CHALMERS
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Impact of Road Work Zones on Traffic Flow and Safety

A VISSIM-Based Analysis of Driving Behavior and Risk Factors

Master's thesis in the Master's Programme Infrastructure and Environmental Engineering

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MASTER'S THESIS ACEX30

Calibrating Swedish Driving Behavior in Work Zones

A VISSIM-based Microscopic Simulation for Traffic Flow and Safety

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Cover:
Cars driving trough the work zone, taken at the case study area.
Department of Architecture and Civil Engineering
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ABSTRACT

To achieve Vision Zero and eliminate all fatalities and severe injuries in road traffic, it is necessary to improve road safety for both road users and road workers. Accidents and incidents that occur in work zones could be prevented by following national regulations and implementing measures such as putting up signs, barriers, and speed limits. Further, the work zone safety is closely related to driving behavior.

The aim of this study is to examine how work zones affect traffic flow and road safety with a focus on the Swedish driving behavior and national regulations. This study fills a research gap addressing the lack of simulation studies on work zones in Sweden. A literature study and interviews were conducted to present the regulations and understand the current situation regarding road safety. A case study area was observed and recorded in connection with a work zone. Machine learning was used to extract parameters from the Swedish traffic flow, which was used to calibrate a simulation scenario that correlated with a general Swedish work zone traffic flow. The model was improved by changing parameters that mimic a lower speed limit in the work zone and driving behavior with earlier merging.

It is found that Swedish drivers generally exhibit non-aggressive driving behaviors, including gap acceptance, adherence to speed limits, and early merging. There is a variation of risks of work zone safety, where several situations are believed to occur due to stressed drivers or a lack of information. Safety issues due to driving behavior were tested in the traffic simulation tool VISSIM, where an improved design simulation scenario illustrated a work zone where the speed limit was reduced and drivers merged earlier compared to the calibrated and adjusted scenario. The improvements impacted travel time by 2.2%, an insignificant increase compared to the enhanced safety to which the lower speed contributes.

Keywords: Work Zone, VISSIM Calibration, Micro Simulation, Road Safety, Traffic Flow, Driving Behavior, Traffic Video Surveillance

Inverkan på Trafikflöden och Trafiksäkerhet vid Vägarbeten.
En VISSIM Baserad Analys av Förarbeteenden och Riskfaktorer.

Examensarbete inom masterprogrammet infrastruktur och miljöteknik

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SAMMANFATTNING

För att nå målet med Vision Zero, att ingen ska omkomma eller skadas allvarligt vid en trafikolycka, måste trafiksäkerheten förbättras för både trafikanter och arbetare. Olyckor och incidenter som är kopplade till vägarbete kan förebyggas genom att följa nationella regler, så som att använda skyltning, barriärer och hastighetsbegränsningar enligt gällande föreskrifter. Vidare är säkerheten vid vägarbeten starkt kopplat till förarnas körbeteende.

Syftet med denna studie är att undersöka hur vägarbeten påverkar trafikflöden och säkerheten på väg med ett fokus på svenska körbeteenden och föreskrifter. Denna studie tillför forskningen eftersom simuleringsstudier som behandlar arbetszoner i Sverige inte undersökts innan. En litteraturstudie och intervjuer genomfördes för att presentera föreskrifter och för att förstå dagens situation gällande trafiksäkerhet. En fallstudie i anslutning till en avstängd väg observerades och spelades in. Maskininlärning användе för att extrahera parametrar som beskriver det svenska trafikbeteendet och trafikflödet vid avstängningen. Modellen förbättrades genom att justera parametrar för att imitera en lägre hastighet och tidigare filbyte vid arbetszonen.

