users). Conflicts were 'converted' to collisions using PC-Crash. Researchers investigated them and determined the timing of C-ITS warning signals. It was analysed whether the timing of warning signals is realistic and whether the driver could see the warnings and react in a proper manner (brake with maximum deceleration). After that, researchers added the reactions of typical road users to conflict models and analysed if they lead to additional hazards.

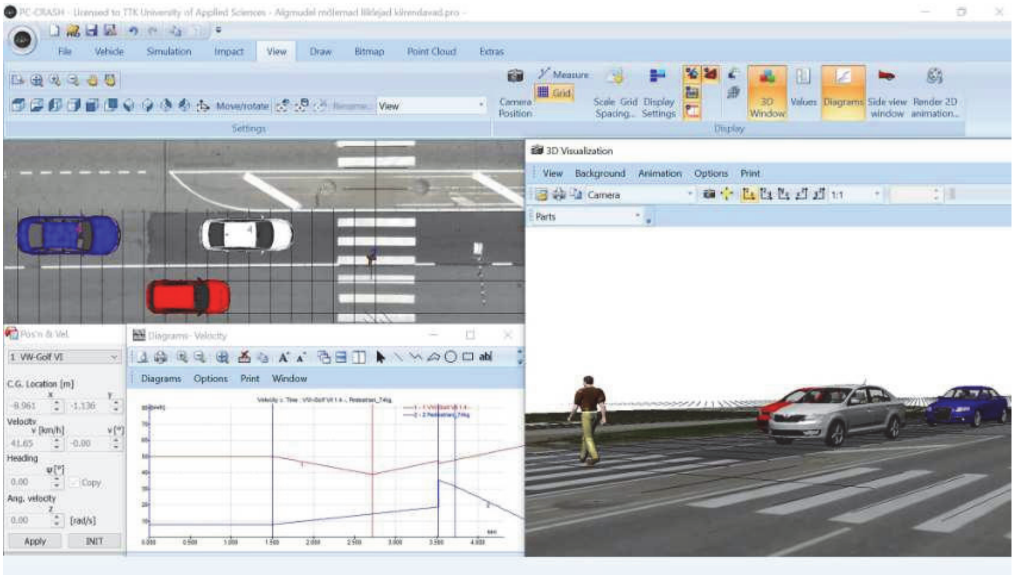


Fig. 2. Using PC-Crash to analyse traffic conflicts

THE STUDY

Conflict study

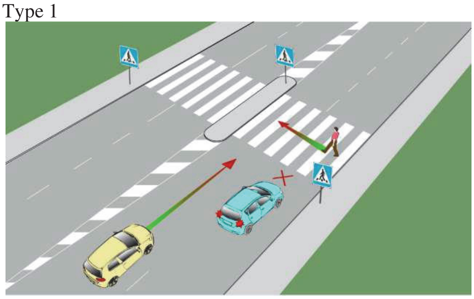
Researchers collected and analysed 1512 hours (approx. 2 months) of video material. A total of 283 hours were recorded during the pilot stage and 1229 hours during the main stage of the study. A total of 90 serious conflicts were determined. Sixteen of them were unclassified (conflicts with alarm vehicles, unusual pedestrian behaviour, vehicle-cyclist conflicts, etc). A total of 74 serious conflicts were selected for analysis. All of them took place at pedestrian crossings situated at multi-lane roads, as no serious conflicts were determined on 1 + 1 roads.

Serious conflicts were classified into three types (see also Figure 3):

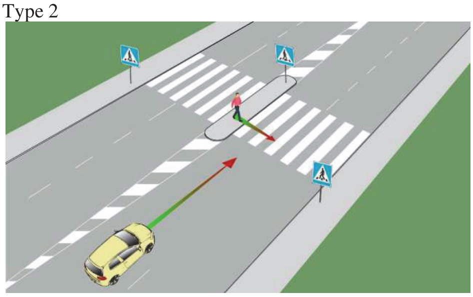
– one vehicle stops before the crossing while another vehicle in the next lane conflicts with the pedestrian (Type 1)
– a vehicle conflicts with a pedestrian who is about to step to the crosswalk from the sidewalk or refuge island (Type 2)
– a vehicle conflicts with a pedestrian who is already crossing the carriageway (Type 3)

The principal difference between Types 2 and 3 lies in the fact that for Type 2, the pedestrian has not yet started crossing the carriageway and the driver may hope that the pedestrian stops before the zebra. For Type 3, the pedestrian is already on the carriageway and the situation is potentially more dangerous.

