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**TESI DI LAUREA**

# SAFETY EVALUATION OF INTERACTIONS BETWEEN CYCLISTS AND MOTORISED VEHICLES THROUGH THE APPLICATION OF SURROGATE MEASURES

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# SUMMARY

# ABSTRACT

The interaction between cyclists and motor vehicles is a significant concern for road safety. Numerous studies have investigated the factors contributing to road collisions involving bicycles, with most highlighting the importance of infrastructure characteristics. It is important to note that outcomes have not always been consistent. The lack of established procedures for extracting safety-relevant indicators from standard on-field surveys are a challenge that hampers the ability of researchers and practitioners to perform reliable and consistent road safety evaluations. However, applying computer vision to observe and analyse objects is a potential solution that can address this issue with confidence.

This study proposes a framework for assessing the short-term safety of bicycle traffic locations, particularly in areas where cyclists share the road with motor vehicles and methodology that could potentially fit with any kind of situation, location, and road its regulation. The study will use computer vision methods to extract trajectories from recordings and identify parameters relevant to interactions between cyclists and motorized vehicles.

The indicators were developed by recording six locations in the urban area of Hannover (Germany): 4 locations over three days in the first campaign 2022, 3 locations over four days in the second campaign 2023. The study aims to suggest a framework for safety assessment for locations of bicycle traffic, particularly in sections where cyclists ride parallel – and mixed with - motor traffic.

The researchers applied computer vision methods to extract trajectories from recordings and used these to identify parameters, which are relevant to interactions between cyclists and motorized vehicles.

The study identified two main scenarios:

the longitudinal ‘Leader-Follower’ scenario and the lateral "Overtaking scenario" The parameters considered for the longitudinal scenario were the minimum Rear clearance (RC) between the rear wheel of the bicycle and the closest point of the following vehicle, Time-to-Collision (TTC), and Post-Encroachment-Time (PET).

For the lateral scenario, the parameters considered were the Lateral Clearance (LC) and the relative speed of overtaking ($\Delta V$).

The calculated parameters were validated in samples based on the recorded videos, and the researchers aim to use the parameters to generate safety indicators for each interaction type to identify problematic road sections.

The study work focused on three different tasks: a comparison between 4 locations with different types of standards, a before and after analysis in one location with a corrective measure and another one with a soft traffic calming improvement. The proposed framework provides a rigorous approach for road safety evaluation, but further research is needed to confirm these results on larger samples.

# ABSTRACT IN ITALIAN


Gli incidenti che coinvolgono ciclisti stanno acquisendo sempre più rilevanza nell'ambito della sicurezza stradale. Numerosi studi hanno analizzato i fattori che contribuiscono alle collisioni che coinvolgono biciclette; la maggior parte di questi mettono in evidenza l'importanza della regolazione del traffico e delle caratteristiche dell'infrastruttura, anche se, va precisato che i risultati non sono sempre stati coerenti.

La mancanza di procedure consolidate per l'estrazione di indicatori rilevanti per la sicurezza da indagini sul campo è una sfida che ostacola la capacità di ricercatori e professionisti di eseguire valutazioni affidabili e coerenti della sicurezza stradale. In questo senso, procedure basate sull'analisi video automatica al fine di studiare le traiettorie possono agevolare lo studio della sicurezza stradale.

Questa tesi propone una procedura di valutazione della sicurezza per brevi segmenti stradali laddove, in particolare, esiste una condivisione dell'infrastruttura tra ciclisti e veicoli motorizzati. La metodologia proposta potrebbe potenzialmente adattarsi a qualsiasi tipo di situazione, luogo e regolamentazione stradale. Lo studio utilizza metodi basati sull'analisi video automatica per estrarre delle traiettorie dalle registrazioni e identificare i parametri rilevanti per le interazioni tra ciclisti e veicoli motorizzati. Il lavoro si è focalizzato sull'utilizzo delle metodologie discusse in tre applicazioni diverse: un confronto tra quattro siti con diversa regolazione dei flussi, un confronto prima-dopo a distanza di un anno in un'infrastruttura soggetta ad un intervento correttivo (inserimento nuova corsia ciclabile); infine, un confronto prima-dopo relativamente ad un'infrastruttura soggetta ad un intervento migliorativo di traffic calming (modifica della colorazione della pista ciclabile).

Nell'ambito delle reciproche interazioni tra ciclista e veicolo, il presente studio si è focalizzato su due scenari: lo scenario di interazione longitudinale ("Leader-Follower") e lo scenario di interazione laterale ("Overtaking").

Per lo scenario longitudinale sono stati considerati le variabili "Rear clearance" (RC), ovvero la distanza tra l'auto che segue e il ciclista, il "Time-to-Collision" (TTC) e il "Post-Encroachment-Time" (PET). Per lo scenario laterale, le variabili considerati sono stati la "lateral clearance" (LC) e la velocità relativa in fase di sorpasso ($\Delta V$).

Le medesime variabili possono idealmente fungere da input per la determinazione di indicatori di sicurezza in grado di descrivere sinteticamente le modalità di interazioni veicolo-ciclista che si realizzano in correnti monodirezionali, restituendo una diagnosi delle condizioni di sicurezza del ciclista in siti aventi caratteristiche differenziate. La metodologia proposta fornisce un approccio rigoroso per la valutazione della sicurezza stradale, ma restano necessarie ulteriori ricerche per confermare questi risultati in contesti diversi e con riferimento a campioni di osservazione più ampi.

# 1 INTRODUCTION

In many urban areas, the modal share of bicycles has been steadily increasing in recent years, partly due to a heightened appreciation of active and climate-friendly mobility (Pucher, Parkin, e de Lanversin 2021). This raises significant concerns about ensuring the safety of cyclists, particularly considering the heightened risk associated with interactions with motorized vehicles.(Wegman et al., 2012)

The lack of quantity and sub-optimal quality of data concerning crash is a significant obstacle to accurately measuring safety and attributing improvements to specific interventions. Following the example set by medical research, a valid alternative for measuring safety in the context of road traffic crashes may be to focus on surrogate measures. A surrogate refers to substitute measures used to represent a specific phenomenon or outcome when direct measurement is not possible. In the field of road safety research such measures are often used to evaluate road sections on the basis of surrogate events, defined as any potential crash that did not occur for various reasons. A key example of surrogates events can be near-misses crashes or traffic conflicts. The research based on surrogate measures provides a more robust methodology for investigating road safety in the absence of enough crash data, as it was better discussed carefully in section 3.4. This thesis work seeks to expose the subject of road safety by an experimental methodology based specifically on surrogate measures.

This thesis work forms part of a wider project called "Meridian" from Mouver. The objective is to assess the safety of cyclists by adopting an alternative methodology. The approach began with traffic observations, with the intention of retrieving indirect measures by tracing the trajectories of cyclists and those of motorists from a specific scenario and defined case study. The proposed scenarios were then compared using specific indicators.

The reference scenario concerns assessment in road segments where bicycles and motorised vehicles travel in the same direction on the same roadway, with the possibility of having collisions. The case study, on the other hand, is based on three different tasks to be analysed, which include video-based traffic observations recorded in different groups of locations within the urban area of Hannover, Germany. These locations include scenarios with parallel cyclists and vehicular traffic, where overtaking cyclists is both possible and common.

One of the main potential uses of the indicators extracted with the methodology described is the ability to compare safety levels between various locations or between before and after adjustment at a certain location. The purpose of this study is to present a framework for safety assessment on locations with bicycle traffic, particularly for same-direction interactions between cyclists and motorized vehicles. Specifically, this study introduces a simple, flexible and easy-to-practice methodology for extracting safety relevant indicators from video-based surveys. The proposed methodology is showcased through an application to several case study locations presenting before-after analyses of two types of infrastructural design interventions.

# 2 THE PHENOMENON OF ROAD CRASHES. EVOLUTION TRENDS FOR CYCLING

The phenomenon of road crashes arises as a complex issue deeply rooted in the socio-economic framework of every nation, projecting itself as a serious social burden on communities in general. As societies increasingly adopt sustainable mobility, understanding and addressing road safety for vulnerable users becomes crucial. This chapter provides some motivations for the thesis.

According to the Global Status Report on Road Safety 2023 published by the World Health Organization, road injuries rank as the 12th leading cause of death and the first cause within the 5-29 age bracket.

Furthermore, road traffic fatalities disproportionately affect males, evidenced by an overall female-to-male fatality ratio of 1 to 3. On a global scale, occupants of four-wheel vehicles constitute 30% of fatalities, followed by pedestrians at 23%, and users of powered two- and three-wheelers comprising 21% (Daniels et al., 2011). The vulnerability of various categories of road users to the high risk of fatal road crashes is aggravated by poorly maintained road infrastructure and safety features (Tarko, 2020a).

In particular the report highlights a significant deterioration in the situation for cyclists, with an increase in fatalities in certain regions. Notably, there has been above 50% rise in cyclist deaths in the European Region and north America in the latest 10 years. (World Health Organization et al., 2023). Moreover, despite an overall reduction in road fatalities during lockdown periods, the decrease among cyclists was limited to just -2%, underscoring the persistent vulnerability of this group of road users.

This worrying trend may be accentuated by a lack of traffic regulation and infrastructure specifically for cyclists and pedestrians, which contributes significantly to their higher fatality rates. In particular cyclists 'crashes may happen more frequently in urban areas, even though injuries may be more severe on rural roads (Boufous et al., 2012). Cyclists compose an approximately 6% of total fatalities resulting from road crashes, although this percentage exhibits regional disparities.

## 2.1 The evolution in Europe

The European Commission has established guidelines and next steps to improve road safety in the European Union, with the long-term goal of reducing road deaths to zero by 2050, as indicated in the "EU Road Safety Policy Framework 2021-2030 - Next steps towards 'Vision Zero'". This approach rejects the idea that the loss of human lives is an inevitable price of mobility and aims to create a road system that considers human physical vulnerability.

The aim is to prevent deaths and serious injuries through safe vehicles, safe infrastructures, safe road use, and improved post-crash care. The measures and tools include the design of "forgiving roads", vehicles equipped with advanced safety technologies, strict enforcement of road rules, and greater attention to post-crash response.

Moreover, the guide encourages to apply a proactive assessment in addition to the more traditional reactive analysis of high crash mapping risks, in order to provide useful tools to assess the safety quality of the road network and to target investment.

Thanks to increased funding, concerted efforts at all national and territorial levels, and the adoption of complex systems at the community level, the European Union has made significant strides in improving road safety, notably also with the implementation such as eCall, an automated emergency call system installed on board of any car. However, a worrying trend emerges regarding vulnerable road users, in specific cyclists, who require further attention and specific measures to ensure their safety on the roads.

Cyclists remain the only road user group in the EU where the number of fatalities has not significantly declined in the past decade: there has been a discernible flow in the incidence of cyclist deaths, escalating from a modest 5% of overall fatalities in 2010 to a 9% in 2021.

Over the past decade, the phenomenon of bicycle crashes in the European Union has undergone significant changes. Between 2010 and 2013, there was a general reduction in the number of cyclist deaths across EU countries, with the EU-25 average showing a decrease of 0.6% annually. However, this positive trend has stagnated since 2010, with less than a 1% year-to-year reduction in cyclist fatalities (European Transport Safety Council, 2016). The phenomenon has reached the pike in 2019 before presenting a forced deflection during the Covid-19 pandemic. Since 2021, the phenomenon has exhibited a tendency to grow once more, reaching pre-pandemic levels (European Commission, 2024).

This stagnation is partly attributed to the increasing popularity of cycling as a mode of active travel among EU citizens, as well as an ageing population that continues to cycle. The rise in the use of electric bicycles, particularly pedelecs and E-bikes, as also influenced crash trends (European Transport Safety Council, 2016). The increasing percentage of cyclist fatalities could also be partially explained by the progresses in safety of other traffic modes. In the next figures 1-2 it is showed how the number of fatalities and severe injures per millions of inhabitants has changed during the latest decade in EU27. These trends are explained in percentage (%) according with the number of occurrences reported in 2010.

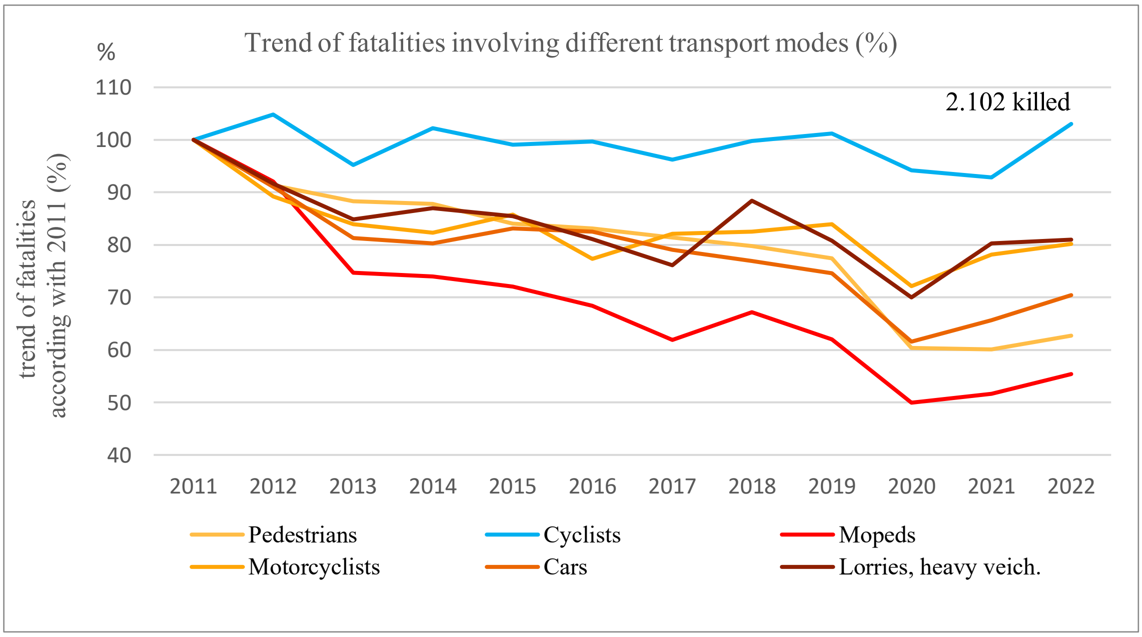


*Figure 1- trends of fatalities by different transport modes in the EU27 (2011-2022): the annual cyclist trend is underscored in light blue. The Y-axis take reference from 2010's data: 100 (%) is the number of fatalities occurred in 2010. Source: CARE European Union's road crashes database, by European Commission (2023) Facts and Figures Cyclists.*

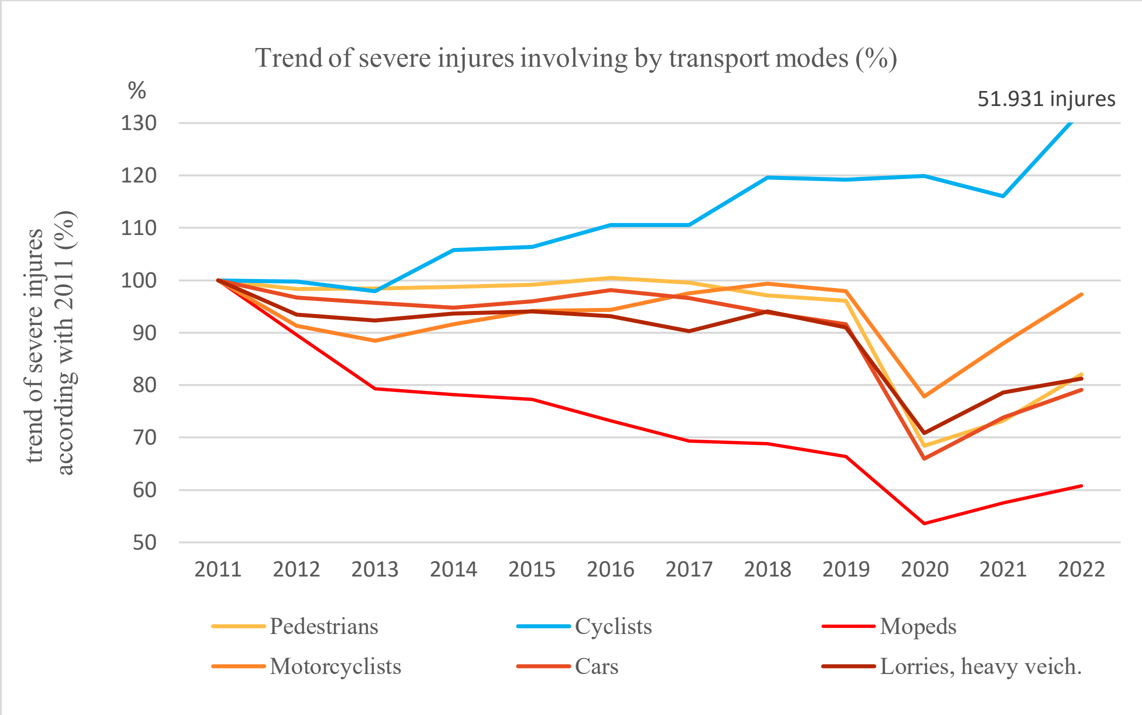


*Figure 2- trends of severe injures by different transport modes in the EU27 (2011-2022): the annual index of injured cyclists trend is underscored in light blue. The Y-axis take reference from 2010's data: 100 (%) is the number of injuries occurred in 2010. Source: CARE European Union's road crash crashes database, by European Commission (2023) Facts and Figures Cyclists.*

Figure 1 illustrates a fluctuating trend in the number of cyclists killed since 2011, with minimal inflection during the pandemic years. After 2022, the number has started to increase once more. In contrast, the trend of users perished in road crashes in other transport modes has been on a steady decline. The years of the pandemic saw a reduction in overall road traffic fatalities. However, Fig. 1 demonstrates that this was not the case for cyclists, who experienced a sharp decline in numbers, in contrast to other transport modes.

In Fig. 2, the trend of serious injuries in crashes involving bicycles shows an increase in serious injuries (+19% in 2020, 32% in 2022). Instead, crashes involving other modes plummeted in 2019 after a period of stability: many modes hit their lowest point in 2021 before resuming the latest descending trends, exception is made for motorcyclists, who deserve a more in-depth study elsewhere. Nevertheless, riding bicycles is the only transport mode that has become more dangerous over the last decade in EU.

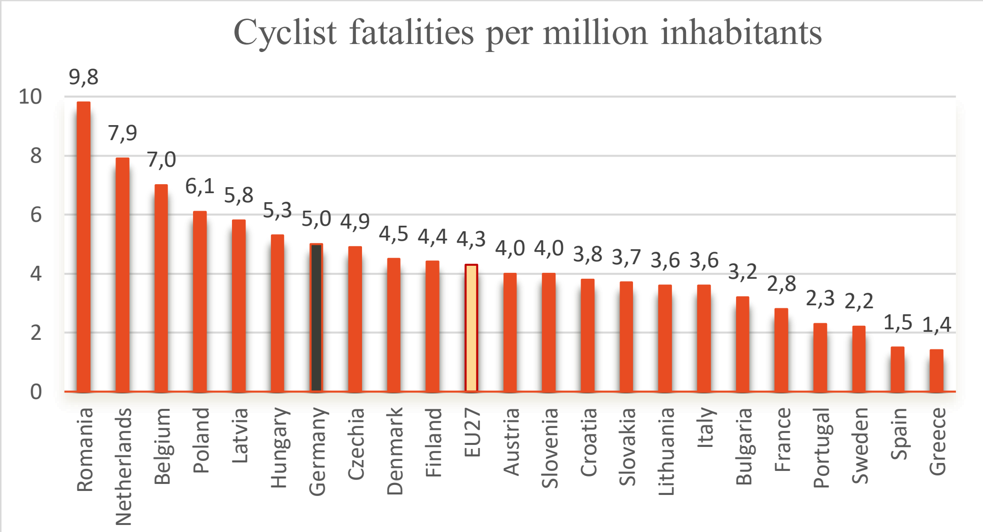


*Figure 3 Cyclist fatalities per million inhabitants per country in the EU27 (2018-2020). Source CARE*

Observing the amount of cyclist killed by country in fig.3, the countries in the upper of the ranking are Romania, the Netherlands, and Belgium. At the latest places, we find Portugal, Sweden, Spain, and Greece. For many of them, the lowest rankings can be attributed to the underrepresentation of bicycles as a primary mode of transportation in those countries. In Figure 3, are illustrated the proportion of cyclists among overall road fatalities along the right vertical axis.

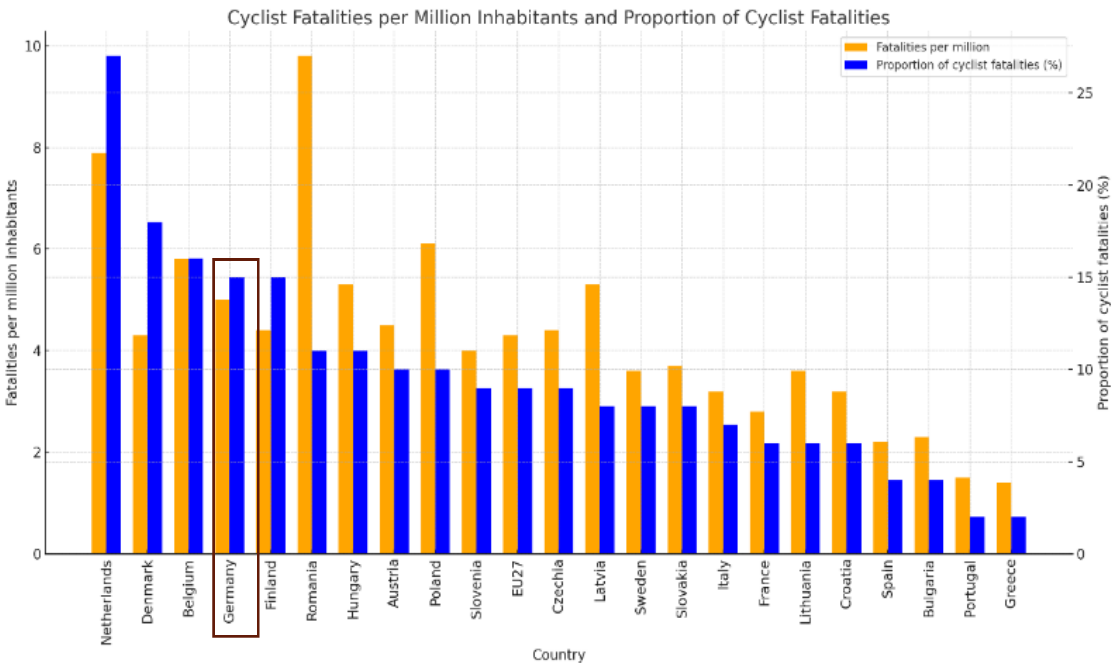


*Figure 4, The yellow bars indicate the number of cyclist fatalities compared to the total number of road fatalities per millions of inhabitants per country in the EU27 (2018-2020). The Blue bars indicate How the national number of fatalities affect the overall fatalities. Source: (CARE)*

Greece, Portugal, and Spain exhibit the lowest rates of cyclist fatalities, while the Netherlands, Denmark, Belgium, and Germany have the highest percentage of cyclists among all modes of transportation, reflecting the highest number of individuals utilizing bicycles.

Romania has fallen in the ranking, showing that the high mortality for cyclists is in line with the overall high mortality in that country. In contrast to Romania, Denmark has risen in the ranking as Germany, the country with the fourth highest share of cyclist fatalities. Cycling in these four neighbouring countries (the Netherlands, Belgium, Germany, Denmark) is known for its popularity and encouraged form the administrations, therefore partly explaining their high cyclists' fatality ratios. (European Commission, 2023)

In 2022, approximately 2,000 cyclists died in road traffic crashes within the European Union, with a significant number of others sustaining severe injuries. In October 2023, the European Commission presented a proposal for a European Declaration on Cycling with the objective of advancing road safety, enhancing the quality of cycling infrastructure and data collection systems across the EU. This declaration acknowledges the significance of cycling as a sustainable, accessible, inclusive, and healthy mode of transportation, underscoring its crucial role in European society and the economy. (European Commission, 2024).

## 2.2 The evolution in Germany

Germany is the country with the highest number of cyclist deaths in Europe. The projections for 2023 show a slight decrease in overall road fatalities, with an estimated 2,750 deaths, 40 fewer than in 2022 and the records pre-pandemic years, which was constantly increasing. This projection indicates that, while remaining above the all-time low of 2,562 deaths in 2021, the number of road deaths is still significantly below and didn't confirm the pre-pandemic trends. (AG DEKRA - Road Safety Report, 2023)

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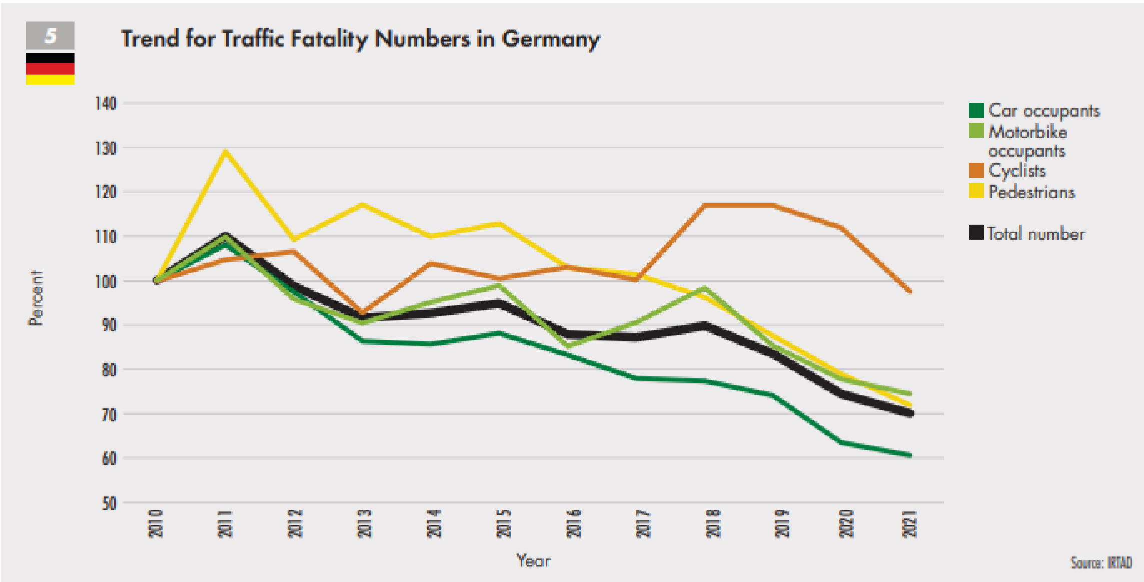



*Figure 5 trends of fatalities by different transport modes in Germany (2011-2022): the annual cyclist trend is underscored in orange. The Y-axis take reference from 2010's data: 100 (%) is the number of fatalities occurred in 2010 Source:(AG Dekra - Road Safety Report, 2023)*

In Germany, the number of cyclists dying on the roads has fluctuated slightly over the past two years. In 2022, 445 cyclist deaths were recorded, up from the previous year. In 2023, however, the number of cyclist deaths decreased slightly to 430. This indicates the need for continued efforts to improve the safety of cyclists, especially in rural areas where dedicated cycle paths often do not exist.

## 2.3 The evolution in Italy

Italy is the country with the highest index of motorization in EU, creating a transportation system heavily centred around automobiles. Consequently, the country's infrastructure often prioritizes cars over cyclists and pedestrians, with limited dedicated spaces and facilities for sustainable mobility.

The issue of traffic crashes represents a significant challenge at the national level, due to the considerable number of incidents that occur. According to ISTAT, Italian national institute of statistics, 3.039 road victims occurred in 2023, with 166.525 crashes and 224.634 injuries. (ISTAT). The social cost is estimated around €16.6 billion.

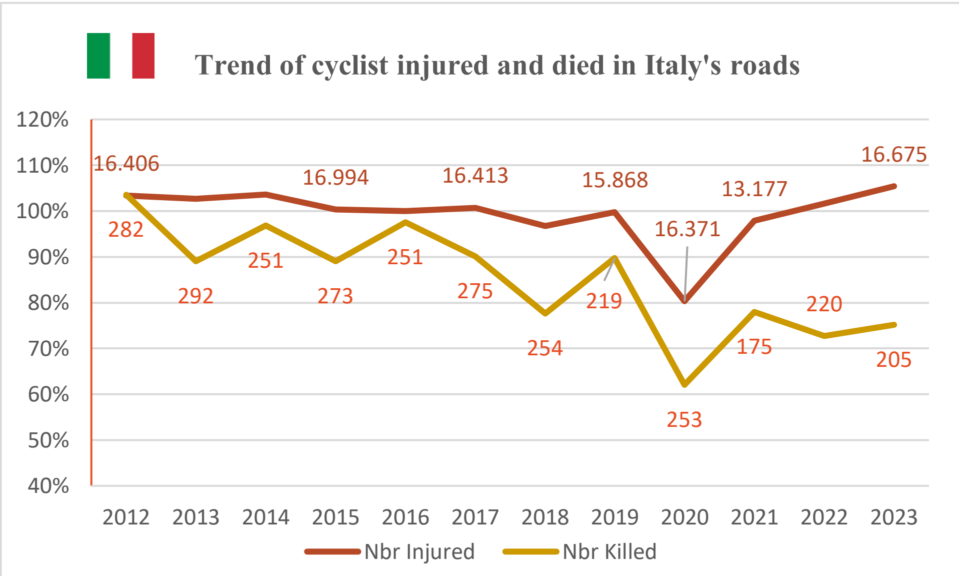



*Figure 6 trends of severe injuries and died in Italy (2011-2022): the annual index of perished cyclists trend is underscored in yellow. The Y-axis take reference from 2010's data: (100 %) equals to the number of fatalities or injuries occurred in 2010. Source: CARE European Union's road crash crashes database*

The decline in the number of cyclist fatalities over the past decades has not been as rapid as had been anticipated in accordance with the forecasts and plans that had been formulated. Italy has experienced a variety of fluctuations over time, influenced by developments in on-board safety, the introduction of new regulations, and the impact of the pandemic. Despite these efforts, the percentage of cyclist fatalities has remained relatively stable, accounting for 8% of total road deaths. In 2023, Italy recorded 212 cyclist deaths, representing a slight decrease from previous years, such as 2011, when the figures were higher. This signifies a 12.5% reduction in cyclist fatalities from 2011 to 2023. However, an analysis of the data on a year-by-year basis reveals that the decline since 2011 has not been consistent and that there is no guarantee that it will continue. Indeed, the number of fatalities increased compared to 2022, with 205 fatalities (+3.4%), and the number of injuries was higher than in 2011. This aligns with the broader downward trend in Europe-EU (ERSO, European Commission, 2024; ISTAT, 2023).

The country is witnessing an increase in awareness of this issue within society, particularly regarding the protection of vulnerable road users, with a primary focus on cyclists. In recent years, cities like Milan and Bologna have led the way in introducing several new initiatives to improve cyclist safety, including the expansion of dedicated cycling lanes, the promotion of cycling-friendly urban planning, and public awareness campaigns. These efforts are designed to reduce the risk of crashes and create a safer environment for cyclists.

# 3 CRASHES IN SAFETY ANALYSIS

The chapter would present an overview of road safety, starting from the general definition to the detailed applications on the thesis. The aim is to provide, within the limits of the thesis context, a comprehensive understanding of the methodologies applied and its position within the research field. The overview begins by clarifying the definition of a crash and approaches an examination of the various factors that contribute to crashes, briefly introducing the major fields of road safety research. In addition, this Chapter highlights the intrinsic limitations of crash data and crash-based approaches and how alternatives like surrogate safety measures enable a more accurate identification of high-risk situations.

Subsequently, this chapter illustrates the existing knowledge about the interaction between cyclists and motorists in the same lane, the methodologies that have been explored in the existing literature and the gaps in the current understanding. In the last two paragraphs, the focus is on the topic of motor vehicles overtaking bicycles, highlighting critical points, and techniques and methodologies of observing conflicts, such as the computer-based method, which is later employed in this thesis.

## 3.1 General definitions

The history of road crashes has evolved significantly since the advent of the automobile in the early 20th century. The phenomenon began to be studied around 1910, coinciding with the introduction of the first traffic regulations aimed at managing the increasing number of vehicles on the roads. Over the decades, the focus on understanding the causes and consequences of crashes has expanded, incorporating various factors such as driver behaviour, vehicle safety features, and road design. This research has been crucial in formulating policies and interventions aimed at reducing crash rates and improving overall road safety. (Tarko, 2020)

Thorough research on road safety indeed requires a historical series of accurate and comprehensive data on all crashes. This foundational data allows researchers to analyse trends, identify patterns, and understand the factors contributing to road safety issues. By establishing a clear and comprehensive definition of a crash, it becomes easier to categorize and interpret this data effectively. The current definition still accepted: “a crash is considered any system failure event involving stationary or moving vehicles that resulted in injuries to individuals” (Vienna convention on road traffic, 1968). This data allows for a better understanding of crash dynamics and helps identify the most significant risk factors for specific types of crashes and the contexts in which they occur.

From a statistical point of view, another definition assigned to crash can be as an independent rare event that occurs randomly with its own frequency. It is:

- Rare; it represents an anomaly compared with the multitude of potential trajectory collisions that could occur in a certain time frame in a reference network. Therefore, it is considered rare because of its low frequency. (Tarko, 2020a)
- Random; the circumstances that lead to a crash can be influenced by factors that are partially deterministic, i.e. controllable, or at least partially measurable. However, many factors contributing to a crash are unpredictable and chaotic, or just partially predictable. To conduct a comprehensive safety assessment, it is essential distinguishing risk factors that are predictable from non-predictable ones.

Crashes data must include information about the frequencies and severity of crashes, due to register and quantify the phenomenon. The total number of crashes occurred within a specific observation period can provide insights into the systematic repeatability of crashes (frequency) or trends that highlight potential indicators. Although, this is information are not sufficient to establish a safety evaluation.

At the same it is important apply a procedure to quantify the severity of crashes due the lability of any crash: damage and consequences for the users depends on multiples and complex variables. For this reason, the severity level of crashes is measured using international scales such as MAIS3+ or KABCO, based on a range from minor crashes to those with fatal consequences to the worst case of fatality damage.(Ivan & Konduri, 2018)

Another important definition for describing the basis of road safety is the risk and the exposure: they depend on time spent driving in a ride, by the category of vehicle, by driving behaviours: The longer time spent driving, the higher the associated risk. The risk may not be entirely eliminated, but it can be mitigated through a comprehensive understanding of the contributing factors.

## 3.2 Contributing to Road Crashes

Understanding the primary factors that contribute to road crashes is critical for developing effective safety measures. This section delves into the three main categories of contributing factors that include the majority of causes: vehicle mechanical conditions, roadway infrastructure factors, and human behaviour. Each of these elements interacts in complex ways, often making it difficult to isolate their specific impacts.

This thesis, and the wider Meridian Project, consistently emphasizes the importance of human and infrastructural elements in the case studies presented. Both the project and thesis focus on the human aspects of road users, such as measuring the discomfort reported by cyclists. Additionally, the safety of different locations is evaluated by

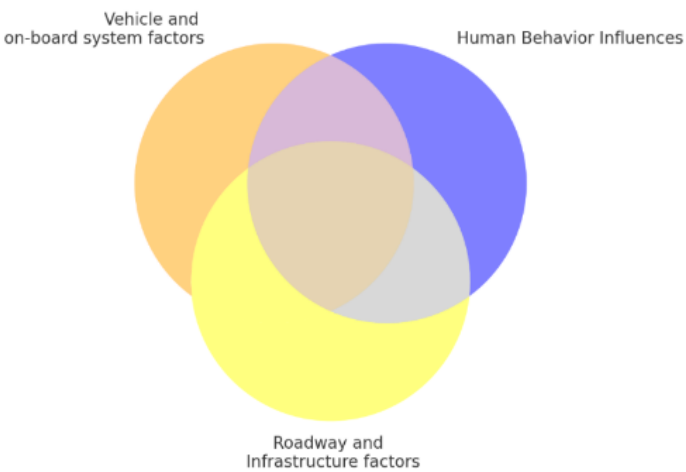



*Figure 7 Road safety factors. A possible minimal scheme of factors influencing Road safety*

considering various types of infrastructure and interventions, such as new lanes or road markings. Therefore, it is crucial to take road conditions into account.

The interaction of these factors demonstrates the complexity of road safety and the necessity for a multifaceted approach. Each category influences and overlaps with the others, indicating that improvements in one area can have positive effects on overall safety. Over the years, the focus and weight of these factors have shifted due to technological advancements, changing behaviours, and enhanced infrastructure. However, the continuous updating and adaptation to these variations are essential for further improving road safety.

It is noted in the research that the roadway features and safety design of motorized vehicles may exhibit linked effects, making it challenging to isolate their specific impacts due to potential confounding factors (Tarko, 2020)

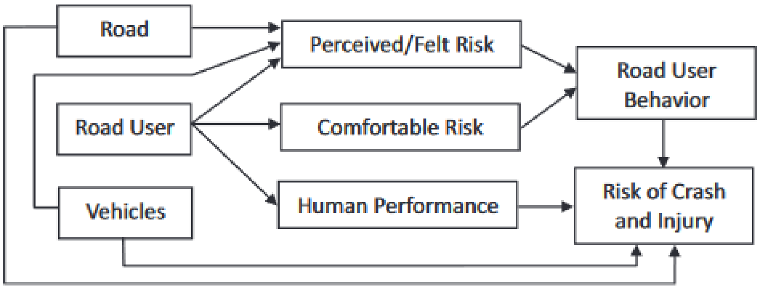



*Figure 8 Human-centered perspective on safety factors. (Tarko,2020)*

An alternative matrix of safety factors, which is widely known, was proposed by Haddon (1980), which divides the factors into three time-consecutive groups: the factors present during the crash-free period preceding the crash, the so-called "pre-crash phase", the factors when the crash is in progress and the "post-crash" period, which depend on the health of the traveller, the Emergency Medical Services response and the integrity of the fuel system. The latter in terms of statistics may last as long as hours, days, or weeks after the crash. It therefore encompasses the entire convalescence of the persons involved until the risk for the injured is zero. (Tarko, 2020).

This paragraph addresses the mechanical conditions of vehicles, infrastructure, and driver status. The objective is not to diminish the importance of these factors by condensing them into a few points, as they are already extensively covered by scientific research across various fields, not just engineering. Rather, the aim is to discuss the origin of crash phenomena and expose essential aspects relevant to this thesis, which focuses on the conflicts between cyclists and motorists. This approach seeks to understand where these factors come into play and how they specifically impact the research, and the dynamics involved.

### 3.2.1 Mention to Vehicle Mechanical Conditions

This category includes the technological and mechanical aspects of the vehicles themselves. Examples are advancements in safety features such as anti-lock braking systems (ABS), electronic stability control (ESC), airbags, and collision avoidance systems. Over the years, the development and implementation of these technologies have significantly impacted vehicle safety. The mechanical condition of vehicles is one of the most predictable and directly causal factors in road crashes. Even though there are issues such as brake failures, tire blowouts, and other mechanical defects that can lead to crashes. Regular maintenance and inspections are essential to minimize these risks. Advanced vehicle technologies and safety features also play a significant role in reducing crash likelihood and severity.

### 3.2.2 Mention to Roadway factors.

Roadway factors concern the design, construction, and maintenance of the infrastructure, traffic signals, signage, and other physical aspects of the driving environment. The quality of road surfaces, visibility and a "forgiving" design are competences to be examined due to avoid collisions.

In the event of a crash, distinguishing the responsibility of the infrastructure is not always obvious. For example, a deformation in the pavement can contribute to a crash if it interacts with the speed of the vehicle. Sometimes It is a mix of factors in which human elements and vehicle conditions play a significant role. Rarely the infrastructure may be solely responsible in case of malformations, failures, or neglected design faults.

A site-by-site analysis may hint that a potential cause of crash can be attributed to the roadway factors group: concentrations of interesting event in a single location may indicate the road features are playing a pivotal role in those dynamics. Similarly, it could happen in locations with comparable scenarios. Indeed, as specified in paragraph 5.1 of this thesis, the objective was to evaluate the efficacy of safety measures by comparing locations with different lane regulations or by assessing changes such as repainting the same lanes. The analysis aimed to identify any significant differences between locations, with the potential to yield valuable insights regarding the safety of bicycles.

### 3.2.3 Mention to Human Behaviour factors

The subject of human behavioural factors is too expansive to be adequately addressed in this chapter. Consequently, we will provide only a cursory overview about the mainly causes of a human error, perception of risk and how they may be relevant to the scenario addressed in this thesis.

Drivers, pedestrians, and other road users often make errors, and they can generate inevitable crashes or risky situations (i.e. near messes events) that can increase the possibility to get negative consequences. The causes that can lead an error belong to different aspect of human beings and may depend on physical, perceptual, or cognitive limitations. Misjudgement, such as vehicle speed or gap width accepted, may be related to distortion of perceptual processes. Workload and fatigue, like sleepiness and drowsiness, are sub-optimal conditions that impose severe cognitive and physical limitations on the driver. In addition, there are distractions and mind wandering caused by external or internal inducements that do not allow full processing of crucial information and deteriorate driving performance. In addition, there are also incorrect decisions caused by lack of knowledge of the rules, slips and interior lapses.

A key issue in risk perception in general cases may be the discrepancy between the perceived and actual level of risk. Drivers often underestimate real dangers, which makes them more likely to engage in risky driving behaviors. Additionally, cognitive biases and the normalization of deviance—where repeated exposure to risky situations without negative outcomes leads to a false sense of safety—further contribute to the gap between perceived and actual risk.

Considering the subject matter of the thesis, it is crucial for motorists to be aware of the potential errors that could result in substantial and severe consequences when interacting with cyclists. In this specific scenario, where interactions occur between two actors (cyclists and vehicles), the perception of risk for the motorist may decrease, rather than with another vehicle (Chaurand & Delhomme, 2013). Whereas for the vulnerable cyclists, conversely, the perceived risk could be heightened more the lateral clearance reduce more overtaking speed increase (Llorca et al., 2017).

Cyclists (and pedestrians) are particularly susceptible to the consequences of other people's misjudgements, as their personal safety depends on their own perception of risk in combination with that of other road users. To improve safety, specific indicators can be used to measure the comfort level of road users, especially cyclists, to identify situations where risks may be underestimated. These comfort and discomfort situations are influenced by the behaviour of other road users, with a significantly greater impact when dealing with cars or heavy vehicles. Indeed, a principal objective of the Meridian Project, from what this thesis took inspiration and derives its focus, is to evaluate the perceived comfort of cycling through surrogate measurements.

## 3.3 Quality of crash data

The quality of collected data is crucial to ensure the accuracy and reliability of road safety analyses. Data quality can be influenced by various methodological factors and the different definition of crash, fatality, and injury's terms, can be essential to ensure consistency interpretation by agencies. Crash databases trend easily to be altered or approximated by the circumstances in referring the events. This Under-Reporting Phenomena can occur for various reasons, such as lack of communication with reporting agencies or the decision not to record minor crashes:

- Incomplete or Missing Data: The lack of complete data can compromise the quality of analyses. It's important to collect comprehensive data on all crashes and related risk factors.
- Reporting and/or Transmission Errors: Errors during the data collection or transmission phase can negatively affect data quality.

- Failure to Report Crashes: Crashes are not reported to reporting agencies for various reasons, such as lack of awareness or a desire to avoid bureaucratic complications.
- Uninformed Reporting Agencies: Agencies responsible for recording crashes may not be informed of a crash that occurred.
- Distortion of the study sample, Drivers involved in crashes may not be a representative sample of the population of drivers, as riskier drivers are likely to be over-represented.
- Non-Intervention by Reporting Agencies: In some cases, reporting agencies may be not called, especially in minor crashes.

In particular, crashes resulting in minor injuries, or no injuries are often under-reported. This can lead to an underestimation of the true extent of road crashes and their consequences, compromising the ability to develop effective road safety policies.

## 3.4 Measuring Road Safety with surrogate events

As discussed in Chapter 3.3, the quality of crash data is a crucial factor in road safety analysis. However, this data often proves to be incomplete or inaccurate, hindering precise and timely assessments. Moreover, even if our chronology includes a sufficient number of statistical samples of crashes, these may introduce a bias in any comparison made between them. This is due to the fact that they are separated by a considerable period of time, which is influenced by the rapid evolution of traffic conditions. The same may be observed in the case of different scenarios, such as the comparison of locations in disparate urban areas or countries. Therefore, it becomes a challenge to measure road safety because of this randomic and sporadic nature of events.

In order to obtain more data for short reference times, which will not affect the boundary conditions of the network or infrastructure, it is necessary to take new conditions that occur more frequently and are easier to detect. (Tarko, 2020b). This is the case with surrogate events, such as traffic conflicts, i.e. those trajectory conflicts that this thesis aims to analyse primarily through video-based analysis. The following chapters want to show how the traffic conflicts should be studied and the types of safety indicators that should be employed in this process.

### 3.4.1 Surrogates events: Traffic Conflicts

Road users experience events in traffic that have a physical impact, but these events are not considered crashes by the people involved, who do not report them either to the police or to insurance companies.

The first surrogate measure applied to road safety dates to the 1960s. It was a term used to introduce a potential collision that required evasive action to avoid contact (Klebelsberg et al, 1964). In 1970, Hayward made the concept of road conflict more specific introducing a threshold with non-conflicts and defining that the collision time should be less than 1 second. The definition of traffic conflict has been modified several times to the formal definition, i.e.: "A traffic conflict is an observable situation in which two or more road users approach each other in space and time to such an extent that there is a risk of collision if their movements remain unchanged" (Güttinger, 1984). This definition was superseded by the Dutch DOCTOR method by adding the connotation of collision as imminent and with realistic probability of personal or material damage.