Type 1



Type 2



Type 3

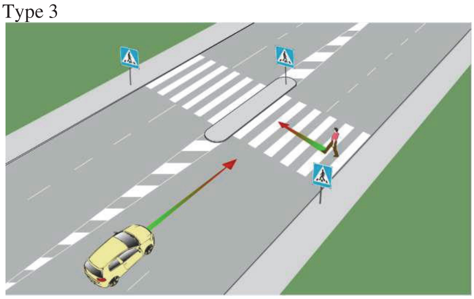


Fig. 3. Typical conflicts

It should be mentioned that between these types of conflicts there have been determined situations when a pedestrian was approaching both from the right and from the left. As it does not change the essence of the conflict, researchers ignored the direction of motion of pedestrians in their classification.

Half of serious conflicts correspond to the first type, one third to the third type, and the rest to the second type (see Figure 4). Much to our regret, due to strict personal data protection legislation, it was impossible to get detailed description of pedestrian accidents from the police, which made conflict validation with real crash data complicated. Researchers were provided only with superficial accident descriptions, which contained little to no detail. Researchers analysed the descriptions of 40 accidents which took place in 2012–2018 at the same multi-lane pedestrian crossings where the traffic conflict study has been conducted. Five vehicle-pedestrian collisions corresponded to the first type of conflicts, also five to the second, and two to the third type. Due to a lack of information, it was impossible to classify the remaining accidents, but analysis showed that conflicts of all three types ended with real traffic accidents.

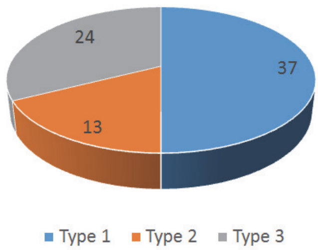


Fig. 4. Serious conflicts by types

Microsimulation and analysis

For every conflict type, researchers selected the most serious conflict and analysed it in T-Analyst and PC-Crash. Researchers used T-Analyst to determine road users' trajectories, speeds and accelerations as well as TTC_{min} and T2. Afterwards this data was imported to PC-Crash to create conflicts' models which were used to analyse capability of the SPC to prevent collision.

The type 1 conflict is presented on Figure 5. The vehicle initially moved at a speed of 36.4 km/h and the pedestrian at a speed of 7.9 km/h. This situation is interesting because of its dynamics. Analysis showed that the dense traffic flow caused visual distraction, so the driver and pedestrian saw each other at the very last moment. In a critical situation, the driver started decelerating while the pedestrian started running and jumped away from the approaching vehicle. TTC_{min} was 1.0 s.

Fig. 5. Model of the type 1 conflict

In case of a collision, the vehicle would have hit the pedestrian at a speed of 34 km/h. Taking into account the speed and road conditions, the SPC should warn the driver at least 18 m before the crosswalk. This distance is relatively small, and one can admit that the driver would see the warning signal even when moving in a dense traffic flow. However, it should be taken into account that the driver does not see the pedestrian ahead and the question arises whether they react in an expected manner (brakes with maximum deceleration)?

In the case of an AEB system, the warning signal should be given at least 9 m before the crosswalk. Because of many moving objects hiding the pedestrian from the sensors of vehicles, the AEB system may not detect the pedestrian in time, especially in difficult conditions (precipitation, fog). For this type of conflicts, the vehicle would need additional input from the SPC.

The type 2 conflict is presented on Figure 6. The vehicle moved initially at a speed of 57.6 km/h (while the speed limit is 50 km/h) and the pedestrian at a speed of 5.4 km/h. It was snowing and the road was slippery. The conflict took place in the dark, but the road lighting was on and the crosswalk had additional illumination. There were no obstacles that could limit the driver's field of view. The driver assessed the situation incorrectly and when it was too late for braking, took the decision to accelerate and pass the crosswalk before the pedestrian. The pedestrian noticed the vehicle just before stepping to the carriageway from the refuge island. He stopped abruptly, slipped, and nearly fell down. $T2_{min}$ was 1.24 s.

Fig. 6. Model of the type 2 conflict

In case of a collision (for instance, if the pedestrian started accelerating), the vehicle would hit the pedestrian at a speed of 57.6 km/h. Taking into account the speed and road conditions, the SPC should warn the driver at least 41 m before the crosswalk. This raises a number of questions. Would the driver notice a warning signal located in front of the crossing? Would the speeding driver realise the danger and react to the warning signal, which is located so 40–50 m ahead? Would the driver take into account road conditions when braking? To sum up, there is certain doubt that warning the driver would have the expected effect in this situation.

In the case of the AEB system, the warning signal should be given at least 27 m before the crosswalk. In difficult weather conditions, the vehicle may not detect the pedestrian with its own sensors and may need additional input from the SPC.