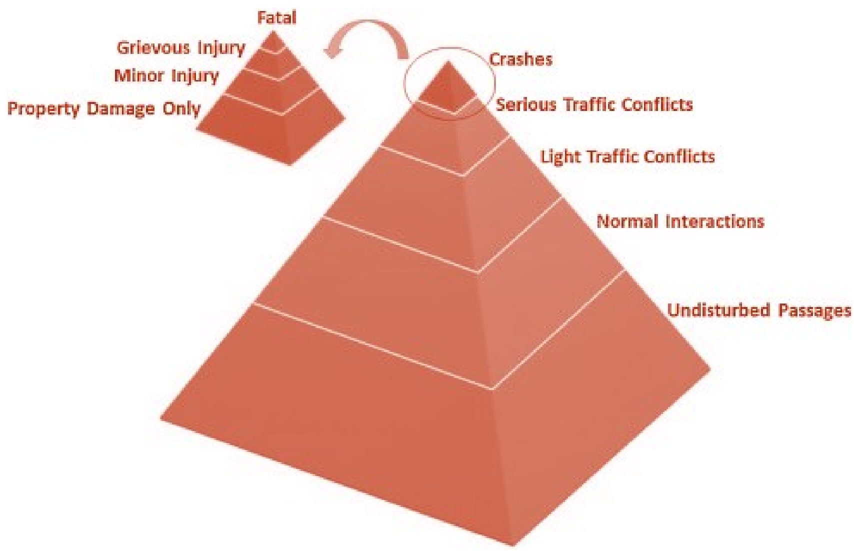



*Figure 9 pyramid of conflicts from source Arun et al. 2021, adapted from Hyden 1987*

If we were to represent this hierarchy in order of appearances, we should consider a pyramid scheme (see Fig.9) where the crash, at the top, counts on a small base. By comparison, conflict, on the contrary, can count on a wider base.

The definition of traffic conflict has been progressively treated to underline the aetiological connection that must exist with crashes and the requirement for corrective action. As a matter of fact, we certainly cannot know whether a traffic conflict would have led to a crash if there had been no evasive manoeuvre. However, it was proposed the causal relationship exists between a traffic failure and the possibility of precipitating events considering a model where conflicts and crashes be considered as events defined on the same probabilistic space, where event is a cause if it is necessary and sufficient to produce an effect. Necessity implies that the effect is unlikely to occur without the causal event, while sufficiency implies that the effect is likely to occur with the causal event. (Davis et al., 2011)

Relying on a model that would have its advantages in that considering a Traffic Failure as the basis cause of a conflict can hardly be refuted. Because if the trajectories between the users were clean and perfect, no crashes would probably occur. Furthermore, this is confirmed by the fact that the same factors that cause Traffic Failure, are the same ones that cause conflicts. A failure in a traffics system could be a technical failure, due to problems with vehicles or regulatory systems, a human operator failure made by a user or a management or planning failure (road Failure).

The issue can be attributed to a combination of factors that collectively contribute to the occurrence of failures in specific types of conflict within specific contexts. For instance, high speeds may precipitate a head-on conflict in a straight line, whereas in a pedestrian crossing, the circumstances are markedly different.

Similarly, at much lower frequencies, the same failures will tend to generate the same type of crash. Thus, a causal model between conflicts and crashes is consistent and almost always applicable as a working hypothesis.

The causal relationship combined with the event population being greater than the number of crashes for the same observation period ensures robustness of the conflict analysis. Another advantage of relying on traffic conflicts is strictly related to findability: studying the conflict does not require data collection on actual crashes, which are often stored and archived by agencies or law enforcement.

A major disadvantage remains the uncertainty in distinguishing real traffic conflicts from those interactions that, although marked, are controlled by both users. Furthermore, the accuracy of conflicts can be influenced by many factors that cannot be controlled, such as the condition of vehicles or the psychophysical condition of drivers.

### 3.4.2 Surrogate measures: Indicators

The qualitative approach offers a more expansive and accessible method for identifying precipitating events. This approach involves the measurement of several parameters and indicators derived from each trajectory, with a particular focus on the direct observation of evasive action performed by drivers to avoid a crash. An evasive action can be considered as a sudden manoeuvre performed by a vehicle driver to avoid a potential collision. This can involve swerving, sudden braking, changing lanes, or any other necessary action to avoid a road crash. Some limitations may come from false positives and false negatives that may alter the interpretation of the event - such as aggressive behaviour that tends to accentuate the manoeuvre or those who do nothing to avoid the potential crash.

Indeed, it is a method that works in cases where there is a high frequency of conflicts, where there are a multitude of evasive manoeuvres within a short period of time.

But if the case study needs to deal with low flows and suggests investigating those conflicts that are not so obvious, it is more appropriate to use the quantification of surrogate safety measures. Most of this work focuses on this approach due to investigate which parameter can be used in bicycle-car conflict.

Surrogate safety measures are indicators of spatial/temporal proximity, capable of quantifying how close two road users came during their interaction.

- Time-based measures: These assess risk in terms of temporal proximity.
- Deceleration-based measures: These focus on how vehicle deceleration can prevent crashes.

- Energy-based measures: These allow for evaluations of the potential severity of a crash.

A collision should happen when the separation between two road users in space and time is approximately zero. This simple fact establishes an equivalence between the proximity of the crash and the measurable separation between road users, which could be represented by Time-based measures.

The most remarkable measures which belongs to this group is **Time-to-Collision** (TTC), i.e. the time interval separating two vehicles, which are on a collision course with each other, assuming that speeds remain constant and that no evasive manoeuvres are performed. It assumes the following general expression:

$$TTC = \frac{R}{RR} = \frac{vL * tGAP}{vF - vL}$$

Where R (range) is the spatial distance between the two vehicles, RR (range rate) is the speed differential between the two vehicles. VL and VF are the speeds of the leading and following vehicles, respectively, and tGAP is the temporal gap that separates them.

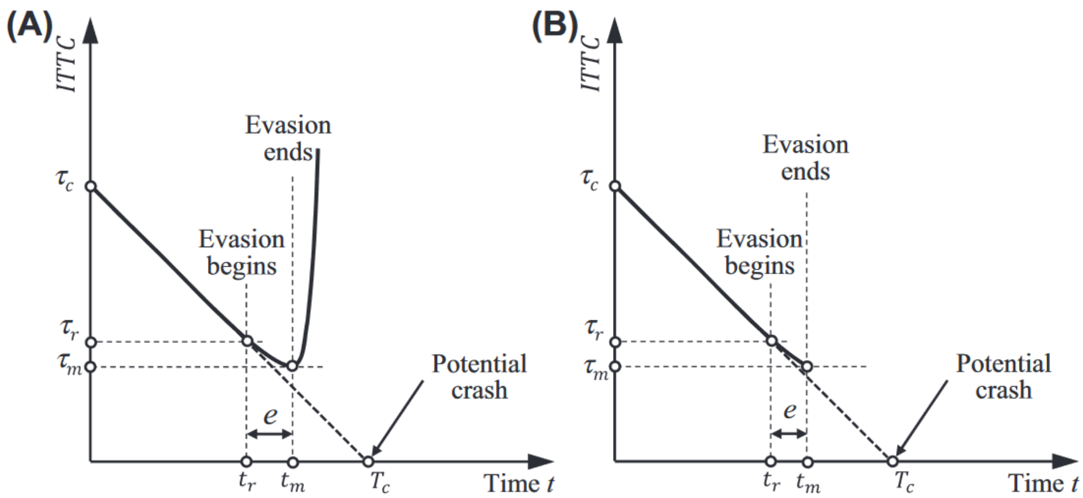



*Figure 10(A) profile of evasion through braking, (B) profile evasion through swerving. (Tarko,2020)*

The TTC is an indicator that changes in time as well as in space and varies depending on the type of manoeuvre performed: the following illustration shows how it changes in the case of braking and swerving. ITTC is referred to as instantaneous Time-To-Collision to indicate continuous function over time. As ITTC approaches zero, the closer the point of collision.

The ITTC indicator formulae can also be easily applied to leader follower systems, and thus inherent to the thesis work, although with the right analytical corrections. In the case of the co-presence of cyclists, the TTC can be an important indicator in the case of a vehicle approaching dangerously at the rear. On trajectories where the movement tends to be curvilinear or where the speed tends to alter at regular intervals, we should rely on alternative indicators, named Post-Encroachment Time (PET).

The PET is a parameter used to assess the safety of road intersections. It is defined as the time that elapses between the moment a vehicle leaves a conflict point and the moment another vehicle enters that point. This parameter is useful for assessing highly dangerous conflicts and is ideally applied where non-parallel trajectories coexist, such as conflicts at intersections or pedestrian crossings.

Indeed, it finds a limit when considering the time needed to cover the distance at low speeds, such as in isolated vehicular flow during congestion, where the indicator will be misleading. However, it can be combined with other indicators to produce more effective parameters.

Other indicators that return useful are delta speed, and overtaking velocity. These are minor kinematic indicators that are useful as surrogate measures in particular analysis conditions, such as overtaking. Speed of overtaking in combination with clearance can be an indicator of risk, which is accentuated when passing a vulnerable user. The speed difference is recorded through the first indicator, Delta Speed. There are other time-based parameters suggested as the Time-to-Overtake.

A parameter worth mentioning as it could be of interest in the possible development of this work is Delta-V. A measure based on energy that allows the masses of the trained vehicles to be included in the analysis. This indicator would not give a crash index or conflict frequency but could introduce an index of severity and possible damage. In the case of vulnerable users, this parameter would be essential. (Laureshyn et al., 2017)

### 3.4.3 Surrogates Safety indicators in overtaking cyclists

Research on bicycle overtaking manoeuvres uses the minimum lateral distance between the cyclist and the vehicle while passing as a surrogate indicator to determine risk thresholds. Although the minimum lateral clearance (LC) during overtaking is certainly a key indicator of safety, an overtaking manoeuvre is a long and complex process that is not limited to the phase in which the vehicle moves parallel to the bicycle; therefore, the manoeuvre cannot be fully described by the transitional lateral clearance alone (Díaz Fernández et al., 2022). In the context of evaluating overtaking interactions in the same direction, lateral clearance is a commonly employed metric to assess both objective and perceived safety (Rubie et al., 2020).

Another crucial indicator is the speed differential (ΔV) between motorized vehicles and bicycles that can influence the stability of the cyclist and the severity of any crashes (Llorca et al., 2017). Furthermore, surrogate measures of safety, commonly used in situations where the trajectories of cyclists and motorized vehicles are on a collision course, can also be applied to same-direction travel (e.g., Time-to-Collision and Time Advantage) (Laureshyn et al., 2010).

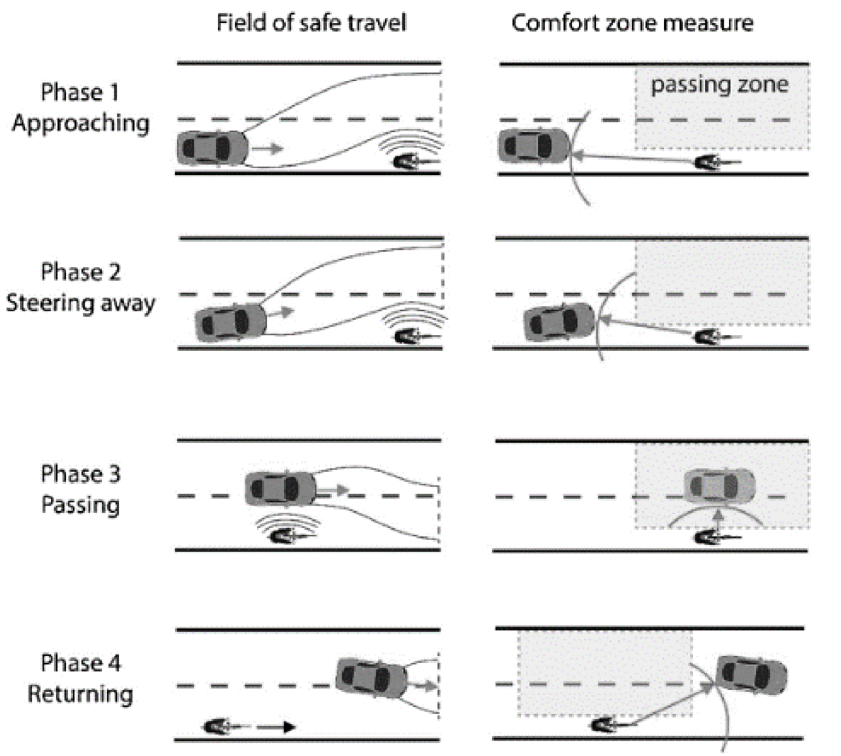



*Figure 11 The four phases in a car-to-bicycle overtaking maneuver. T M. Dozza et al.2016 / Crash Analysis and Prevention*

Several studies have combined these safety indicators with a multiphase model to further assess the safety of overtaking interactions (Bianchi Piccinini et al., 2018; Dozza et al., 2016). According to Dozza et al. (2016), any overtaking manoeuvre can be divided into four stages: Approaching, steering away, Passing, Returning.

During all overtaking phases, the driver of the motorized vehicle can actively control the safety of the interaction. The lateral space in an overtaking interaction thus represents the boundary of the driver's comfort zone during the overtaking phase (Kovaceva et al., 2019). Moreover, the same paper cites an additional distinction that can be made within cyclist overtaking manoeuvres. here are two main types of cyclists overtaking manoeuvres (Matson, T., Forbes, T., 1938): "Flying overtaking", where drivers will still a considerable distance and keep a constant speed in control, "accelerative overtaking" when drivers are going to close the manoeuvres sooner. The same paper suggests that the lateral distance margin during the overtaking is, on average, 0.31 meters shorter in "flying" overtaking compared to "accelerative" overtaking (Kovaceva et al., 2019).

## 3.5 Techniques and Methodologies of observing Conflicts.

The Conflict Tracking System is based on the first detection of vehicles, tracing the trajectory by measuring position and speed, while the cameras provide video images showing the projection of the trajectory itself. Vehicles are classified according to their size, traffic category, time of arrival and time of departure from the frame. These labels will become very useful in the post-processing phase of data collection.

The data needed to measure road conflicts can be collected using various instruments. Of these, roadside sensors play a crucial role. These include video recordings, inductive loops, radar, and LiDAR, which together provide a detailed view of traffic dynamics. In addition to these, vehicle sensors can provide additional relevant information directly from moving vehicles. In the study Dozza et al. (2016), Lidar technology was utilized to gather detailed data on overtaking maneuvers from the cyclist's perspective. Fixed on board e-bicycles, the Lidar system collected data at a frequency of 20 Hz, providing continuous and high-resolution information on the distance between the bicycle and the overtaking vehicle throughout the entire overtaking maneuver. The Lidar data allowed the researchers to measure the "Comfort Zone Boundaries" (CZBs) during each phase of the overtaking maneuver. These measurements were used to understand how factors such as the presence of oncoming traffic, vehicle type, and speed influenced driver behaviour and safety margins.

In parallel, another valid approach is the simulation: detailed traffic models are generated in predicted scenarios, where conflicts are planned. The driving simulator can be another valuable tool that is not dealt with in this work but allows the same scenarios to be generated as in the on-site study. Moreover, simulating scenarios gives possibility to set conditions of drivers or weather that could not be applied differently.

### 3.5.1 Trajectory processing for motor vehicles and bicycles

When assessing the safety of different infrastructure designs, there is a lack of established methods for extracting safety-related indicators from standard field studies. For example, dedicated probe bicycles are often used to obtain lateral clearances during overtaking. A trajectory processing can develop an established method for extracting data that can be applied without limit in temporal cover. These are equipped with sensors that record the passing distance (Dozza et al., 2016); however, these detection methods do not allow for continuous detection and the application is limited in temporal cover. This limits the ability of researchers and practitioners to make reliable and consistent assessments of road safety, especially over longer periods of time.

To overcome these challenges, video-based tracking coupled with artificial intelligence methods emerges as a promising approach, enabling continuous monitoring of interactions (Mansell et al., 2024; Zangenehpour et al., 2016). Mansell et al. (2024) specifically utilized computer vision technology to measure bicycle volumes directly, which helped in overcoming the traditional limitations of collision data that often suffer from underreporting. The study focused on signalized intersections where right-turning vehicle and bicyclist conflicts were prevalent, using video analytics to capture and analyse these interactions.

This enhancement is pivotal for traffic safety studies as it allows for more precise and real-time monitoring of dynamic road interaction. Although traffic safety analysis using automated video trajectory extraction is not commonly used in practice and research (Saunier and Sayed, 2007), recent advancements in neural networks (Wang et al., 2023) have allowed higher accuracy detections leading to more accurate estimations of distances between studied traffic participants.

Despite the importance of studying same-direction interactions between cyclists and motorized vehicles, there are relatively few works approaching this issue from a video-based perspective, which could be particularly useful for the continuous monitoring of cycling infrastructures or for conducting localized before-after evaluations. Rubie et al.'s (2020) review revealed that most studies investigating motorized vehicles overtaking cyclists were based on instrumented vehicles, and that only a minority (38%) were based on video observations. Rasch et al. (2023) recently emphasized the scarcity of observational data in cycling-overtaking studies, noting that naturalistic data on cyclist-overtaking maneuvers have been limited in previous research.

In addition, most of them adopted a manual or semi-automatic procedure to extract safety-relevant indicators: In Apasnore et al., 2017, video data was manually reviewed to identify passing events and relevant vehicles and bicycles' variables. Then a self-administered online survey was conducted with a sample of cyclists to assess their comfort level during passing events. (De Ceunynck et al., 2017) processed video footage by using a software designed for semi-automated video analysis. Specifically, this tool helped in efficiently identifying and analysing interactions between buses and cyclists. The software still required human oversight to flag relevant events, calibration, and refinement, such as in (Debnath et al., 2018) .

In the case of this study, all traffic data processing is taken directly from the video footages following the approach developed by Trifunovic et al. (2021): There are main components in the processing process: marking fixed objects as reference or road markings; the transformation of the marked points from the monitor plane to the road surface by a homographic transformation; the estimation of the object's trajectory as a sequence of positions in time and the real detection and estimation of road conflicts. This approach has previously been applied in other studies of shared spaces, including studies of pedestrian movements and of pedestrian crossings (Batista and Friedrich, 2022a, 2022b; Orsini et al., 2023; Tzouras et al., 2023). This thesis introduces the aforementioned approach to detection, as outlined in section 6.1, for the first time in the context of a scenario involving bicycle vehicles travelling in the same direction.

# 4 Regulatory framework for Cycling Infrastructure

## 4.1 Status of German Regulations

### 4.1.1 Driving safety rules

As this work was carried out in Germany, it is provided with a summary of the main points of the German regulations and traffic codes. In Germany, overall traffic regulations are regulated at federal level, so the main laws contained in the traffic code StVO (Straßenverkehrs-Ordnung) are uniform throughout the country. In addition, the RASt (Richtlinien für die Anlage von Stadtstraßen) contains guidelines for the design of urban roads.

The cyclist is only obliged to use cycle lanes in the relative direction of driving when these are present and if they are signposted. Cyclists may also use the right-hand lane if there are no cycle lanes and no obstructions for pedestrians. In urban areas, it is not allowed to ride on cycle paths for mopeds and e-bikes, whereas out of urban areas, it is permitted. The walkways may not be used by cyclists, except for certain categories of users, such as children under 8y.o. (StVO § 2 Abs. 4)

In terms of road regulation, drivers may overtake cyclists, even two in a row. Overtaking two bicycles may therefore be permitted. In the case of overtaking pedestrians, cyclists, and drivers of small electric vehicles with motor vehicles, in urban areas the sufficient side distance is at least 1.5 m and outside urban areas at least 2.0 m. No speed limits are imposed in the presence of bicycles, but the standard recommends caution and reducing speed. (StVO §5 Abs. 4).

### 4.1.2 Characteristics of cycle paths

In addition to the regulations already mentioned, the document 'Empfehlungen für Radverkehrsanlagen' (ERA) 2010 and 2023 editions, which contain the guidelines for cycling, are given as sources. Based on the ERA 2023, we can find these cycling road types in Germany:

| | | |
|---|---|---|
|  | 1) Radschnellweg:<br>- Bicycle highway, only bicycle, E-bike are allowed.<br>- Width 3.00-4.00m |  |
|  | 2) Radfahrerzone:<br><br>- Road open to authorised vehicles only. Priority is given to the cyclist free to cycle and stop. These are 30 km/h areas. |  |
|  | 3) Schutzstreifen:<br><br>- Cycle lane within the roadway allocated to cyclists and E-bikes.<br>- a motorised vehicle may pass temporarily but may not overtake someone in this lane unless the opposite lane is free.<br>- Min. 1.50m, +0.75m Width by the edge. |  |
|  | 4) Radfahrstreifen<br>- It is a cycle lane marked by a continuous line and exclusively for cyclists. It is located on the roadway but is clearly separated from the part of the road used by motor vehicles.<br>- Min. 2.50m two way.<br>- Min. 2.00m two way. |  |

| | | |
|---|---|---|
| <br> | 5) Gemeinsamer Geh- und Radweg & Radweg im Seitenraum.<br>- located in a separate exclusive area from the roadway.<br>A distinction is made between a pedestrian cycle lane, indicated as a common area, and a separate pedestrian and cycle lane. |  |

## 4.2 Status of Italian Regulations

In Italy, the regulation of bicycle lanes is outlined in the “Codice della Strada” (Highway Code), along with the associated updates, DM 96-2001, and DM 557/99, which establish the technical characteristics of bicycle lanes. The guidelines for road infrastructure are integrated in DL76/2020 “Progettare ciclabilità sicura” (Designing Safe Cycling), into the “Piano Generale della Mobilità Ciclistica Urbana e Extra Urbana (General Plan for Urban and Suburban Cycling Mobility) 2022-2024” issued by the Minister of Infrastructure and Sustainable Mobility (MIMS) in accordance with Law No. 2 of January 11, 2018.

### 4.2.1 Characteristics of cycle paths

Bicycle Lane: Introduced only in 2020, this lane is a longitudinal part of the carriageway, usually located on the right, marked by a continuous or discontinuous white line, selected for the circulation of bicycles in the same direction as other vehicles. It is marked with the bicycle symbol and is not to be crossed, except in cases of parking or stopping parking bay on the right side. (Codice della Strada, ACI, 2022)

Two-Way Bicycle Lane: Located on a one-way urban roadway, it is marked by a discontinuous white line, crossable and for mixed use, allowing bicycles to travel in the opposite direction to other vehicles. It is also marked with the bicycle symbol and must be at least 1.50 meters wide. It is applicable on roads with a speed limit not exceeding 30 km/h or in limited traffic zones. (Codice della Strada, ACI, 2022)

Urban Bicycle Street (E-bis): Defined as an urban street with a single roadway, sidewalks, and a speed limit not exceeding 30 km/h, with priority given to bicycles. The lane use is exclusive when the carriageway dimensions allow, otherwise non-exclusive. (Codice della Strada, ACI, 2022)

### 4.2.2 Driving safety rules

Regarding overtaking cyclists, Italy has not yet introduced a mandatory minimum lateral distance to be respected. However, according to the ACI (Automobile Club of Italy), on urban cycling roads, the driver of a motor vehicle overtaking a bicycle must take particular precautions to ensure a greater lateral safety distance and a safety relative passing velocity.

However, it is remarkable that there is a draft amendment to the Highway Code, which requires motorists to maintain a distance of 1.50 meters when overtaking a cyclist. A that moment, this draft is currently under approval by the republic's upper house of Italy (ANSA, 2023) ***.

## 4.3 Differences with German Regulations

In contrast to Germany, where the distinction between bicycle lanes and other carriageways is more clearly defined and strictly enforced, in Italy, bicycle lanes may also be used by other vehicles if marked by a dashed line. This mixed use is permitted only for short distances, with priority given to cyclists. The flexible application and simplified signage in Italy result in a less distinct separation compared to German regulations, which tend to be more stringent.