The type 3 conflict is presented on Figure 7. The vehicle initially moved at a speed of 41.4 km/h and the pedestrian at a speed of 6.5 km/h. It was snowing and the road was slippery. The pedestrian moved along the road off the pavement (the trajectory is shown on Figure 7 with the blue line). He did not turn his head before crossing the road and because of his hood, he did not see the approaching vehicle in his peripheral vision. The driver started decelerating after the pedestrian had stepped to the crosswalk. Due to the late reaction, the car passed just in front of the pedestrian. $T2_{min}$ was 0.27 s.

Fig. 7. Model of the type 3 conflict

In case of a collision, the vehicle would have hit the pedestrian at a speed of 42.5 km/h. Taking into account the speed and road conditions, the SPC should warn the driver at least 26 m before the crosswalk. In the case of the AEB system, the warning signal should have been given at least 16 m before the crosswalk. In both cases, the warning should be given before the pedestrian changes direction to cross the road, i.e. before it is clear that he intends to step on the crosswalk. This case shows that in some situations, the SPC should give false positive warnings, especially in locations where the pavement is situated just next to the carriageway and the pedestrian can either cross the street or proceed walking parallel to it. Both for drivers and for AEB-equipped vehicles false positive signals would mean that sometimes they will have to brake 'just in case'. However, this speed behaviour is typical for defensive driving style and many drivers are doing it in real traffic every day.

Coming back to the potential efficiency of SPC, in this situation, it is likely to prevent collision by warning the driver, as he or she sees the pedestrian, but postpones braking for the moment when it is too late. A warning signal would help to take a decision in time. It is important to note that in this particular case, one cannot expect the AEB to react in time without a warning signal from the SPC. As the pedestrian changes his direction suddenly and is very close to the crosswalk, the AEB will not consider him a conflicting object, before he actually turns and starts crossing. As a result, the vehicle will start decelerating later than needed. This means that the SPC should be 'smart' enough to predict the trajectories of pedestrians and to assess possible risks. It sets high standards to its software and processing power. Most probably the system should be based on machine learning, i.e. it should 'learn' the behaviour of road users from real traffic.

RESULTS

According to analysis performed withing microsimulation for all the situations studied, researchers answered the question 'Would an SPC help to prevent a collision?' Results are presented in Table 1.

Table 1. Ability for preventing collisions by type

Type of warning	Type 1	Type 2	Type 3
Warning the driver	likely	doubtful	likely
Warning the AEB-equipped vehicle	yes	yes	yes

Source: own work

Results show that the SPC will work most efficiently by warning AEB-equipped vehicles – they do not fail to react, and their pre-braking time is shorter. At the same time, in all the three situations studied, the AEB might need additional input, especially in case of visual distractions and difficult weather conditions. Warning the driver is assessed rather pessimistically, as with our current knowledge, we cannot be sure that the driver will react at the warning signal as expected. If we warn the driver, he or she might not notice the warning signal or react properly. At the other hand, conflict study showed that 53% of drivers involved in serious conflicts did not take any action. They might have assessed situation incorrectly or were distracted, so the warning signal might be useful. In this context, the efficiency of the SPC will highly depend on the efficiency of warning signals (first of all, on their type and location).

To sum up, from the cases studied, one can conclude that SPCs have a good potential to prevent typical vehicle-pedestrian crashes at uncontrolled crossings. Warning the vehicles has better potential than warning the drivers, because the efficiency of SPCs will largely depend on the quality of warning signals.

FEATURES TO PROVIDE EFFICIENCY OF THE SPC

In the scope of their study, researchers determined certain 'must have' features for an efficient SPC. First, an important feature for the SPC is calculating the stopping distances. If the road is dry and the vehicle's speed is 50 km/h, the SPC should warn the driver at least 30 m before the crossing, but in case of snow on the carriageway, 68 m before the crossing. The system should be smart enough to know the coefficient of static friction and to warn road users and vehicles in time.

Secondly, the SPC should predict road users' behavior. Analysis of traffic conflict showed that road users behave in different ways in pre-crash situations. The most common behavior for drivers is taking no action at all (53%); however, 1% start accelerating. The most common behavior for pedestrians is deceleration (74%), while 7% start accelerating. Researchers added the most typical behaviour patterns to traffic conflict models and checked if these patterns increase collision risks. Results are presented in Table 2. Impossible scenarios are marked with '-'.