*** *https://www.ansa.it/canale_motori/notizie/speciali/2024/03/27/nuovo-codice-della-strada-tutte-le-novita_0101ec17-5ef7-4ab6-babc-a31fb4c9bfce.html*

# 5 EXPERIMENTAL ANALYSIS

The case studies analysed in this thesis are included in the research activities carried out within the MERIDIAN (Multicriteria Evaluation with RapID Image Analysis) project. The project is designed to investigate multiple aspects of road safety that have been neglected so far in the scientific literature: it aims to converge on indicators to quantify the degree of comfort and risk perceived by users in the traffic. It is a project conceived by mouver® GmbH, a German research start-up founded at the Institute of Transport and Urban Engineering of the Technical University of Braunschweig by Prof. Dr.-Ing.Friedrich B., Dr.-Ing.Fourati W., Dr.-Ing. Trifunovic A.

The project in this campaign aimed to analyse traffic conflicts, focusing on the trajectories of each user. This involved a first detection phase, followed by the automatic extraction of indicators for safety facilities. The objective of the campaign was to evaluate the safety of cyclists in relation to interactions between bicycles and motorised vehicles in different locations. In particular, reference is made to situations in which there are interactions between cyclists and approaching vehicles, which can influence cyclist behaviour and increase perceived risk and discomfort levels.

The project is based on the recording with fixed video cameras of critical locations of risky road sections or intersections, reported by local administrations. The selection of each location was made by the local administrative authority, which did not depend on any safety record and thus on the severity of the area. The locations included different scenarios: like pedestrian crossing in a straight line and in intersections right-hand drive.

However, the primary focus of this work was on the bicycle lanes and mixed lanes scenarios, running in same direction segment. The capturing was made with a temporary camera set up at a height of 4-5 metres from the ground, with the angle fixed to the road segment. The framing filmed the entire roadway with a wide-angle aperture and a wide depth of field.

From the video recordings, the trajectories of each user are tracked, obtaining their position, direction, traffic category, instantaneous speed, and acceleration. From the subsequent analysis steps implemented, it was generated a screening of surrogate measurements for each interaction considered as an event, consisting of a cyclist and a motorised driver. In this case the interaction could be either approach and overtaking of the cyclist, or simple approach and rear-end following the cyclist: a differentiated approach was developed for these two scenarios.

One of the main potential uses of the indicators extracted with the described methodology is the possibility of comparing safety levels between different locations or between before and after a change in the configuration of a given location. The latter is the main objective of this thesis.

## 5.1 Case of study

The Meridian project planned a first data campaign in June 2022, spread over three consecutive weekend days (Friday, Saturday, Sunday) during daylight hours. The cameras used were from the start-up company mouver® GmbH.

To test and demonstrate the application of the suggested methodology explained in chapter 6.1, multi-day recordings were conducted at different locations in the northern suburbs of Hannover, Germany, each before and after an intervention to the cycling infrastructure. Recording over multiple days allowed to surmount fluctuations due to weather condition sensibility of bicycle traffic, on the one hand and, to increase the sample size for analysing the overtaking behaviour.

The devices were temporarily mounted on streetlight or road vertical sign, pointing as possible in the direction of the traffic. Only daylight hours were considered in the analysis, as bicycle traffic was almost insignificant in the night. They were equipped to take videos with a frame rate of 30 FPS.


*Figure 12 a sample of camera detecting, Source: mouver® GmbH official site*

The Meridian Project planned a second data campaign between June and August 2023. At same time, another single camera was placed again in Location 2 for 4 days in June 2023 due to make a comparison one years later. Indeed, in this location, during November 2022 a semi-protected bicycle lane was added (dashed lines). Then, in April 2023, the bicycle lane's surface was painted in red.

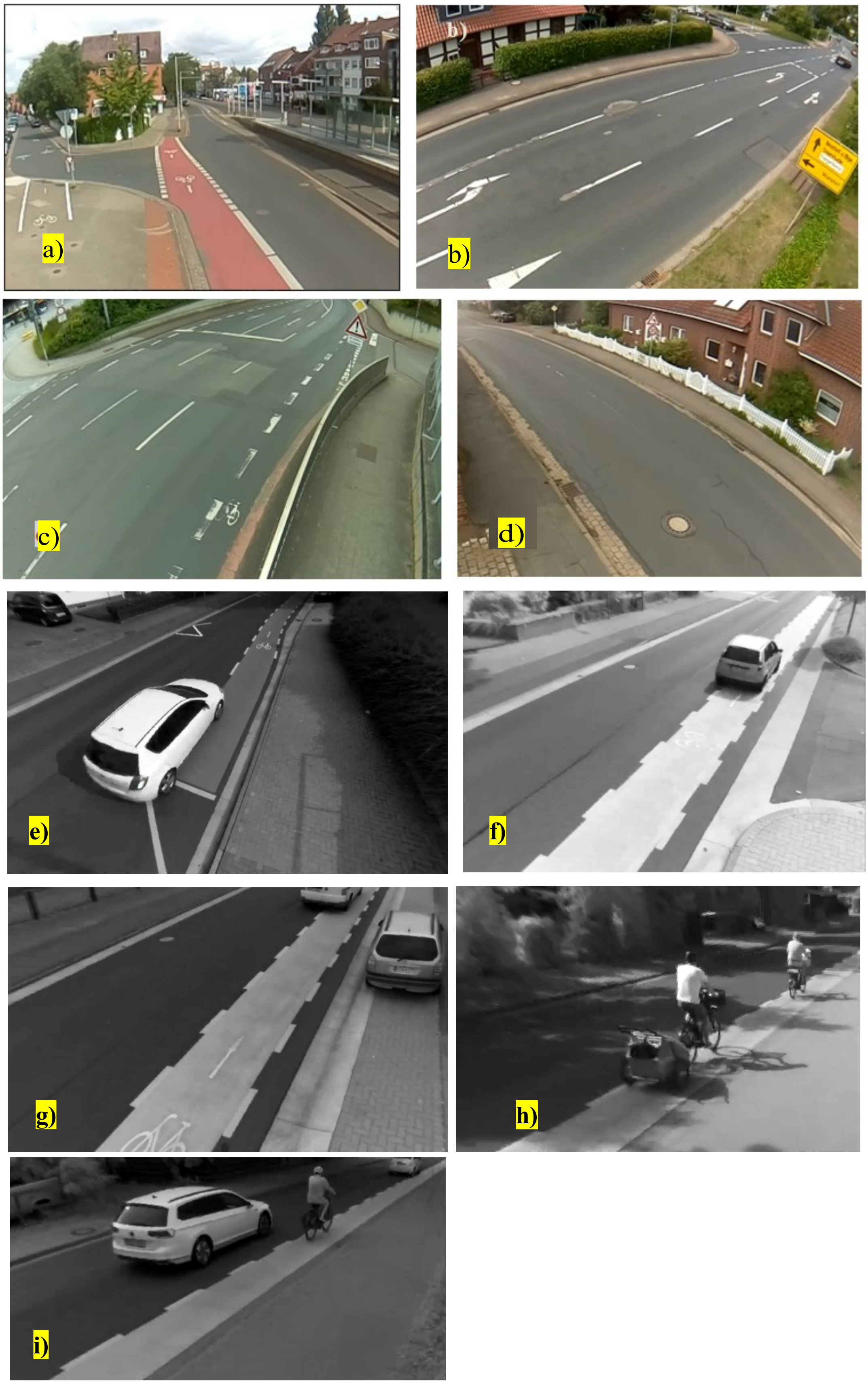
*Table 1- Planning of experimental campaigns and temporal distribution of activities. The table shows the schedule of activities conducted during three experimental campaigns in different periods: The symbols indicate for each campaign which Location it took place.*

| | | | Location | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Campaign | Period | | **1** | **2** | **3** | **4** | **5A** | **5B** | Tot. days |
| 1st | June 2022 | | ● | ● | ● | ● | | | 3 |
| 2nd | June 2023 | | | ● | | | ● | ● | 4 |
| | August 2023 | | | | | | ● | ● | 4 |

Locations 5A and M3 were recorded during 4 days in June 2023 and 4 days in August 2023, with 3 and 2 video cameras respectively positioned along the studied street segment. A semi-protected lane already existed in the first recording campaign but was painted in red between the two campaigns and the opposite lane has changed in a "radfarhrerzone" (type n°2), 30 km/h limit. The selection of these locations was a decision endorsed by the suggestions of the Region of Hanover, our partner in the case study. The analysis of these places enabled us to compare the initial impacts and assess the efficacy of the methodology in a relatively short timeframe, in just one year.

Fig. 13 illustrates the camera field-of-view in both recording campaigns.

*Figure 13 Cameras angles footage, a) Location 1. b) Location 2, c) Location 3. d) Location 4 e) Location 5a first camera, f) Location 5a second camera, g) Location 5a third camera h) Location 5b first camera, i) Location 5b second camera*



### 5.1.1 Concerning the Locations

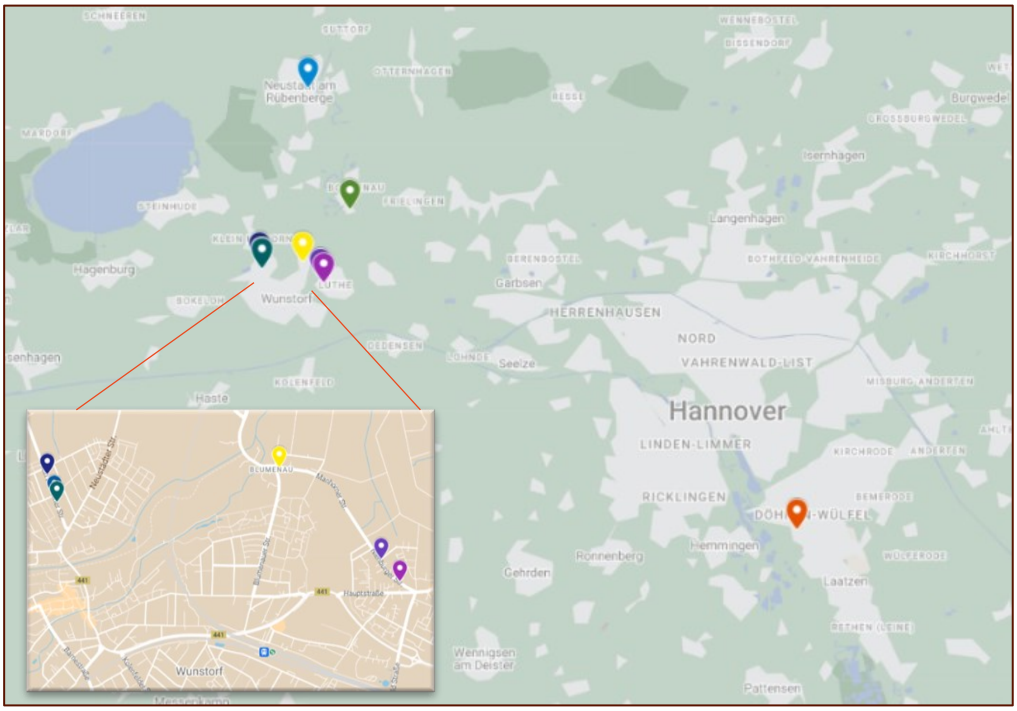



*Figure 14 Map of the selected locations: Location 1 (red dot) is the only location in the Hannover Urban city; the others are collocated in proximity of Wundstorf, which was zoomed in the smaller images.*

From the Meridian video library, we considered three different locations in urban areas in the district of Hannover. Except for the first, which is in the inner city of Hanover, the others were conducted in urban northern suburbs with lower population densities where the number of vehicles, bicycles and pedestrians passages are on average lower than in the city location:

- Location1: Hildesheimer Str., Hannover, Germany
- Location2: Manhorner Str., Wunstorf, Germany
- Location3: Marktstraße, Neustadt am Rübenberge, Germany
- Location4: Frielinger Str., Neustadt am Rübenberge, Germany
- Location 5A: Klein Heidorner Str., Wunstorf, Germany.
- Location 5B: Nienburger Str Wunstorf, Germany.

Locations were chosen because they represent four different type of solutions that can be found according to German traffic code.

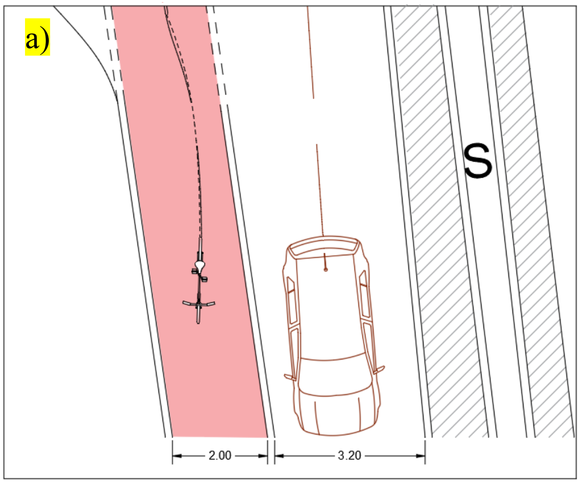
## 5.2 Description of Locations analysed.

The following table summarizes the features of Locations 1 through 5b, including aerial perspectives, main characteristics, identified limitations in detection and in the traffic volumes and the speed limit.

| | | |
|---|---|---|
| *5.2.1.1 Location 1*<br>First Campaign – June 2022 | 09/06/2022<br>10/06/2022<br>11/06/2022 | Cod.02<br>Hildesheimer Str., Hannover |

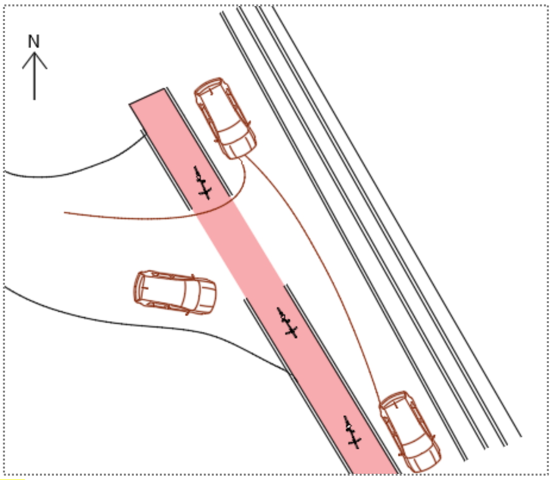


*Figure 15 aerial View Location 1, yellow arrow position of camera*




The first location is in an urban context with a high level of traffic of different categories.

The analysed road segment has a length of 100 metres and is focused on the west side of a road with two lanes, one for each direction of travel, separated by two tramways and a central platform. Only the west half-lane, visible from the camera, is considered, bordered on the external side with a b)


c)

*Figure 16 Location 1, a) same direction passing conflict scheme, b) street-view Google Maps c) typical scheme of vehcicle's critical trajectories*

bicycle lane at the same level, separated from the vehicular lane by a continuous strip.

On the left, the vehicular lane borders the tramway, which slightly reduces the width of the lane at the southernmost end, closest to the camera. Continuous road markings prohibit vehicles from passing over the cycle lane.

In the north-west part of the location, there is a junction with a secondary road with a speed limit of 30 km/h, where bicycles have right of way, coming from the left, although the traffic flow coming from the secondary road is very limited.

Bicycle traffic has been analysed even if only partially running on the cycle lane, parallel to the traffic flow of the main road.

Despite the presence of a dedicated lane for cyclists, it was deemed appropriate to consider this segment for some specific reasons:

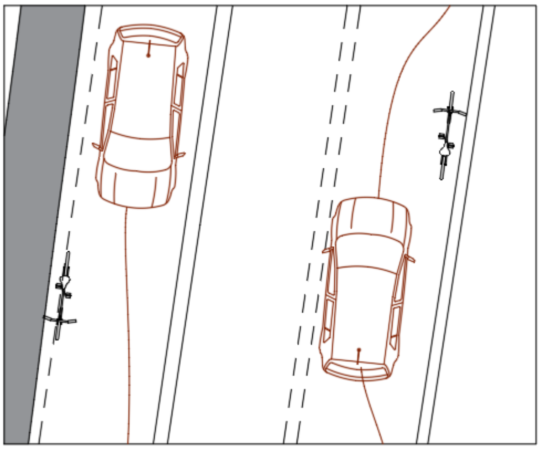
1) Vehicle trajectories tend to approach the cycle lane at the end of the crossing, to avoid the narrowing of the roadway caused by a 15 cm raised separator to the left of the tram. This phenomenon is accentuated during the passage of bulky vehicles such as buses.

2) The cycle lane, while having a width that allows cyclists to feel relatively safe, can be limiting due to the speed at which vehicles overtake. Although overtaking occurs with greater lateral distance, this can lead to a higher perception of risk for the vulnerable user.

| 5.2.1.2 *Location 2 BEFORE*<br>First Campaign – June 2022 | 09/06/2022<br>10/06/2022<br>11/06/2022 | Cod.06<br>Manhorner Str., Wunstorf |
|---|---|---|

*Figure 17 aerial View Location 2, yellow arrow position of camera*


a)



The second location is in a rural area, on a road connecting two residential neighbourhoods, at a junction between a main road and a secondary road. this main road is provided by a third central lane for left-turning and oncoming into traffic from the second. it presented an average traffic level consisting mostly of automobiles, goods and commercial vehicles and bicycles turning left or proceeding on. The segment is two-way, with mixed lanes for cyclists and vehicle traffic in both directions.

In the first campaign, the lanes are 3.15 metres wide which is not enough to overtake a cyclist without occupying the middle lane. The central b)


c)

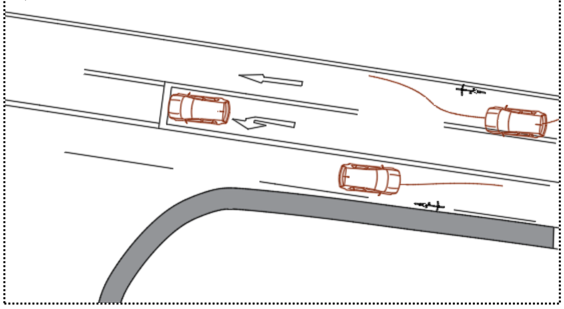


*Figure 18 Location 2, a) same direction passing conflict scheme, b) street-view Google Maps c) typical scheme of vehcicle's critical trajectories*

lane is a pre-selection lane for turning left, which is not widely used for this purpose. However, it is heavily used for passing slow users, such as cyclists, in both directions even though that is not allowed by traffic rules.

This manoeuvre is only permitted in the direction from right to left, until the pre-selection lane ends or is already occupied by vehicles turning left. However, this is a common phenomenon, which should be noted.

The traffic flow in the oncoming lane is not included in the study to avoid distance errors and distortion of the parameters. Another problem in the oncoming lane is the passage of vehicles in the process of overtaking a cyclist: their volumes can obstruct the cyclist's visibility, interrupting the trajectory detected by the automatic detection systems and causing a loss of continuity in the analysed interaction.

This location has two critical issues, symptoms of a high perception of risk and extremely cautious, but incorrect, cyclist behaviour:

1) The number of cyclists who tend to use the road lane is very low: 67% do not prefer to cycle on the side walkway on the side opposite the direction of travel. This can be interpreted as a sign of poor safety when crossing the crossing or the main road.
2) The majority of overtakes are made overcrossing the dashed line.

| 5.2.1.3 Location 2 AFTER<br>Second Campaign – June 2022 | 27/06/2023<br>28/06/2023<br>29/06/2023<br>30/06/2023 | Cod.06<br>Manhorner Str., Wunstorf |
| --- | --- | --- |


*Figure 19 aerial View Location 2, yellow arrow position of camera*


In the second campaign of the study, location 2 had an adjustment.


*Figure 20 Location2, with the newest regulation 2023, with a new cycle lane*

It is changed the roadway width distribution between the lanes. In the westbound direction, a cycle lane with discontinuous markings was introduced, which also allows it to be crossed by motorised vehicles, and the main lane was shortened. In this way, a cyclist followed by a vehicle cannot be overtaken if there is not enough space. The width of the central lane remains unchanged. While the central opposing lane has been changed to one of the third type under German law, with a speed limit of 30 km/h, where cyclists have right of way and overtaking is prevented.

| 5.2.1.4 *Location 3* First Campaign – June 2022 | 09/06/2022 10/06/2022 11/06/2022 | Cod. 09 Marktstraße Neustadt am Rübenberge |
|---|---|---|



*Figure 21 aerial View Location 3, yellow arrow position of camera*

a)

b)

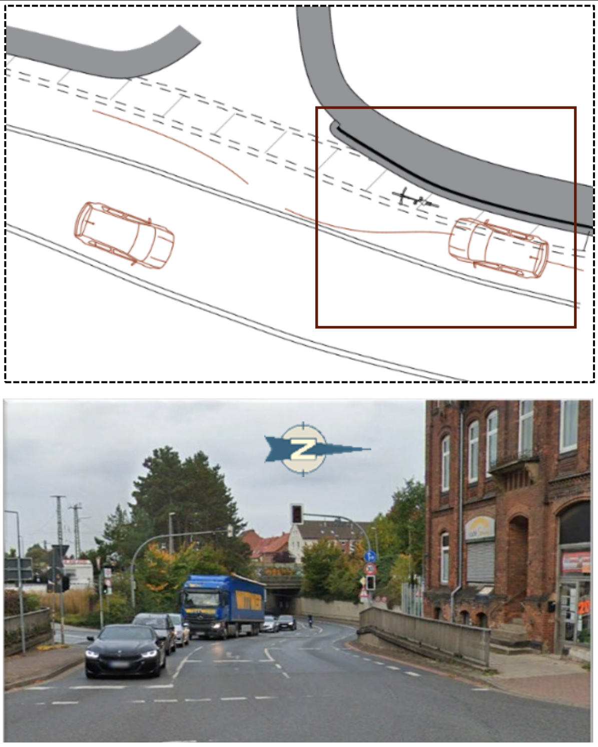
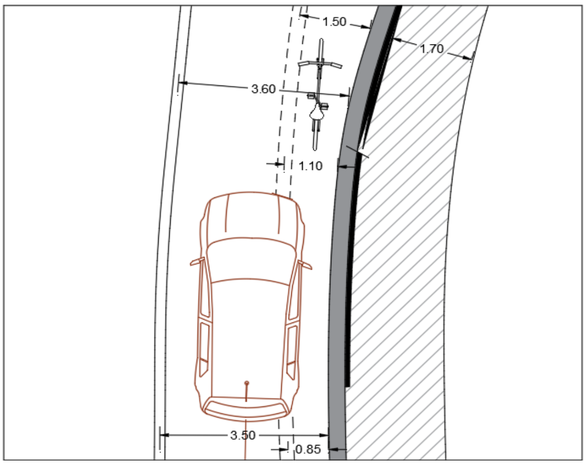


*Figure 22 Location 2, a) same direction passing conflict scheme, b) street-view Google Maps: c) details of manoeuvres*

This is a segment that, like the other two cases, focuses on a single direction's lanes, the one most favourable to the camera. It is a road in the centre of a small town, adjacent to a railway subway. As can be seen from the picture, in the semi-roadway to the right, there is only one vehicular lane and a narrow cycle lane, passable by cars, with an approximate width of 70 cm.

This limited space forces motorists to pass extremely close to cyclists travelling in their dedicated lane. On the right-hand side there is a pedestrian path with a

| | |
|---|---|
| c)   *c) See below* | raised step higher elevation and a railing. This step represents an additional element of risk, as a simple skid could cause sudden changes in trajectory in order to avoid a collision.<br><br>The pedestrian path on the right is not cyclable due to the presence of a ramp with a step. It is not used by cyclists, except for cyclists on foot. b) |

In this location, too, it was necessary to consider certain features that disrupted the analysis and processing:

1) The entering cars arrive from an intersection regulated by traffic lights, located just 15 metres behind the camera. Consequently, arriving cars, proceed at low speed, except if they are in the green phase. Indeed, from this traffic light-regulated intersection, cars cannot drive into this segment unless arriving from the left or right, making a 90-degree turn. It is not possible for motorised vehicles to enter this segment at a high speed. It is quite frequent that the cyclist arrives at the same speed as the motorised vehicle. The expected outcome in these cases is that bike & car have reduced the speed gap to zero, despite to have increased the time to overtake.

2) There is an entrance road on the right which does not lead to a significant increase in traffic volume, with only a couple of cars per hour. If this road had been busier, the segment would have had to be assessed more cautiously, as the trajectories of cyclists and vehicles intending to turn right could have caused several conflicts, no longer belonging to the same-direction-conflict hypothesis. Moreover, manoeuvres can be completed passing through the central lane.

3) A further factor that can affect behavioural patterns and future outcomes is the declining slope of the segment.

| | | |
|---|---|---|
| 5.2.1.5 *Location 4*<br>First Campaign – June 2022 | 09/06/2022<br>10/06/2022<br>11/06/2022 | Cod 10<br>Frielinger Str. Neustadt am Rübenberge |

*Figure 23 aerial View Location 4, yellow arrow position of camera*


*Figure 24  Location 4, street view and camera set*

Location 4 is located in a small rural locality with a low population and low vehicle flows, with a modest presence of cyclists. It is a two-way road structure where overtaking is possible. In this case, both flows were considered because they are equivalent from the point of view of speed limits, width, and overtaking possibilities. In the direction north-south lane there is a reduction in the visibility suitable for overtaking in the background due to a curve.

There were 10% riding bikes on the pedestrian path. Although there were some notable interactions, like 3 critical cases of longitudinal rear-end scenario, but the number was not sufficiently representative for a comparison.

| 5.2.1.6 *Location 5A - BEFORE*<br>Second Campaign – June 2022 | 27/06/2023<br>28/06/2023<br>29/06/2023<br>30/06/2023 | Cod M1<br>Klein Heidorner Str., Wunstorf |
|---|---|---|

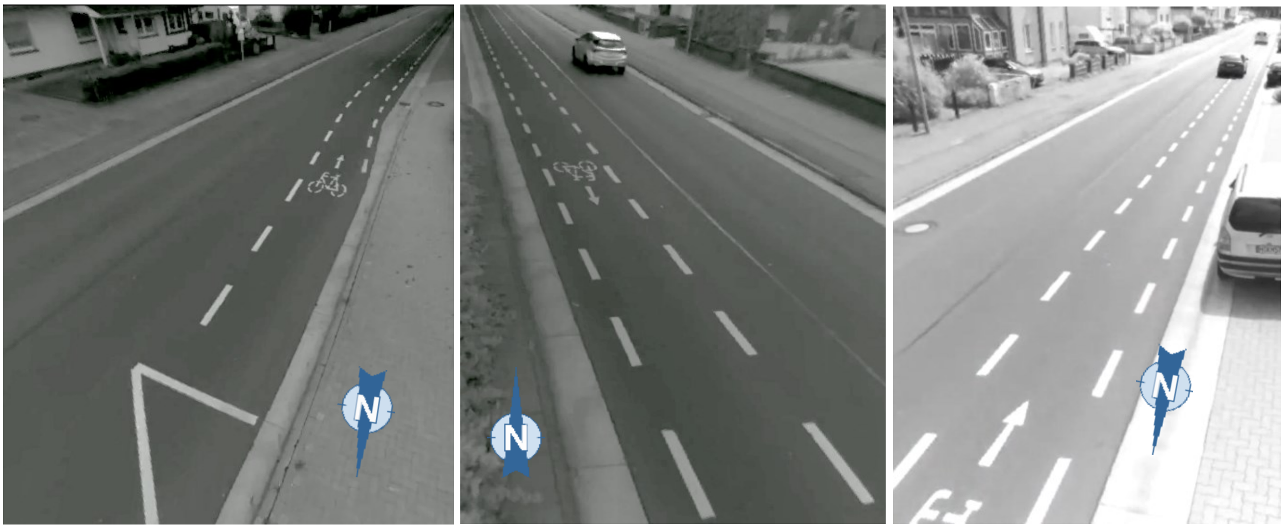


*Figure 25 Location 5a, Camera shots taken by first, second and third postion, 150 metres far from each other's*


The 5A location is considered a two-way neighbourhood street, with a cycle lane on which motorised vehicles can also travel, giving cyclists priority and forcing them to overtake. Traffic consists almost exclusively of cars and commercial vehicles, with an average presence of cyclists. Three video cameras have been installed, placed about 150 metres apart.

### 5.2.1.7 Location 5A-5B - AFTER

Second Campaign – June 2022

27/06/2023
28/06/2023
29/06/2023
30/06/2023

Cod M2,

Nienburger Str., Wunstorf,

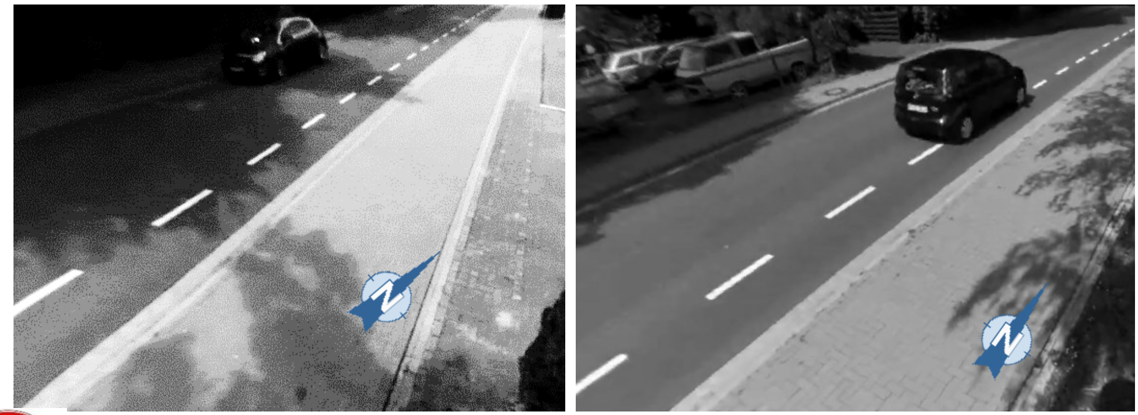



*Figure 26 Location 5b, Camera shots taken by first and second postion, 150 metres far from each other's*

Location 5B is also a neighbourhood street, located on the same boulevard as location 2, but 1000 metres away. For this reason, the number of passages is comparable to the flow at that location. Again, an infrastructure of the third type mentioned in the standards chapter has been included. There is a pavement on both sides, but there are no reports of cyclists passing on this location. Two cameras have been installed at 150 metres from each other

### 5.2.1.8 Location 5A-5B - AFTER

Second Campaign – August 2023

24/08/2023 26/08/2023
25/08/2023 27/08/2023

Cod 5A 5B,

*Figure 27 Location 5a - 5b, Camera shots taken by first of 5a and second position of 5b. The camera is scale of grey, but its possible note the difference in the picture above*

In the second campaign of the study, the lane for cyclists was painted over in red, while still allowing vehicles to drive over it.

# 6 Methodology

The general methodological framework used in the analysis is illustrated in Fig 28. It is independent of the data extraction method used, and only requires a set of trajectories projected onto a planimetric X, Y plane. This tool has been developed in MATLAB, but it is suitable to be replicated in other programming environments.

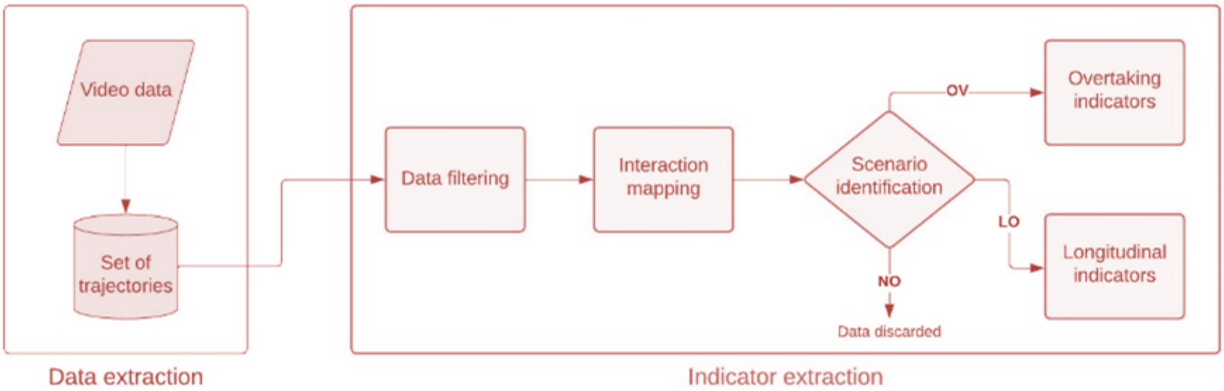



*Figure 28 . Methodological framework of the thesis work. It includes data extraction and process to extract indicators by scenario observed.*

The process starts with the video data, from which all trajectories are extracted. In a second step, the data are subjected to a data filtering and first discard phase: data cleaning and the removal of irrelevant trajectories take place. The next step involves identifying the type of interaction from the mapping of mutual trajectories between different types of road users, such as cyclists and motor vehicles. From this last step, the corresponding scenario and indicators are determined.

## 6.1 Data extraction procedure

In order to extract trajectories that are suitable for indicator extraction, the video recordings were subjected to a three-step computer vision process, comprising detection/classification, tracking and projection. This procedure has previously been applied in other studies on the interaction between motorised vehicles and vulnerable road users like pedestrians (Batista and Friedrich, 2022; Orsini et al., 2023; Tzouras et al., 2023).

In the initial stage of the process, objects were identified and categorised in each frame of the video using a trained neural network. The categories that could be discerned were pedestrian, motorcyclist, cyclist, car, bus, delivery vehicles, truck, roller, semi-trailer truck, tram, and trailer.

In the tracking step, detected objects at close positions in consecutive frames compose a trajectory. Once a new frame of trajectory has been recorded, a new point is projected to the plan in camera frame coordinates (pixels). It is crucial explain that position plotted of the pinpoint matches the barycentric tag of the vehicles. In order to study interactions between objects using distance, speed, and acceleration in uniform manner at any region of the observed view, a transformation of the coordinates from 3D-perspective to 2D-plan is necessary. This is the third and final step of the trajectory extraction process:  A set of reference pairs of points that match between the two views helps create a homographic matrix, as a transformation of coordinates to another reference system.

In the next images (fig.29 -30), the homography points for each of Location 4 and Location 1 are reported.

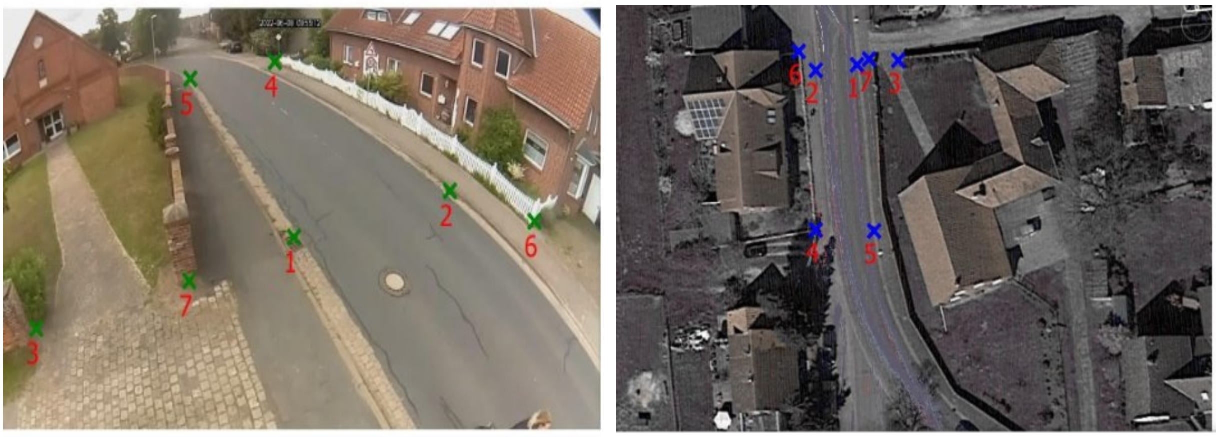



*Figure 29 :  Homography points in Location 4: camera perspective view and in the 2D in the first picture, aerial view with matching pairs of testers in the right. Source: Mouver-google Maps*

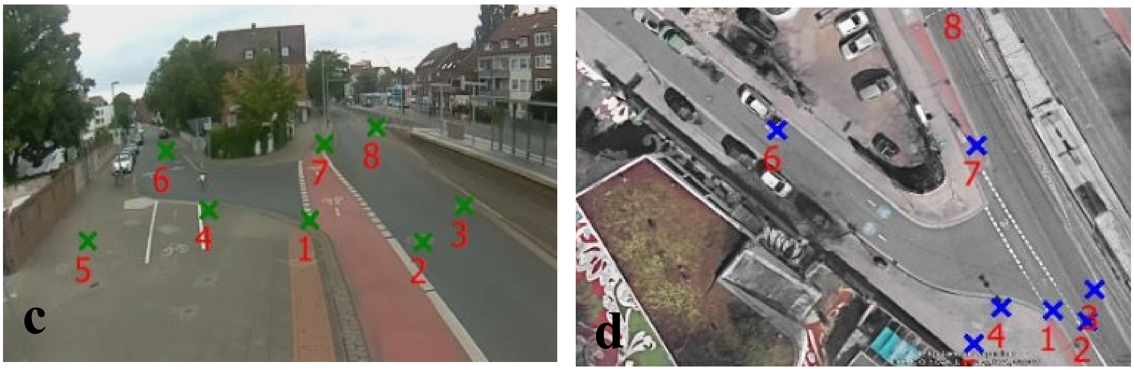



*Figure 30 Homography points in Location 1: camera perspective view and in the 2D in the first picture on left, aerial view with matching pairs of testers on the right. Source: Mouver-google Maps.*

It is essential that these points are derived from fixed natural points at the level of the street, such as horizontal signs, the angles of pavements, and the bases of streetlamps. It was considered that some points should be taken at background or in areas attached to the road included and captured in the screen. If the projected trajectories initially differed from the actual vehicle trajectories, more pairs of visible reference points were selected for the next trial in order to improve accuracy. The greater the number of points placed, the more similar the 3D trajectory will be to the real one.

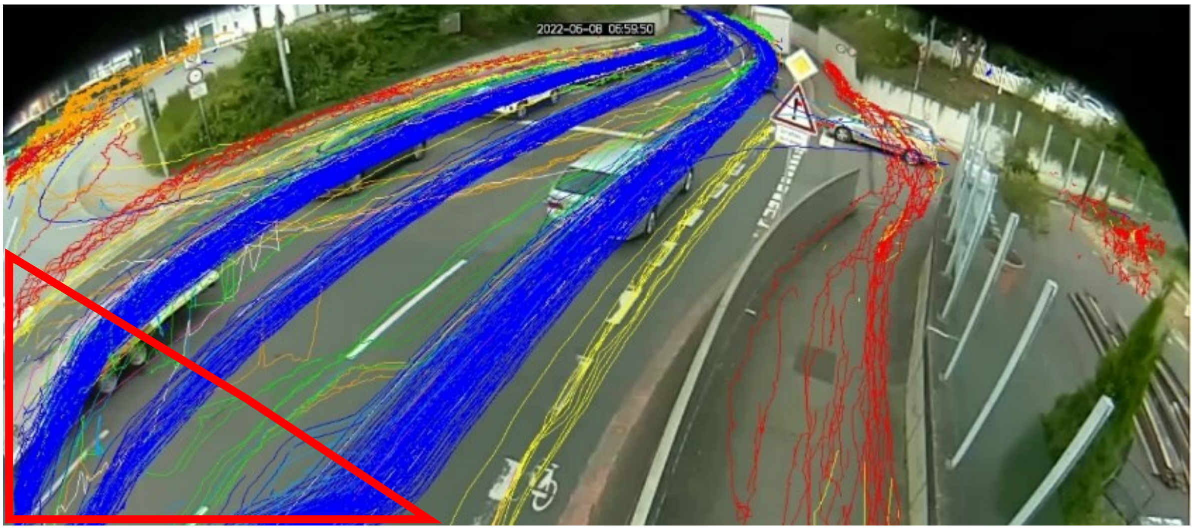



*Figure 31 trajectories in Location 3, the output of the tracking process is presented in this figure, still sorted by categories: blue for vehicles, yellow for bicycles, and red for pedestrians. Other colours such violet, orange and green are distinguishing other mode traffic.*

*The red triangular framework is indicative of one distorted area, which is hypothesised to affect the trajectories in the vicinity of the camera's edge (see below).*

## 6.2 Manual Integrations in the Vehicle Detection and Tracking Process

The vehicle detection process demonstrates excellent performance in recognising and accurately classifying vehicles, due to neural network training. However, a natural limitation of this detection is the difficulty of accurately placing the tag at the actual centre of mass of the vehicle. This margin of error is more pronounced for long vehicles, such as buses, where the compressed image recognises the vehicle but cannot accurately determine its length. As a result, the detection process may cause the tag to be displaced from the centre of mass, positioning it either forward or backward, to the right or left, depending on the direction of roads, width, length, and also the height and inclination of the installed camera. This error affects cyclists more marginally, due to their shorter length.

Another limitation of the tracking process is the inability to detect the centre of mass of vehicles and bicycles before they have fully entered the camera's field of view. In these cases, the detection process is successful and can identify the categories of the incoming users. However, the tracker inserts the tag in each frame based on what has been detected. This limitation becomes particularly problematic when critical interactions occur directly within the camera's field of view, when both bicycle and car are too close to the framework of view: Even only the front of a car enters the field of view in a given shot, the system places the tag in front of the driver's cab. In this case, the trajectory of car can be distorted (fig 31, in red framework), and the system can produce inaccuracy in measuring the distance between the vehicle and other users becomes significant.

In fact, in order to conduct a quality check of the following calculation process, it was necessary to adopt an alternative procedure.

For these reasons, it was necessary to resort to a manual tracking phase to integrate or complete the automatic detection in critical cases. Manual tracking was used in all cases where the minimum distance was less than 2.50 metres. The values obtained were compared with those obtained manually, frame by frame. In rare cases, the trajectory was adjusted by interpolating the parameters obtained with the two measurement methods.

Manual tracking was conducted using the Tracking.Gui software developed by mouver (Dr.-Ing.Fourati W., Dr.-Ing. Trifunovic A.), by carefully selecting for each frame the contact point between the front lateral tyre of the follower vehicle and the contact point of the rear tyre for the cyclists. This procedure made it possible to bypass the entire phase of generating the vehicle box and calculating the net clearance from the vehicle chassis to the bike. Regardless of where the automatic detection places the centre of mass of the vehicle, this manual approach can be considered an absolute measure and considered effective.

This detection covered all interactions recorded in the first campaign, sampling 29 interactions in location 1, 13 in location 2, 35 in location 3, and 18 in location 4. The manual method revealed some variations in distance measurements, but these discrepancies do not appear to correlate with infrastructure, direction of travel, location, or vehicle category. The variations are fluctuations that occur only in certain sections of the trajectories of the follower-leader pairs. A variation can occur both close to the camera and in the background.

It is important to note that when analysing all the manual trajectories and comparisons made, the variations were more limited near the camera (about 10-15 cm), whereas they reached larger discrepancies (25-40 cm) in the background. These results confirm the statements made by the manufacturers of the Tracking.gui software regarding the precision of the tool, which is said to be unreliable at more than 15 metres from the installation. After a preliminary check, the two methods were found to be consistent within the previously mentioned limitations.

In the second phase of the campaign, it was resolved that reliance should be placed solely on the automatic procedure, as this produced highly accurate clearance results that were comparable to those achievable through video checking. Furthermore, the camera's framing was enhanced, focusing on segments no longer than 20 metres, with tracking now confined to this restricted shot. As a consequence, in the second campaign, it was determined that the manual tracking phase was no longer necessary, although sample checks were performed on the most critical interactions, showing satisfactory correspondence between manual and automatic tracking.