Table 2. Potential probability for preventing collisions by type

Driver	Pedestrian	Type 1	Type 2	Type 3
Does nothing	Accelerates	No collision	Collision	Collision
Accelerates	Does nothing	Collision	No collision	High collision risk
Accelerates	Accelerates	Collision	High collision risk	Collision
Turns away	Does nothing	-	No collision	-
Turns away	Accelerates	-	No collision	-
Turns away and accelerates	Does nothing	-	No collision	-
Turns away and accelerates	Accelerates	-	No collision	-
Turns away and decelerates	Does nothing	-	No collision	-
Turns away and decelerates	Accelerates	-	High collision risk	-

Source: own work

Results show that in most cases, the acceleration of a conflicting road user leads to collision or high collision risk. Analysis of Type 3 conflict showed that the SPC should be capable to predict pedestrian's trajectory. At the same time modelling typical behaviour patterns of road users indicate that to prevent collisions effectively the SPC should also predict possible acceleration of the driver and the pedestrian.

In the third place, the SPC should be orientated not only to the vehicles, but also to the road users. The system will be most efficient for the AEB-equipped vehicles, but their share in traffic will be relatively low during the next decade. According to Estonian Transport Administration, the average age of a passenger car in Estonia is 12.9 years. The total number of passenger cars is approximately 910,000, while the number of annually sold new cars (which will be all AEB-equipped starting from 2022) is approximately 26,000. It means that the SPC should warn not only vehicles, but also drivers and its efficiency will largely depend on the warning signals. This topic needs additional research. It is important to understand which warning signals are most efficient for drivers and if it makes sense to warn pedestrians as well. One of the most important questions is where will road users look when they see (or hear) the warning? Is there a risk that they will pay attention only to the warning signal and fail to see the hazard?

How to measure efficiency of the SPC

A question arises how to estimate or measure efficiency of the SPC. This can be done by comparing number of collisions or traffic conflicts before and after implementing the SPC, but this approach will be very time-consuming. Both collisions and conflicts are rare events in traffic and getting a trustful sample size would be complicated, so alternative approach can be used.

In a broad sense, the SPC is a new generation traffic calming measure (TCM). Both the SPC and classic TCMs serve the same purpose – make drivers choose safe speeds – with the only difference being that classic TCMs do not 'understand' if there is a risk of collision or not. Therefore, when analysing the efficiency of the SPC, one can proceed from TCMs.

Ess and Antov proposed methodology to estimate the effectiveness of TCMs from the perspectives of vehicle speed and public acceptance [Ess and Antov 2016]. It assumes measuring speeds in certain locations in front and behind the TCM and calculating 85th percentile location speed and mean location speed. On the one hand, the choice of speed should guarantee traffic safety, but on the other hand, also smoothness of motion. In the context of the SPC, it means that the vehicle should reduce speed to the needed extent, but only if there is direct need for that. Warnings should not be given 'just in case' – the number of false positive signals forcing to brake should be as low as possible. The SPC is feasible to measure both speed parameters and share of false positive warnings automatically and use this data to improve its algorithms.

Public acceptance, i.e. road users' attitudes towards the TCM, is also taken into account – the better this attitude, the more efficient the TCM. Drivers and pedestrians should understand that the SPC is implemented not to disturb, but to help them. The better is their attitude towards the SPC, the more efficient it is. Public acceptance is estimated by means of survey.

Methodology described above can be used to estimate efficiency of the SPC, but also to compare different warning algorithms to improve road safety.

CONCLUSIONS

The general conclusion is that the SPC has good potential to prevent vehicle-pedestrian collisions at uncontrolled pedestrian crossings.It defenetly makes sense to invest money and time in research and development. The most effective is to warn AEB-equipped vehicles, as they react faster and brake automatically. Most importantly, in many situations, AEB will need input from the SPC and will not be able to prevent collision on its own. At the same time cooperation between AEB and C-ITS system would be able to prevent all types of conflicts analysed in the scope of this study.

Warning the drivers also has good potential, but much will depend on the quality of warning signals. Additional research is needed to understand how to warn drivers in the best way and whether it makes sense to warn the pedestrians along with the drivers. At the same time, it is important to warn not only the vehicles, but also the road users, as the share of AEB-equipped vehicles is rather small and will increase slowly.

To work efficiently, the SPC must be able to predict change in the speed and direction of road users as well as calculate the braking distance of vehicles according to the coefficient of static friction of the carriageway. False positive warnings are inevitable, but the number of such warnings should be as low as possible. The attitude of road users towards SPC should be positive, otherwise it cannot be considered effective.

The study results were used in working out the first prototype of the C-ITS warning system. At the moment of publication, it is being tested in Tallinn in the scope of Finnish-Estonian project "FinEst Twins", which aims at selecting smart city pilots with strong scientific, innovative and commercial potential for future studies [FinEst webpage]. The C-ITS prototype is equipped with cameras and sensors and uses narrow artificial intelligence algorithms to analyse the traffic situation and detect potential vehicle-pedestrian conflicts [Bercman Technologies webpage and webpage of the city of Tallinn]. The project will end last from 01.01.2020 to 31.08.2023.

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