## 6.3 Data cleaning and preparation

The first operation is to import in MATLAB the dataset of extracted trajectories as a table. Within this table, each line corresponds to a specific frame, reporting X, Y coordinates (referring to either a geographical or a local reference system) and a Label indicating the vehicle type. Successively, the instantaneous speed and acceleration between successive frames are calculated based on these coordinates. The dataset was sorted by ID_trajectory, with the number increasing in the order in which the first frame was detected. As a second condition, the trajectories were categorised by frame /date. In this case, any rows represented a frame moment for a specific user.

| 1<br>TRAJECTORY_ID | 2<br>FRAME_NO | 3<br>X | 4<br>Y | 5<br>WIDTH | 6<br>HEIGHT | 7<br>DETECTED | 8<br>CONFIDENCE | 9<br>LABEL | 10<br>time | 11<br>stream | 12<br>dist | 13<br>v | 14<br>a |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2158 | 137238 | 50.4442 | 58.8878 | 24 | 69 | 1 | 0.7935 | "radfahrer" | 2022-06-08 03:16:... | "Hildeshei... | 0.2203 | -0.6039 | -18.1169 |
| 2158 | 137239 | 50.3103 | 58.7782 | 24 | 69 | 1 | 0.7769 | "radfahrer" | 2022-06-08 03:16:... | "Hildeshei... | 0.1730 | -1.4171 | -42.5136 |
| 2158 | 137240 | 50.2011 | 58.6920 | 24 | 68 | 1 | 0.7427 | "radfahrer" | 2022-06-08 03:16:... | "Hildeshei... | 0.1391 | -1.0177 | -30.5306 |
| 2158 | 137241 | 50.0922 | 58.6042 | 23 | 68 | 1 | 0.7676 | "radfahrer" | 2022-06-08 03:16:... | "Hildeshei... | 0.1399 | 0.0223 | 0.6676 |
| 2158 | 137242 | 49.9689 | 58.5025 | 24 | 66 | 1 | 0.6753 | "radfahrer" | 2022-06-08 03:16:... | "Hildeshei... | 0.1599 | 0.6001 | 18.0038 |
| 2158 | 137243 | 49.8410 | 58.3967 | 23 | 65 | 1 | 0.7129 | "radfahrer" | 2022-06-08 03:16:... | "Hildeshei... | 0.1660 | 0.1843 | 5.5282 |
| 2158 | 137244 | 49.7275 | 58.3030 | 22 | 64 | 1 | 0.7432 | "radfahrer" | 2022-06-08 03:16:... | "Hildeshei... | 0.1471 | -0.5658 | -16.9734 |
| 2158 | 137245 | 49.6310 | 58.2204 | 23 | 64 | 1 | 0.6401 | "radfahrer" | 2022-06-08 03:16:... | "Hildeshei... | 0.1270 | -0.6049 | -18.1468 |
| 2158 | 137246 | 49.5370 | 58.1325 | 23 | 64 | 0 | 0 | "radfahrer" | 2022-06-08 03:16:... | "Hildeshei... | 0.1288 | 0.0539 | 1.6159 |
| 2158 | 137247 | 49.4365 | 58.0316 | 23 | 64 | 1 | 0.5034 | "radfahrer" | 2022-06-08 03:16:... | "Hildeshei... | 0.1424 | 0.4077 | 12.2318 |
| 2158 | 137248 | 49.3400 | 57.9316 | 21 | 62 | 1 | 0.5615 | "radfahrer" | 2022-06-08 03:16:... | "Hildeshei... | 0.1390 | -0.1007 | -3.0224 |
| 2158 | 137249 | 49.2569 | 57.8448 | 21 | 62 | 0 | 0 | "radfahrer" | 2022-06-08 03:16:... | "Hildeshei... | 0.1201 | -0.5659 | -16.9776 |
| 2158 | 137250 | 49.1724 | 57.7579 | 21 | 62 | 0 | 0 | "radfahrer" | 2022-06-08 03:16:... | "Hildeshei... | 0.1212 | 0.0317 | 0.9499 |
| 2158 | 137251 | 49.0462 | 57.6312 | 21 | 61 | 0 | 0 | "radfahrer" | 2022-06-08 03:16:... | "Hildeshei... | 0.1788 | 1.7293 | 51.8792 |
| 2158 | 137252 | 48.8414 | 57.4294 | 21 | 61 | 0 | 0 | "radfahrer" | 2022-06-08 03:16:... | "Hildeshei... | 0.2875 | 3.2593 | 97.7783 |
| 2158 | 137253 | 48.5753 | 57.1696 | 21 | 60 | 1 | 0.5771 | "radfahrer" | 2022-06-08 03:16:... | "Hildeshei... | 0.3719 | 2.5325 | 75.9762 |
| 2158 | 137254 | 48.3162 | 56.9175 | 20 | 58 | 1 | 0.5674 | "radfahrer" | 2022-06-08 03:16:... | "Hildeshei... | 0.3615 | -0.3112 | -9.3359 |
| 2158 | 137255 | 48.1134 | 56.7181 | 20 | 58 | 1 | 0.6045 | "radfahrer" | 2022-06-08 03:16:... | "Hildeshei... | 0.2844 | -2.3142 | -69.4274 |

*Figure 32 A database of trajectories has been constructed. Each row represents a trajectory and its associated characteristics within a single frame. In this figure, the standard database is presented, containing the gap, velocity, and acceleration for each frame of Vehicle n°2158, from the 58,8878th to the 567,181st recorded frame of the day. The variables X and Y indicate the position, while the "Label" variable denotes the traffic mode (i.e., "radfahrer" means "cyclist" in German). The "stream" variable specifies the direction, and the "v" and "a" variables represent the instantaneous velocity and acceleration, respectively.*

After extracted the dataset, traffic flows in the different directions were separated, selecting only those directions most clearly visible according to the camera field of view. This choice depends by location, width of the roadway, obstacles, frequency of large vehicles and visibility. It is possible for larger vehicles with important volumes, such as trucks or buses, to hide a cyclist during an overtaking manoeuvre for a few seconds, but in the most critical moments, they may obscure the target to detection.

The trajectories under examination were required to align with the defined study scenarios. Therefore, the trajectories of cyclists which were using sidewalks or protected bicycle lanes, were excluded to reduce the number of interactions to be analysed. This operation involved the comparison of the coordinates of the cyclists' trajectories with the coordinates of the natural references, such as the pavement edge or barriers.

Furthermore, we identified the list of trajectories and printed them out in an aerial view, with the X and Y coordinates clearly visible. From this graph, we could identify the trajectories that were significantly distant from the rules or were not suitable for consideration. For instance, cyclists driving in the opposite lane respect the stream that they belong to.

The approach used to identify risk indicators in the studied conditions begins with identifying interactions between a cyclist (Leader) and a following vehicle (Follower).

Databases were extracted for each detection day and location from the video recordings. Each trajectory state corresponds to a specific frame, identified by an ID variable. Subsequent trajectories follow in order of appearance. When multiple trajectories are present in the same time frame, the entire trajectory is displayed first, followed by the others. Each recording includes the ID, temporal reference, spatial reference with X and Y coordinates of the tag, confidence level, and label indicating the type of vehicle. Additionally, the instantaneous speed between frames and correlated acceleration can be derived from the coordinates of each frame.

The trajectories were initially sorted by label in order to isolate only cyclists. Subsequently, we selected non-vulnerable users' trajectories that were simultaneous with the reference cyclist's trajectory. Specifically, the selection kept only vehicles that began or ended within the time interval occupied by the cyclist to complete their trajectory in the camera's field of view. To capture trajectories just before and after the reference interval, the offset was extended by a certain lag (e.g., in our case study application we used 10 seconds). This reasonably ensures that all possible interactions are captured. Subsequently, a manual validation was conducted on a video sample to check for any potential exclusions.

After obtaining the list of contemporary Follower-Leader pairs for at least one frame within the recording, a preliminary selection was made. However, the majority of the events on the list were discarded by calculating the minimum distance recorded between them. It is important to note that the preliminary distance calculation did not correspond to the effective distance as it merely measured the space between the Cyclist's Tag and the vehicle's Tag. To ensure objectivity, a maximum threshold of 15 metres has been set. This threshold applies even in cases where the Follower is an articulated lorry, such as buses or trucks, where the size can hide shorter clearances or critical cases.

## 6.4 Scenario definition and identification

For all other bicycle-vehicle pairs that were not discarded in the previous step, parameters are calculated according to the type of interaction that occurs between the trajectories of the two subjects in the visible scene. For these interactions, two main scenarios were defined, each with a separate method for calculating the safety-relevant indicators:

- The Overtaking scenario (OV), which occurs when the motor vehicle moves alongside the cyclist and performs an overtaking manoeuvre.
- The Longitudinal scenario (LO), in which the motor vehicle trails behind the cyclist, waiting to overtake or simply following them.

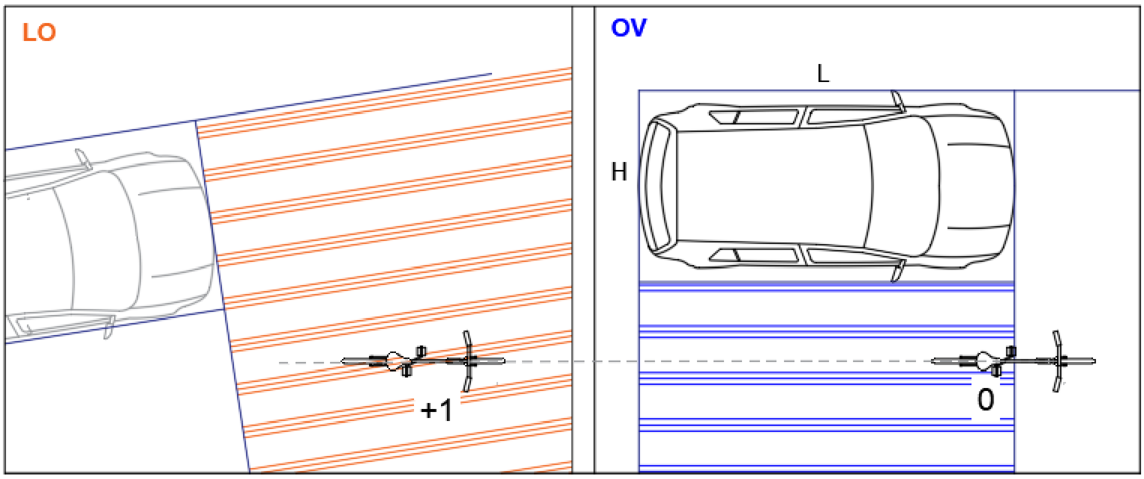



*Figure 33 : two different scenarios: Longitudinal scenario (1), Lateral scenario (2)*

In order to correctly identify these two scenarios, it is necessary to obtain information regarding the positions, directions, and estimated dimensions by bounding box, of the two users at same moment. The box, representing the dimensions of the motor vehicle; it is reconstructed starting from the coordinates associated with the tag on the vehicle. The rectangular projection element has a width (H) and a length (L), with the tag positioned at the centre of mass. The dimensions of the 'box' are determined by the vehicle type. It is important to note that the classification of vehicles in greater detail allows for more precise definitions of the boxes.

| Vehicle Type | H(m) | L(m) |
|---|---|---|
| Car | 2.02 | 4.75 |
| Truck | 2.60 | 10.40 |
| Delivery Vehicle | 2.4 | 6.0 |
| Semi-trailer Truck | 2.5 | 16.5 |
| Bus | 3.3 | 12.50 |

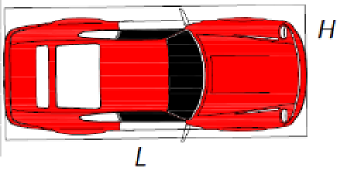



*Figure 34 Height and Width of Standard German car*

To correctly fit the box position within the reference system, it is necessary to know the motor vehicle trajectory direction, that in principle may change at any time instant. For each time frame, this direction is defined by an angle α (alpha) obtained by comparing the position of the tag with a few tenths of a second later, derive the direction. Once the rotation is determined, the rectangular projection of the vehicle can be reconstructed. Similarly, for the bicycle, two significant points were identified, representing the extremities of the rear and front wheel.

With these points, we could reconstruct the frame-by-frame type of interaction occurring between the follower-leader pair and determine the scenario in which the

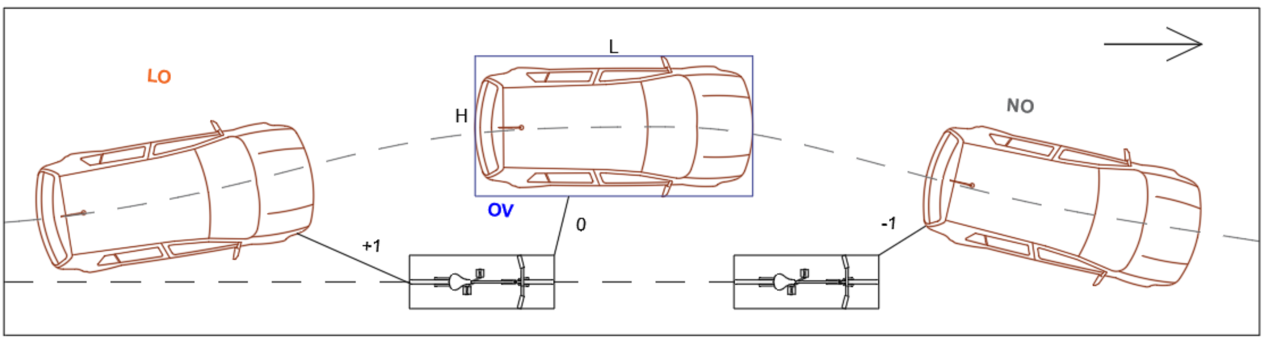



*Figure 35 mapping interaction by where the cyclist in those frames is according to the vehicle's reference system. "Firstly, Lo condition, then OV and at the end No, is the correct sequence to complete an overtake* case resides. The methodology used a condition by a macro-area division of the space around the follower:

Using these points, it is possible to systematically reconstruct the interaction between the vehicle-bicycle pair frame by frame. To interpret each interaction and determine the specific scenario in which each case unfolded we adopted an approach that we called "interaction mapping" (Fig.35):

A numerical sequence was assigned to each interaction based on the bicycle position relative to the motor vehicle. A specific time frame was assigned an index of '+1' if both wheels of the cyclist were in front, an index of '0' if at least one point of the cyclist's footprint was to the right of the vehicle, and an index of '-1' if the cyclist position was elsewhere, such as to the left or behind the vehicle.

By observing the numerical sequence of each trajectory, it was possible to assign the event to the scenario where it belongs:

- if the cyclist will be in front throughout the trajectory, and his sequence only consist of indices equal to 1, then the event will belong to the first Leader-Following (LF) scenario.
- if the cyclist's sequence includes a transition from 1-0-(-1), the event can be considered as a complete overtaking (OV).
- If the sequence only passes from 1-1-0, probably the overtaking recorded inside will not be complete as well. In any case it belongs to the second scenario (OV).

If a sequence did not match any of the predefined scenarios, it was identified as an anomalous case and labelled as (NO). These cases could occur when cyclists turned left simultaneously while the vehicle overtook them on the right, when the bike overtook parked cars, or when cyclists exhibited unusual behaviour. The percentage of 'NO cases' depended mainly on the location's characteristics and traffic.

After a careful manual selection of which cases could be re-assessed as interesting for the topic, this category of events was eliminated.

## 6.5 Computation of safety-relevant indicators

Once a given vehicle-bicycle interaction is assigned to a specific scenario, the safety-relevant indicators can be computed. In this study, the indicator extraction methodology was developed to consider the following variables, but alternative and additional indicators can potentially be retrieved.

For the overtaking scenario: LC [m], the minimum lateral clearance, defined as the minimum distance between cyclist and motor vehicle in an OV scenario; ΔV [km/h], the speed difference between cyclist and motor vehicle at the time frame of minimum lateral clearance.

For the longitudinal scenario: RC [m], the minimum rear clearance, defined as the minimum distance between cyclist and motor vehicle in a LO scenario; THW [s], the minimum time headway between cyclist and motor vehicle in a LO scenario; TTC [s], the minimum time-to-collision between motor vehicle and the bicycle.

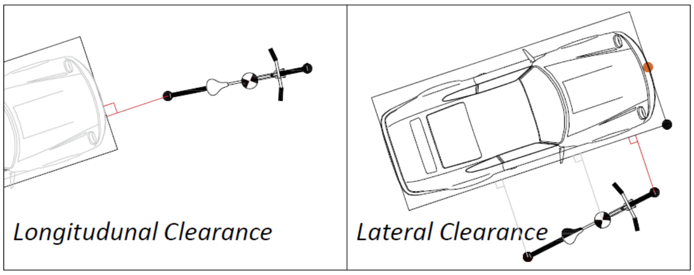



*Figure 36 Longitudinal Rear distance RC (1), Lateral Clearance (2)*

An RC threshold can be used to filter out those scenarios that were initially labelled as "LO" but in which the motor vehicle was at such a considerable distance from the cyclist that it did not constitute a genuine interaction.

Regardless of the scenario, the tool can extract aggregate information regarding a single trajectory (e.g., the average speed of a specific tracked bicycle) or at a database-level (e.g., traffic counts or average speeds of vehicles in a specific road cross sections).

# 7 RESULTS AND DISCUSSION

## 7.1 Results of First Campaign

The purpose of this campaign is to focus on the safety surrogate indicators in the first location and to compare each of them. The first task of our study was to analyse the data collected during the previous campaign, which aimed to compare all locations numbered 1, 2, 3 and 4, each representing different scenarios and contexts. This comparison is crucial to understanding the dynamics of interactions between cyclists and other road users in various environmental and infrastructural situations.

The following table 2 shows the descriptive statistics for the number of interactions with a safe distance of less than 2.00 metres for the different OV Scenario and LO Scenario. As can be seen, locations 1 and 3 show a significant number of interactions, while locations 2 and 4 show a very small number of cases, making a direct comparison between all locations difficult.

*Table 2: Descriptive Statistics of first campaign, number of interactions in each Locations by Scenario*

| | Number of interaction (Clearance < 2,00m) | | | |
|---|---|---|---|---|
| | LOC1 | LOC2 | LOC3 | LOC4 |
| OV | 218 | 7 | 134 | 18 |
| LO | 0 | 3 | 1 | 2 |

The different locations are almost incomparable in terms of the number of interactions compared. Locations 1 and 3 present enough instances of interactions between cyclists and other users to be able to derive some significant data.

Therefore, we will limit ourselves to a descriptive analysis that may highlight some relevant aspects.

- Since it is a cycle track, location 2 has no LO events, only OV events.
- In the case of location 3, there are a few LO-type events, but the vast majority fall into the OV category.
- Location 4 has very few cases recorded overall, reflecting a low level of traffic. However, the interactions that did occur represent some critical issues: there were a couple of LO-type cases, including one between a bicycle and a bus, and a few OV-type cases.
- Location 2 had an extremely low number of recorded interactions, which can be attributed to the rural area in which it is located, characterised by a very low number of interactions overall. This low number of interactions is also influenced by the frequent misbehaviour of cyclists, who often ride on the pedestrian path.

Therefore, before comparing all four locations analysed, it was decided to improve the sample of location 2 for the 2022 campaign, including those interactions that initially occurred in the opposite lane. Based on the observations captured by videos, there was a possible equivalence observed between the two streams regarding the availability to overtake the cyclist. In the opposite flow, the same visibility, the same lane width is present. Moreover, the middle lane is persistently employed for overtaking manoeuvres, which would be proscribed in the opposite direction of traffic flow.

Accordingly, only for both streams of the locations 2, we introduced a MANOVA and ANOVA tests to check whether the two flows will match in terms of Lateral Clearance and Realistic Velocity.

*Table 3 MANOVA: Pillai Test in comparing Two Flow of Location 2 to merge flows in a single sample.*

| Cases | df | Approx. F | $Trace_{Pillai}$ | Num df | Den df | p |
|---|---|---|---|---|---|---|
| (Intercept) | 1 | 194.326 | 0.968 | 2 | 13.000 | < .001 |
| Stream | 1 | 1.364 | 0.173 | 2 | 13.000 | 0.290 |
| Residuals | 14 | | | | | |

Pillai's trace (MANOVA) indicates whether the overall mean of the response variables is significantly different from zero. The significance of the intercept ($p<0.001$) suggests a substantial effect. However, the traffic flow direction is not significant ($p=0.290$), indicating that the stream to which the interaction belongs does not significantly influence the dependent variables in the model.

*Table 4: Anova test for variables Lateral Clearance LC just in LOC2. The table presents the analysis of variance (ANOVA) conducted to evaluate the effect of the "Stream" factor on clearance. The results include the sum of squares, degrees of freedom (df), mean square, F-statistic, and p-value for each component.*

ANOVA: Clearance

| Cases | Sum of Squares | df | Mean Square | F | p |
|---|---|---|---|---|---|
| (Intercept) | 53.782 | 1 | 53.782 | 154.862 | < .001 |
| Stream | 0.090 | 1 | 0.090 | 0.258 | 0.619 |
| Residuals | 4.862 | 14 | 0.347 | | |

*Table 5: Anova test for variables rel. velocity just in LOC2. The table presents the analysis of variance (ANOVA) conducted to evaluate the effect of the "Stream" factor on relative passing speed. The results include the sum of squares, degrees of freedom (df), mean square, F-statistic, and p-value for each component.*

ANOVA: DeltaV

| Cases | Sum of Squares | df | Mean Square | F | p |
|---|---|---|---|---|---|
| (Intercept) | 6.342.542 | 1 | 6.342.542 | 116.295 | < .001 |
| Stream | 159.601 | 1 | 159.601 | 2.926 | 0.109 |
| Residuals | 763.538 | 14 | 54.538 | | |

Both the intercept is highly significant ($p<0.001$), showing a significant baseline effect and the variable Stream don’t affect enough significantly clearance and speed.

Overall, these tests show that while there is a significant baseline effect in all cases, the variable Stream does not significantly influence either the clearance or DeltaV variables in this analysis. Thus, data from the other direction can be added (6 events) to the comparison of speed and distance, aligning with the assumptions made.

### 7.1.1 Lateral Clearance

The following table shows descriptive statistics for the clearance measured at four different locations (LOC1, LOC2, LOC3, LOC4). The data include the number of valid observations, mean, standard deviation, variance, minimum and maximum values, as well as the results of the Shapiro-Wilk test for normality:

*Table 6 descriptive statistics: numbers, mean of interesting interaction: descriptive statistics of variable Lateral Clerance, i.e. the minimal distance has ever recorded in a single interaction.*

| | **LOC1** | **LOC2** | **LOC3** | **LOC4** |
|---|---|---|---|---|
| Valid | 218 | 16 | 137 | 18 |
| Missing | 0 | 0 | 0 | 0 |
| Mean | 2.676 | 1.633 | 2.036 | 1.408 |
| Std. Deviation | 0.535 | 0.403 | 0.859 | 0.644 |
| Variance | 0.286 | 0.162 | 0.738 | 0.415 |
| Shapiro-Wilk | 0.952 | 0.896 | 0.951 | 0.829 |
| P-value of Shapiro-Wilk | < .001 | 0.119 | < .001 | 0.004 |
| Minimum | 0.811 | 0.978 | 0.514 | 0.611 |
| Maximum | 3.493 | 2.079 | 3.500 | 3.419 |

The statistical analysis of the different locations provides an overview of the characteristics of clearance between cyclists and other road users. LOC1 has the largest number of valid observations (218), with a mean clearance of 2.676 metres and a standard deviation of 0.535. LOC3 also has a significant number of observations (134), with a mean of 2,021 metres and a standard deviation of 0.862. LOC2 and LOC4 show a very small number of valid observations (16 and 18 respectively), with averages of 1,749 and 1,408 metres.

The Shapiro-Wilk test, used to check the normality of the data, indicates that the distributions of the variable clearance in the LOC1 and LOC3 locations are not normally distributed (p-value < .001), while the LOC2 and LOC4 locations show a distribution that does not deviate significantly from normality (p-value of 0.530 and 0.004 respectively).

The following table shows the results of the analysis of variance (ANOVA) applied to the clearance data at the four locations (LOC1, LOC2, LOC3, LOC4). This test was conducted to determine whether there were statistically significant differences in the averages of the clearance distances between the different locations.

*Table 7 ANOVA results for the effect of Location. The table displays the analysis of variance (ANOVA) assessing the impact of the "Location" factor. The results include the sum of squares, degrees of freedom (df), mean square, F-statistic, and p-value for the "Location" factor and the residual.*

| **Cases** | **Sum of Squares** | **df** | **Mean Square** | **F** | **p** |
|---|---|---|---|---|---|
| Location | 59.318 | 3 | 19.773 | 44.049 | < .001 |
| Residuals | 171.472 | 382 | 0.449 | | |

*Note.* Type III Sum of Squares

The mean square for locations is 18.689, and for residuals is 0.458. The F-test value, which is the ratio of the mean square of the locations to that of the residuals, is 40.800.

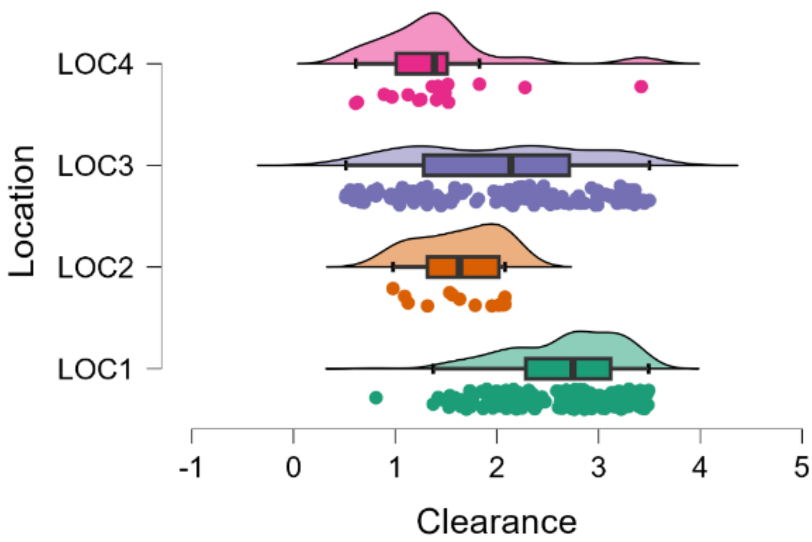



*Figure 37 Distribution of Lateral Clearance (LC) by Location.*

*The figure illustrates the distribution of lateral clearance (LC) values across four different locations (LOC1, LOC2, LOC3, and LOC4). The violin plots show the density of the data at different values of clearance, while the box plots provide a summary of the median, interquartile range, and potential outliers.*

This high F-value, combined with a p-value of less than 0.001, indicates that there are statistically significant differences in the averages of the lateral clearance between the four locations.

The distribution for location 1 appears to be the most dispersed, exhibiting a relatively wide range of LC values. The box plot indicates that the median LC is higher than in some other locations, and the presence of numerous individual data points suggests a high degree of variability within this location. However, an isolated event was recorded and highlighted as the minimal clearance in the recording, represented with an isolated dot on the left side of the violin plot. Further details will be provided in the conclusion, in section 7.1.4. The distribution for location 2 is more compact, with a smaller range of LC values in comparison to the first. The median is lower, and the distribution appears to be somewhat asymmetrical to the right, indicating that the majority of values are clustered at the lower end of the range, with a few higher outliers. The distribution of LOC3 is comparable to that of LOC2, exhibiting a narrow range and a higher median. However, it appears to be slightly more concentrated around the median, suggesting a higher degree of consistency in the data points. The density of data points is higher around the median, indicating a more consistent set of LC values. Location 4 has a distribution similar to Location 1, with a relatively wide range of LC values. However, Location 4's median is the highest among the four locations, and the density plot suggests a bimodal distribution, indicating two peaks in the data, which may suggest different underlying subgroups or conditions within this location.

After identifying significant differences between the mean clearances between the four locations using ANOVA, it is crucial to investigate which specific groups differ from each other. However, due to the non-normality of the distribution in some locations, a non-parametric analysis was necessary.

*Table 8 Post-hoc Tukey's HSD test for pairwise comparisons between locations.*
*The table presents the results of Tukey's (HSD) test, which was conducted to compare the mean lateral clearance (LC) between different locations following a significant ANOVA result: mean differences, standard errors (SE), t-values, and adjusted p-values (ptukey).*

| | | Mean Difference | SE | t | $p_{tukey}$ |
|---|---|---|---|---|---|
| LOC1 | LOC2 | 1.043 | 0.191 | 5.455 | < .001 |
| | LOC3 | 0.640 | 0.073 | 8.759 | < .001 |
| | LOC4 | 1.268 | 0.164 | 7.718 | < .001 |
| LOC2 | LOC3 | -0.404 | 0.194 | -2.076 | 0.163 |
| | LOC4 | 0.225 | 0.244 | 0.922 | 0.793 |
| LOC3 | LOC4 | 0.628 | 0.168 | 3.741 | 0.001 |

*Note.* P-value adjusted for comparing a family of 4

The post hoc analysis shows that:

- LOC1 shows statistically significant differences in safety distances compared to LOC2, LOC3 and LOC4.
- LOC3 shows significant differences compared to LOC4.
- There are no statistically significant differences between LOC2 and LOC3, nor between LOC2 and LOC4.

These results confirm the differences observed in the ANOVA analysis and provide a more detailed understanding of the specific location pairs that differ.

The Kruskal-Wallis test is a non-parametric test, alternative to the ANOVA that does not assume normality in the data. The Dunn's test is a non-parametric method used for multiple comparisons. It is particularly useful when dealing with data that do not follow a normal distribution. These combined tests provide detailed insight into the differences between locations, allowing us to better understand the dynamics of interactions between cyclists and other road users in the different areas studied.

*Table 9 Kruskal-Wallis test for differences in lateral clearance across locations*

Kruskal-Wallis Test

| Factor | Statistic | df | p |
|---|---|---|---|
| Location | 84.820 | 3 | < .001 |

*Table 10 Dunn's post-hoc test for pairwise comparisons between locations.*
*This table presents the results of Dunn's test conducted to identify which specific pairs of locations differ significantly in terms of lateral clearance. The table includes the z-scores, sum of ranks for each location (Wi and Wj), and various p-values adjusted for multiple comparisons.*

| Comparison | z | $W_i$ | $W_j$ | p | $p_{bonf}$ | $p_{holm}$ |
|---|---|---|---|---|---|---|
| LOC1 - LOC2 | 4.792 | 236.032 | 83.385 | < .001 | < .001 | < .001 |
| LOC1 - LOC3 | 6.871 | 236.032 | 152.453 | < .001 | < .001 | < .001 |
| LOC1 - LOC4 | 6.056 | 236.032 | 70.333 | < .001 | < .001 | < .001 |
| LOC2 - LOC3 | -2.133 | 83.385 | 152.453 | 0.033 | 0.198 | 0.066 |
| LOC2 - LOC4 | 0.321 | 83.385 | 70.333 | 0.748 | 1.000 | 0.748 |
| LOC3 - LOC4 | 2.936 | 152.453 | 70.333 | 0.003 | 0.020 | 0.010 |

Significant differences ($p < .001$) are observed mainly between the urban location 1 and the other locations (LOC2, LOC3, LOC4) and between LOC3 and LOC4, indicating significant variations in lateral safety distances between them. These results confirm the heterogeneity of safety distances between locations and suggest the need for further investigation to better understand the local dynamics influencing these differences. This should continue with an analysis of the other variable involved, so the relative velocities of interactions. Therefore, the conclusions derived from this comparison are postponed in §7.1.4 after the following speed analysis.

### 7.1.2 Relative passing Velocity

This metric is crucial for understanding the dynamics of movement between cyclists and road users at the different locations. The statistical analysis includes descriptive statistics, ANOVA tests, the Kruskal-Wallis test and post hoc comparisons to identify significant differences between locations.

*Table 11 descriptive statistics: numbers, mean of interesting interaction: descriptive statistics of variable Relative Passing velocity, i.e. the higher speed gap in overtaking ever recorded in a single interaction.*

| Location | N | Mean Rel. P. Velocity | SD | SE |
|---|---|---|---|---|
| LOC1 | 218 | 30.935 | 11.912 | 0.807 |
| LOC2 | 16 | 21.877 | 7.210 | 2.000 |
| LOC3 | 137 | 10.370 | 6.661 | 0.569 |
| LOC4 | 18 | 26.446 | 8.704 | 2.051 |

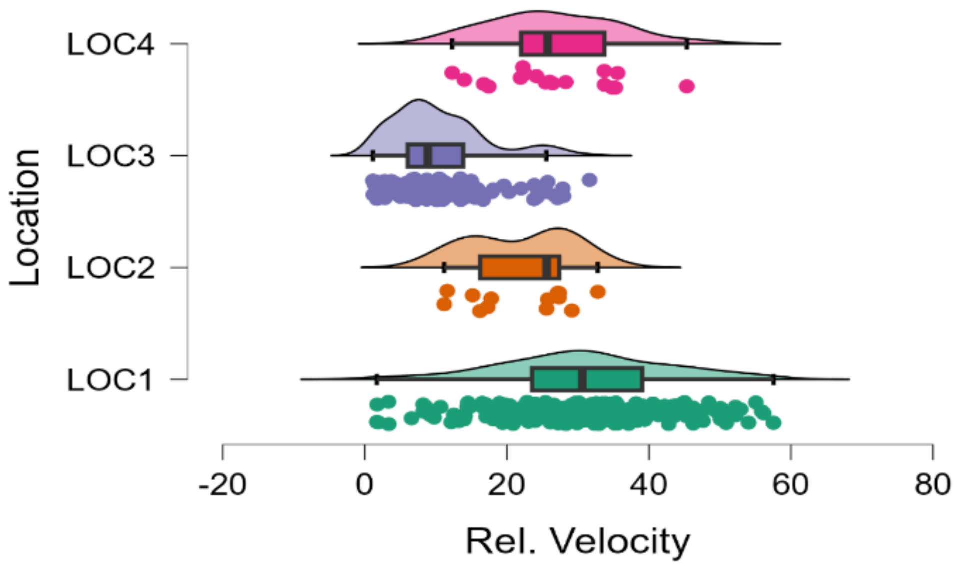



*Figure 38 Distribution of relative passing velocity by Location. The figure illustrates the distribution of speed relative values across four different locations (LOC1, LOC2, LOC3, and LOC4). Each distribution is represented by a combination of a violin plot, box plot, and individual data points.*

- **LOC1** has the highest average relative speed (31.272 km/h) with a standard deviation of 12.739 km/h. In addition, the green distribution in Fig. 38 shows a high range of recorded relative speeds and a larger sample in the study, which may include more combinations of speed pairs (cyclist's and motorist's speed): there may be leaders driving slower than standard (widening the gap) or, more rarely, faster riding mixed with high volume of traffic in the lane that can reduce the gap. In any case, the higher average speed is justified by the constant traffic volume of both traffic modes and probably by lane separation.
- **LOC2** has an average of 23.491 km/h with a standard deviation of 9.073 km/h, but the sample is very small (N=16). The relative yellow distribution shows a bimodal trend but still in the most restricted range among locations.
- **LOC3** shows the lowest average relative speed (10.347 km/h) with a standard deviation of 6.717 km/h as expected, given the segment's conformation with low vehicle speeds. The relative distribution is asymmetrical to the left, suggesting a tendency to have a lower gap, as expected.
- **LOC4** has an average of 26.446 km/h with a standard deviation of 8.704 km/h, in line with location 2.

*Table 12 ANOVA results for the effect of Location. The table displays the analysis of variance (ANOVA) assessing the impact of the "Location" factor. The results include the sum of squares, degrees of freedom (df), mean square, F-statistic, and p-value for the "Location" factor and the residual.*

| Cases | Sum of Squares | df | Mean Square | F | p |
|---|---|---|---|---|---|
| Location | 35.807.140 | 3 | 11.935.713 | 117.703 | < .001 |
| Residuals | 38.736.982 | 382 | 101.406 | | |
| Relative Velocity | | | | | |

The ANOVA shows that there are significant differences in the relative speeds between the different locations (F=105.560, p<.001). A p-value of less than .001 indicates that at least one of the location averages is significantly different from the others. To identify which locations, differ, a post hoc analysis is required.

*Table 13 a non-parametric Kruskal-Wallis Test*

| **Factor** | **Statistic** | **df** | **p** |
|---|---|---|---|
| Location | 191.122 | 3 | < .001 |

The Kruskal-Wallis test, a non-parametric alternative to ANOVA, confirms the significant differences between the locations (Statistic=191.122, p<.001). This result further reinforces the need for a post hoc analysis to identify the specific locations that are different.

*Table 14 Post-hoc Tukey's HSD test for pairwise comparisons between locations.*
*The table presents the results of Tukey's (HSD) test, which was conducted to compare the mean relative velocity between different locations following a significant ANOVA result: mean differences, standard errors (SE), t-values, and adjusted p-values (ptukey).*

| | | Mean Difference | SE | t | $p_{tukey}$ |
|---|---|---|---|---|---|
| LOC1 | LOC2 | 9.058 | 2.875 | 3.151 | 0.009 |
| | LOC3 | 20.566 | 1.098 | 18.732 | < .001 |
| | LOC4 | 4.490 | 2.470 | 1.818 | 0.266 |
| LOC2 | LOC3 | 11.508 | 2.922 | 3.938 | < .001 |
| | LOC4 | -4.569 | 3.665 | -1.246 | 0.598 |
| LOC3 | LOC4 | -16.076 | 2.525 | -6.368 | < .001 |

*Note.* P-value adjusted for comparing a family of 4

*Table 15 Dunn's Post Hoc Comparisons – Location per Relative Velocity.*
*This table presents the results of Dunn's test conducted to identify which specific pairs of locations differ significantly in terms of lateral clearance. The table includes the z-scores, sum of ranks for each location (Wi and Wj), and various p-values adjusted for multiple comparisons.*

| Comparison | z | $W_i$ | $W_j$ | p | $p_{bonf}$ | $p_{holm}$ |
|---|---|---|---|---|---|---|
| LOC1 - LOC2 | 2.080 | 257.62 | 191.385 | 0.038 | 0.225 | 0.113 |
| LOC1 - LOC3 | 14.011 | 257.62 | 87.197 | < .001 | < .001 | < .001 |
| LOC1 - LOC4 | 1.103 | 257.62 | 227.444 | 0.270 | 1.000 | 0.540 |
| LOC2 - LOC3 | 3.218 | 191.38 | 87.197 | 0.001 | 0.008 | 0.005 |
| LOC2 - LOC4 | -0.888 | 191.38 | 227.444 | 0.375 | 1.000 | 0.540 |
| LOC3 - LOC4 | -5.014 | 87.19 | 227.444 | < .001 | < .001 | < .001 |

Post-hoc test shows significant differences in relative speeds between locations, with LOC1 differing significantly from all other locations. LOC3 differs significantly from LOC4, while there are no significant differences between LOC2 and LOC3, nor between LOC2 and LOC4. For many conclusions about comparison between location, to the next chapter (§7.1.4).

### 7.1.3 Correlation between Relative Speed and Clarance

In the following table, a brief mention is made of the correlation between relative speed and overtaking clearances. A Pearson for correlation is introduced.

*Table 16 Pearson's correlation between clearance and relative velocity. The table presents the Pearson correlation coefficient (r) and corresponding p-values assessing the relationship between clearance and relative velocity.*

| **Variable** | | **Clarance** | **Rel. Velocity** |
|---|---|---|---|
| 1. Clarance | Pearson's r | — | |
| | p-value | — | |
| 2.Rel. Velocity | Pearson's r | 0.347 | — |
| | p-value | < .001 | — |

Pearson's correlation coefficient value, r = 0.347, indicates a moderate positive correlation between safety distance (Clearance) and relative speed (Rel. Velocity). This means that, on average, an increase in relative speed is associated with an increase in safety distance between cyclists and other road users.

### 7.1.4 First campaign Discussion

In terms of relative speed, lateral distance, and the number of cases, the trends in these locations are quite distinct.

Location 1 shows statistically significant values for relative speed and lateral distance compared to the other sites. The interactions between vehicle and bicycle trajectories are less pronounced here, likely due to the infrastructure design, which clearly separates bike lanes from car lanes. Even though we might let concludes that this location might be safer than others, however one critical traffic conflict between a cyclist and a bus was captured in the recordings: the trajectory of cyclist overtaken was converging to the lane of bus. The cyclist completed the evasion manoeuvre without such big difficult. The event was evidenced in the distribution Clearance in Fig.37 & Fig.39 as an isolated point in location 1 and it represents the minimum clearance in table 6 (minimum in clearance 0.816). This isolated event cannot be considered representative of the overall safety of the location, as it is a single incident in a large sample, which inevitably has a certain frequency of return. While this may result in an overestimation, it cannot be stated with certainty that the location is completely safe, despite the presence of a clearer distinction of roadways.

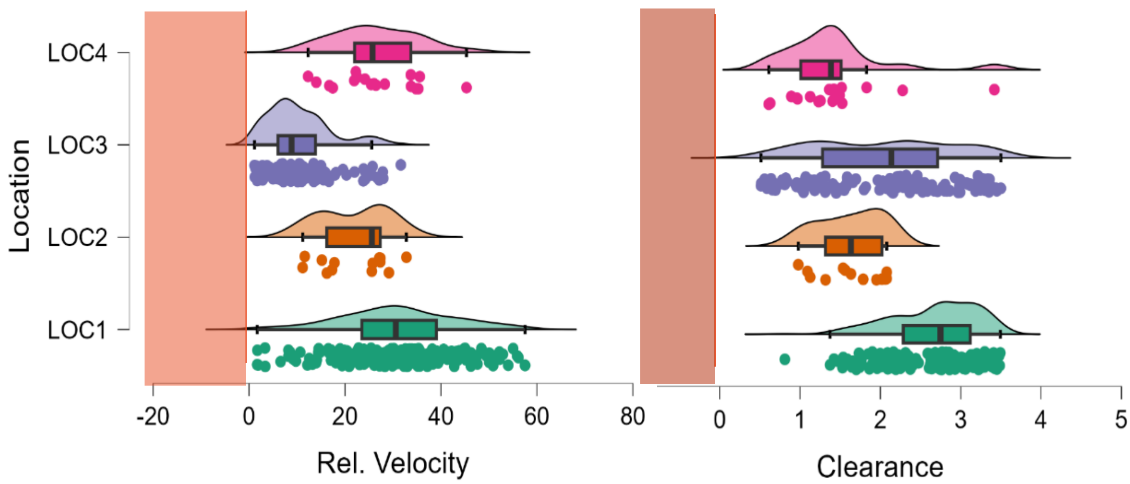



*Figure 39 Comparison between the distributions among 4 Location by two indicators: on the left Relative Passing Velocity, which may be negative whereas there is Cyclist run faster than o motorist. On the right, Lateral Clearance distributions.*

Location 2 indicates an overtaking speed of approximately 1.97 m ± 0.72, aligned with the results of Dozza et al., 2016 and Kovaceva et al. 2019, where the overtake must be done in the same lane. In this location, both relative speed and lateral clearance distributions are bimodal, featuring two distinct peaks. They shouldn't depend on the different flows in the same sample, as already demonstrated in chapter §7.1.0. Perhaps it's plausible that a condition could be due to different overtaking strategies adopted by drivers: "flying" or "accelerative" overtakes. It is possible to categorise and verify the type of overtaking manoeuvre by analysing video footage or the kinematic profiles of trajectories. However, no further investigation has been conducted at this stage. Moreover, average lateral clearance is higher than the other maybe due to the fact that motorists sometimes take more gap stand in the central lane, designed for turning left, to complete the maneuver. Furthermore, the mean lateral clearance is greater than the other, potentially due to the fact that motorists on certain occasions occupy in the central lane, which is designed for turning left, in order to complete the manoeuvre with a larger gap.

In location 3, vehicle speeds are generally reduced, and the relative speed difference may be negative (<0), suggesting that there may be fewer instances of cyclists overtaking to the right. Despite the reduction in relative overtaking speeds, there was no particular effect on the lateral distances maintained by the follower. The distributions of the lateral clearance variable do not match those of the other sites. there were cases with exceptionally large distances where the manoeuvre may have encroached on the middle lane, or critical cases where there is little clearance (minimum distance 0.50m). The limited width of this segment of road, combined with the conditions existing both before (back) and after (beyond) the camera, makes it particularly complex to assess the overall safety of this location compared to others. In comparison to other monitored areas, where the roadways are wider or better separated, numerous instances were observed here where vehicles pass closer to cyclists, although at extremely moderate speeds, creating conditions that can potentially discomfort cyclists.

The location 4, presenting too limited number of conflicts observed, and the comparison with other sites become challenging: it had to represent a different infrastructure, a different scenario and traffic types. We can consider it as scenario where cyclist and motorist must share the lane and the interactions observed showed smaller lateral distances, highlighting potential safety concerns. The narrowing of the roadway can lead motorists to encroach upon the oncoming lane by a significant margin or to decelerate and overtake with inadequate clearance.

The results of this campaign have highlighted how the geometric characteristics of the different locations significantly influence the dynamics of interaction between cyclists and other road users. Specifically:

- In location 1, the scenario, characterized by a high traffic volume and clear lane separation, exhibited the highest relative speeds and the widest lateral distances between cyclists and other vehicles. These findings suggest increased safety due to reduced collision risk, attributed to the traffic segregation.
- In location 2, located in a rural area with low traffic volume and features that encourage cyclists to divert onto the pedestrian path, it recorded few interactions.
- Same scenario was in Location 4 where there were few interactions.

- Although location 3 has a road layout that limits speeds, it still showed significant interactions, with lateral distances and speeds that indicate a risk of interference between cyclists even though the relative speed is minimal.

While the four locations analysed are not easily comparable due to their differing geometric and infrastructural characteristics, the study has nonetheless highlighted some practical issues that may arise in real-world scenarios. These insights are particularly useful for planning the second phase of the campaign, where such differences can be further explored and addressed.

## 7.2 Results of Second Campaign

The application of the proposed framework is showcased by focusing on OV scenarios. This is primarily due to the low amount of LO scenario observed, which limited the possibility for meaningful comparisons.

While primarily serving as a proof-of-concept application of the proposed methodology, these case studies offer several discussion opportunities, although caution is warranted due to the relatively small sample size of the observed bicyclist overtakes. In the following tables 16 & 17 the comparison of first and second recording by volumes and average speed are presented.

*Table 17*

*Daily volumes at the three locations studied, before and after the intervention. St. dev. in round brackets.*

| | Bicycle volume [veich/h] | | Motor vehicle volume [veich/h] | |
|---|---|---|---|---|
| Loc. | Before | After | Before | After |
| 2 | 50 | 37 | 3,484 | 2,103 |
| 5a | 48 | 121 | 10,533 | 10,628 |
| 5b | 78 | 167 | 8,366 | 7,841 |

*Table 18*

*Daily volumes and mean speed at the three locations studied, before and after the intervention. St. dev. in round brackets.*

| | Bicycle speed [km/h] | | Motor vehicle speed [km/h] | |
|---|---|---|---|---|
| Loc. | Before | After | Before | After |
| 2 | 18.1 (9.4) | 18.1 (4.3) | 37.5 (13.2) | 42.4 (5.7) |
| 5a | 22.6 (7.9) | 23.0 (5.7) | 41.1 (6.0) | 44.8 (7.0) |
| 5b | 17.5 (6.1) | 17.0 (6.0) | 40.6 (8.2) | 38.8 (7.8) |

Table 19 presented Number of overtakes, mean lateral clearance and mean delta velocity, before and after the intervention. St. dev. in round brackets.

*Table 19 Number of overtakes, mean lateral clearance.*

| | Overtakes | | Lateral clearance [m] | | Delta speed [km/h] | |
|---|---|---|---|---|---|---|
| Loc. | Before | After | Before | After | Before | After |
| 2 | 16 | 29 | 1.83 (0.58) | 1.44 (0.44) | 19.9 (7.8) | 25.5 (7.6) |
| 5a | 12 | 33 | 1.75 (0.63) | 1.97 (0.66) | 25.2 (5.2) | 22.6 (7.1) |
| 5b | 11 | 10 | 1.83 (0.56) | 1.63 (0.85) | 28.9 (12.8) | 21.1 (9.7) |

### 7.2.1 Implementation of a new bicycle lane (location 2)

BEFORE AFTER

*Figure 40: corrective implementation before After Location 2. On the right, the newest regulation with a red cycle lane*

A before-after comparison was conducted at Location 1, where a new bicycle lane was added in the East-West direction between the two surveys. Here, the daily volumes of both vehicles and bicycles differed significantly before and after the intervention, likely due to seasonal effects, as the second recording took place in mid-summer, typically a holiday time with significantly less traffic. It is noteworthy, however, that the path choices of cyclists significantly shifted in the "after" scenario.

| | | | |
|---|---|---|---|
| Bikes on the wrong side of the pedestrian walkway | 2022 | 298 | 67% |
| | 2023 | 28 | 16% |

*Table 20 the percentage considers those cyclists who choose Path B, which is considered more convenient than Path A for both continuing on the main road and for turning left.*

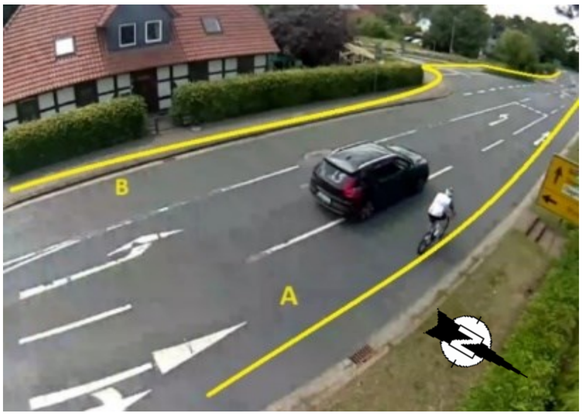



*Figure 41 Location 2: two paths used by cyclists*

Prior to the intervention, a considerable portion of cyclist volume (67%) utilized the sidewalk on the opposite lane to travel in the East-West direction (Fig. 41), whereas after the intervention, only 16% of cyclists did so. Notably, this indicates an increased perception of safety and comfort in riding within a bicycle lane, aligning with previous research (Abadi & Hurwitz, 2018 ; Rivera Olsson & Elldér, 2023). The analyses were conducted at a single location; thus, only the Intervention factor (with 2 levels, “before” vs. “after”) was considered in the statistical analyses.

*Table 21Descriptive Statistics before and after of two variables DeltaV (relative passing velocity) and LC (lateral Passing distance), In addition, Shapiro wilk tests were included.*

| | BEFORE | | AFTER | |
|---|---|---|---|---|
| | DeltaV | LC | DeltaV | LC |
| Valid | 16 | 16 | 29 | 29 |
| Missing | 0 | 0 | 0 | 0 |
| Median | 17.542 | 1.869 | 24.222 | 1.294 |
| Mean | 19.910 | 1.833 | 25.532 | 1.443 |
| Std. Deviation | 7.845 | 0.575 | 7.624 | 0.438 |
| 95% CI Variance Upper | 84.844 | 0.525 | 91.022 | 0.280 |
| 95% CI Variance Lower | 34.266 | 0.138 | 25.735 | 0.104 |
| P-value of Shapiro-Wilk | 0.216 | 0.642 | 0.026 | 0.032 |
| Minimum | 7.008 | 0.978 | 13.609 | 0.772 |
| Maximum | 32.799 | 2.984 | 45.486 | 2.392 |

Since variables distributions did not meet normality assumptions in the second campaign (AFTER), we opted to employ the Mann-Whitney U test. The effect size was assessed using the rank-biserial correlation. Significance level was set at $\alpha = 0.05$, p-values between 0.05 and 0.10 were reported as marginally significant.

*Table 22 Independent Samples T-Test of the Speed of vehicles. "statistics "means the results of test. "df" is the degrees of freedom. The(p) p-value associated with each test indicates the significance level. A lower p-value (typically less than 0.05) suggests that the difference between groups is statistically significant. Note. For the Student t-test, effect size is given by Cohen's d. For the Mann-Whitney test, effect size is given by the rank biserial correlation.*

| | Test | Statistic | df | p | Effect Size | SE Effect Size |
|---|---|---|---|---|---|---|
| Speed inst. | Student | 31.299 | 18423 | < .001 | 0.463 | 0.015 |
| | Mann-Whitney | $5.225\times10^{+7}$ | | < .001 | 0.241 | 0.009 |

Regarding average speed, in the "after" scenario, the Mann-Whitney U test unveiled a significant effect of the Intervention factor with a small effect size on motor vehicles, U=5.2*10^7, p=0.001, rank biserial correlation=0.24, as their speed increased by 4.9%, but no effect was observed on cyclist speed. However, the observed tendency for car drivers to increase their speed should be interpreted with caution, as it may be linked to the observed decrease in traffic volumes in the "after" scenario.

*Table 23 Independent Samples T-Test of two variables. "statistics "means the results of test. "df" is the degrees of freedom. The(p) p-value associated with each test indicates the significance level. A lower p-value (typically less than 0.05) suggests that the difference between groups is statistically significant.*

| | Test | Statistic | df | p | Effect Size | SE Effect Size |
|---|---|---|---|---|---|---|
| LC [m] | Student | -2.558 | 43.000 | 0.014 | -0.796 | 0.329 |
| | Welch | -2.364 | 24.803 | 0.026 | -0.764 | 0.327 |
| | Mann-Whitney | 137.000 | | 0.024 | -0.409 | 0.180 |
| Delta V [km/h] | Student | 2.344 | 43.000 | 0.024 | 0.730 | 0.326 |
| | Welch | 2.324 | 30.299 | 0.027 | 0.727 | 0.326 |
| | Mann-Whitney | 305.000 | | 0.086 | 0.315 | 0.180 |

*Note.* For the Student t-test and Welch t-test, effect size is given by Cohen's d. For the Mann-Whitney test, effect size is given by the rank biserial correlation.

The analysis of overtaking behaviour revealed intriguing findings. The Mann-Whitney U test indicated significant effects on both LC and ΔV. Post-intervention, LC decreased by 0.39 m, which was significant with a medium effect size, U=137, p=0.024, rank biserial correlation=0.41; at the same time, ΔV increased by 5.62 km/h, which was marginally significant with a medium effect size, U=305, p=0.086, rank biserial correlation=0.32.

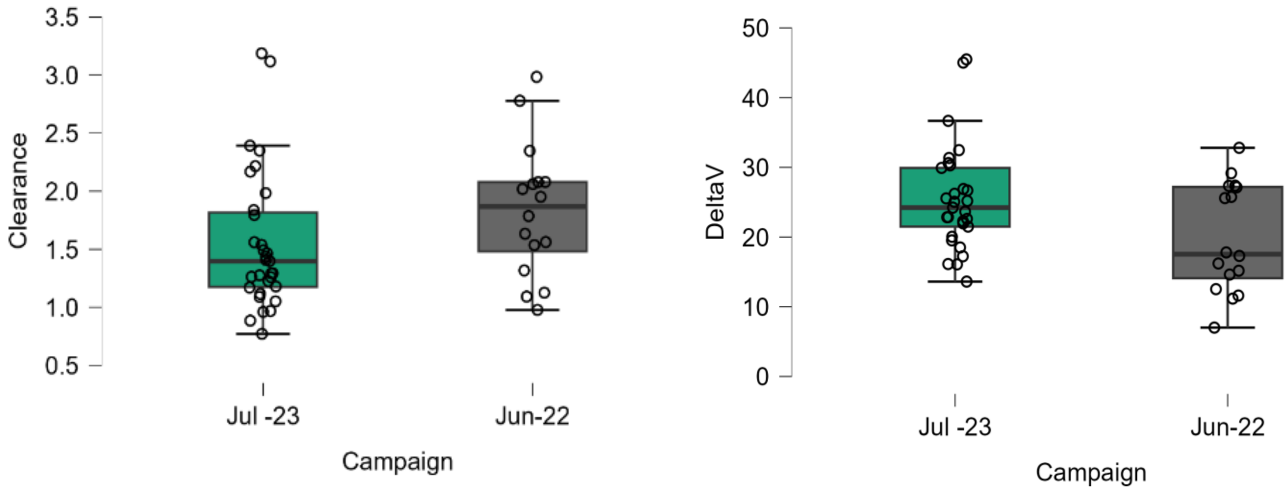



*Figure 42 Boxplots 's comparison Before and After of LOC 2: on the left variable Lateral Clearance, on the right Delta V*

This closely aligns with findings from (Parkin & Meyers, 2010) who explained this by noting that in situations where there is no designated bicycle lane, the cyclist shares the same lane as the driver, necessitating a deliberate overtaking manoeuvre by the driver; conversely, when the cyclist is in on a bicycle lane, the driver perceives a clear lane ahead, eliminating the need for overtaking. An alternative but consistent interpretation can be given within the context of the overtaking strategy theory (Dozza et al., 2016): without the presence of a bicycle lane drivers were induced to adopt an accelerative strategy, with the bicycle lane some of them switched to the flying strategy, which is characterized by lower clearances and higher delta speed (Bianchi Piccinini et al., 2018; Farah et al., 2019).

In any case, the present case study shows an intriguing dichotomy: while increasing proximity and relative speed between road users suggest a less-safe situation, it also indicates that drivers and cyclists are becoming more comfortable with each other, as evidenced by an increased ratio of cyclists choosing to use the road instead of the sidewalk. Additionally, despite the influence of cycling lanes on lateral clearance has been extensively researched, findings have been contrasting, as demonstrated by the meta-analysis by Rubie et al. (2020), which found an overall small, albeit nonsignificant, negative effect of bicycle lanes on lateral clearance. This implies that several other factors should be considered including, notably, bicycle lane width, as emphasized by (Bella & Silvestri, 2017) in their simulator study, which showed that wider lanes are associated with larger lateral clearances. In this sense, it should be noted that the bicycle lane in Location 2 was indeed relatively narrow (only 1.2 meters).

### 7.2.2 New paint colour on existing bicycle lane (locations 5a and 5b)

The corrective measure implemented involved the recoloration of the cycle lane, detailed as number 2 in paragraph 4.1, using red paint. The analysis that follows is a before-and-after comparison, similar to the approach used in the first task of this thesis. The table below presents a before-and-after comparison of overtakes, lateral clearance, and delta speed at two locations (5a and 5b) following the adjustment.

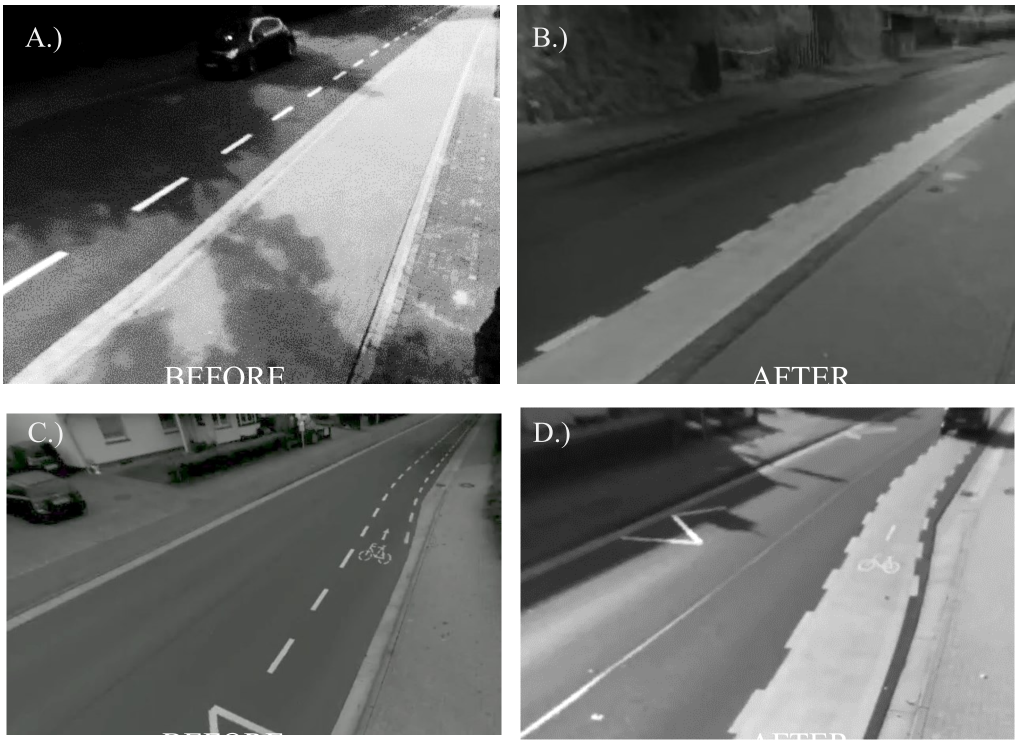



*Figure 43 Implementation introducing surface painted in Location 5a, and in 5b. In figure a-b, painting in Loc 5a (first camera), in figure c-d painting in Loc 5b (second camera)*

*Table 24 Descriptive statistics of How many cases in Overtake are in the location 5a and 5b, before means fist campaign in June 2023, after in august 2023*

| | Overtakes | | Lateral clearance [m] | | Delta speed [km/h] | |
|---|---|---|---|---|---|---|
| Loc. | Before | After | Before | After | Before | After |
| 5a | 12 | 33 | 1.75 (0.63) | 1.97 (0.66) | 25.2 (5.2) | 22.6 (7.1) |
| 5b | 11 | 10 | 1.83 (0.56) | 1.63 (0.85) | 28.9 (12.8) | 21.1 (9.7) |

As regards locations 5a and 5b, Table 24 reveals that the volume of vehicles remained similar before and after the intervention, while the volume of bicycles more than doubled. This increase might have been partly influenced by seasonal factors, although the weather conditions were comparable in the two surveys.

To analyse the effects (in terms of vehicle speed and overtaking behaviour) of the intervention in the two different locations, a two-way ANOVA with factors Intervention ("before" vs. "after" or "June 2022" vs "June 2023") and Location ("5A" vs. "5B") was first considered.

ANOVA: Clearance

*Table 25 Anova test for variables Lateral clearance between in LOC5A-5B. The table presents the analysis of variance (ANOVA) conducted to evaluate the effect of the "Stream" factor on relative passing speed. The results include the sum of squares, degrees of fre*

| Source | Sum of Squares | df | Mean Square | F | p |
|---|---|---|---|---|---|
| Campaign | 0.003 | 1 | 0.003 | 0.006 | 0.936 |
| Location | 0.229 | 1 | 0.229 | 0.512 | 0.477 |
| Camp.✻ Location | 0.561 | 1 | 0.561 | 1.254 | 0.267 |
| Residuals | 27.752 | 62 | 0.448 | | |

*Table 26 Anova test for variables rel. velocity just in LOC5A-5B. The table presents the analysis of variance (ANOVA) conducted to evaluate the effect of the "Stream" factor on relative passing speed. The results include the sum of squares, degrees of freedom (df), mean square, F-statistic, and p-value for each component.*

| ANOVA: Delta V | Sum of Squares | df | Mean Square | F | p |
|---|---|---|---|---|---|
| Location | 16.804 | 1 | 16.804 | 0.237 | 0.628 |
| Campaign | 356.254 | 1 | 356.254 | 5.021 | 0.029 |
| Loc.✻ Campaign | 89.369 | 1 | 89.369 | 1.259 | 0.266 |
| Residuals | 4399.317 | 62 | 70.957 | | |

However, since assumption of residual normality and equality of variances were not met, Kruskal-Wallis H test, a non-parametric alternative to ANOVA, was conducted.

It shows that motor vehicle speed increased in Location 5A after the intervention (+3.7 km/h) and decreased in Location 5B following the intervention (-1.8 km/h). The analysis indicated significant differences before and after the intervention but with a small effect size, H (1, n=74,254) =865, $p<.001$, $\eta2=0.01$. Conversely, bicycle speed did not exhibit a significant change before and after the intervention. The factor Location was also significant, H (1, n=74,254) =3,713, $p<.001$, $\eta2=0.05$, with higher speed recorded at Location 5A.

As regards changes in overtaking behaviour, indicates that in Location 2 lateral clearance tended to increase (+0.22 m), while in Location 2, it tended to decrease (-0.2 m); however, Kruskal-Wallis H test found no statistical difference. Regarding ΔV, a decrease was observed in both locations (-2.6 km/h in Location 5A, -7.8 km/h in Location 5B), and in this case the effect of the Intervention factor was marginally significant, with a small effect size, H (1, n=66) =3.37, $p=.066$, $\eta2=0.04$. Factor Location did not show any significant effect on overtaking behaviour (Almallah et al., 2024).

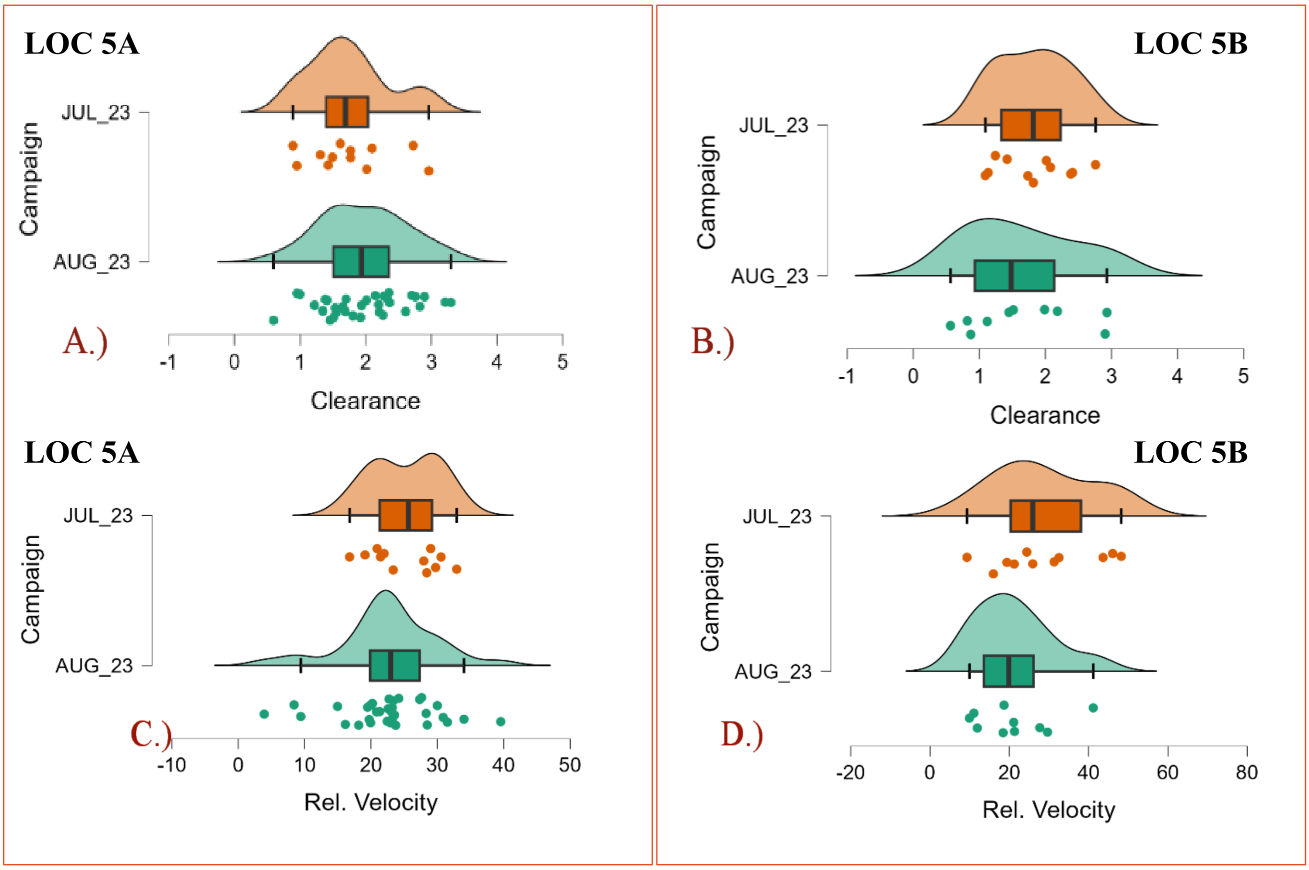



*Figure 44*
*A, C) Comparison and Raincloud Plots of Clearance and Rel Velocity in Loc.5A B, D) Comparison and Raincloud Plots of Clearance and Rel Velocity in Loc.5B*

It is possible that the lane markings heightened drivers' spatial awareness, prompting them to reduce speed when overtaking cyclists. Limited research exists on this specific topic, except for a recent driving simulator study by which found no difference in passing speed between coloured and uncoloured bicycle lanes Conversely, no significant effect on lateral clearance was observed, consistent with findings by Almallah et al. (2024).

# 8 CONCLUSION

This study presents a procedure for extracting safety-relevant indicators from video recordings in order to analyse interactions in the same direction between cyclists and motor vehicles. Within this procedure, two different situations indicated in the literature as those most prone to crash severity were analysed. The distinction was made between longitudinal overtaking (OV) interactions, especially in the passing phase, and rear-end conflict (LO).

The study was conducted to identify the parameters that could affect safety in both the situations. The aim was to validate the reliability, applicability, and critical points of the methodology.

The methodology was applied to three case studies as a proof-of-concept application illustration. This allowed for a comparison between different locations, a before-after comparison on lanes adjustment intervention and two traffic calming interventions.

The procedure, developed in MATLAB, was intentionally designed in clear and uncomplicated steps to facilitate the applicability and usability of the tool for practitioners. However, it can serve as a starting point for more sophisticated research-oriented analyses. This process has potential for yielding insights into user behaviour towards weaker cyclists through the use of video. Consequently, this method has the potential to be applied in a unique manner to any context, to any volume of traffic combined with the volume of cyclists, and to any road regulation.

In this thesis, analyses were carried out from the observation of the German regulation, which differs positively from other national regulations in terms of the number of different types of cycle lanes and for the careful about cyclist's safe. It turns out to be a fast method to carry out research on the verification that what is expressed in the regulation is respected, e.g. the safety distance in approaching and passing phase of an overtake.

Furthermore, the flexibility of the indicator extraction tool was evident in its ability to analyse data collected from three distinct locations during two separate surveys without the needs of location-specific adjustments. Several visual and manual tracking comparisons verified consistency in lateral clearances across locations and surveys.

However, it is noteworthy that despite the extensive survey duration, few actual overtaking events were observed. This scarcity can be attributed partly to low overall cyclist volumes at the specific studied locations, highlighting the need to conduct more prolonged surveys in such contexts. The locations were not selected based on a ranking of data derived from crashes or a comparison of bicycle and e-bike traffic volumes. For rear-end longitudinal scenarios, it would have been more appropriate to identify segments with higher traffic intensity or with any traffic devices that would have made overtaking more complex. At least, this would have slowed it down from an initial queuing phase behind the cyclist (LO scenario) to the overtaking phase (OV scenario). It is notable, however, that in these locations there have been just sporadic cases.

On the other hand, this is related to an inherent limitation of the image capture tool: the capacity of the camera allows it to cover a field of view where only part of the road segment is perfectly covered by the detection (approximately 15 metres length with discardable errors on clearance). Including an additional camera on the opposite side, approximately at an average distance of 50 metres, should be a proposal for a possible development a better detection in a segment. This would make the clearance calculation cleaner and more accurate. It would also eliminate the problem of the discarded interaction as the oncoming cyclist is being obscured by the silhouette of the overtaking vehicle.

As currently configured, the tool extracts a limited set of indicators, offering only a partial view of cycling infrastructure safety. For example, in the overtaking scenario, investigating not only lateral clearance but also "comfort zone boundaries" (Kovaceva et al., 2019) could be insightful. Similarly, automatically distinguishing between accelerative and flying manoeuvres, as defined by Dozza et al. (2016), could be of interests, although operationally it is not straightforward, particularly regarding local characteristics that may influence manoeuvre differentiation (e.g., the vehicle speed threshold to distinguish the two types of manoeuvres may depend on the cyclists' speed, as explained in (Rossi et al., 2021).

To overcome these limitations, continued refinement of the tool will involve the inclusion of additional indicators to improve its functionality and provide an even more comprehensive assessment of cycling infrastructure safety.

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