Studien visar att svenska förare har ett lågaggressivt körbeteende när det gäller mellanrum för filbyte, följa hastighetsbegränsningar och tidigt filbyte. Det är en mängd risker som är kopplade till trafiksäkerheten, vilka tros bero på stress eller brist på information hos förarna. Säkerhetsaspekter gällande körbeteende testades i VISSIM där ett förbättrat scenario illustrerade en arbetszon med en sänkt hastighet och ett förarbeteende som byter fil tidigare jämfört med det kalibrerade och justerade scenariot. Dessa förbättringar påverkade restiden med 2.2% vilket är en obetydlig ökning jämfört med den förbättrade säkerheten en hastighetssänkning innebär.

Translated with DeepL.com (free version)

Nyckelord: Arbete på väg, VISSIM kalibrering, Mikrosimulering, Trafiksäkerhet, Trafikflöde, Förarbeteenden, Trafik Inspelning

Contents

Preface

This study is carried out in collaboration with Skanska Industrial Solutions. We are grateful to Skanska and all employees who have provided a rewarding work environment. A special thanks to Maria Nordanmyr for providing us with invaluable supervision, support, and introduction to Skanska. In addition, we would like to thank the interviewees at the Swedish Transport Administration and at Skanska for providing us with insightful responses.

We express our gratitude to Omkar Parishwad at Chalmers for always believing in us and supplying us with valuable insights and solutions throughout our work. A thanks to Kun Gao for being our examiner and a major congratulations to your promotion.

Lastly, we want to thank our family and friends for supporting us and listening to all our ideas. A special thanks to Pontus for support in programming when we needed it the most.

Gothenburg, June 2025
Elin Johansson, Elin Morin

Notations

Swedish - English word list

Fast arbete	Fixed work
Intermittent arbete	Intermittent work
Omledning	Rerouting
Rörligt arbete	Mobile work
Trafiklots	Traffic controller
Trafikverket	The Swedish Transport Administration
Överledning	Diversion

Abbreviations

AADT	Average annual daily traffic
CC1	Gap time distribution
CC2	Following distance oscillation
FPS	Frames per second
QEHS	Quality, environment, health and safety
TA - Plan	Traffic arrangement plan
PPM	Pixels per meter

1 Introduction

The World Health Organization (WHO, 2021) has presented a global plan to achieve the target of reducing road traffic deaths and injuries by at least 50% between 2021 and 2030. WHO aims to guide governments and stakeholders in implementing and designing policies that ensure safety throughout the transport system. The Swedish government has implemented Vision Zero, a strategy aimed at eliminating all fatalities and severe injuries in road traffic (The Swedish Transport Administration, 2020b). Vision Zero acknowledges that accidents are unavoidable; however, it emphasizes that no accidents should result in severe consequences, including loss of life. The motion, 2017/18:2746 sent to parliament, states that actions to enhance road safety include reducing speed limits, preventing the use of alcohol and drugs, and banning the use of communication devices such as phones when driving (Svensson Smith, 2017). According to Vision Zero, speed limits should be adapted based on the vulnerability of road users in the location (Malmström & Tunmarker, 2023).

Each year, around 300 accidents in which people are injured in connection with road work are recorded in Sweden. In recent decades, on average, workers who are operating on the road are affected by 6% of these accidents by injuries or fatalities (Liljegren, 2023). The most common road work accidents, approximately 1/3 of reported cases, involve vehicles hitting other vehicles in the rear (Ihs, 2020). Reasons for these types of accidents could be drivers not noticing the speed change, late warnings about upcoming roadwork, or changes in driving behavior from the vehicles ahead. To reduce these accidents, it is crucial to implement measures that encourage drivers to slow down and pay attention to the current traffic situation. Violence and threats are common for traffic workers on the job, especially traffic controllers when directing traffic (Wikström Melin, 2024). Everyone should feel safe at work, and therefore, it is of interest to understand what causes these accidents and how to prevent them.

Accidents occurring in connection with work zones are a significant problem and can be prevented by using traffic control devices such as signs and barriers (Rathnasiri et al., 2024). Work zone safety is largely dependent on driving behavior, for example, how drivers act when changing lanes (Ma et al., 2023). Several studies exist regarding the calibration and simulation of traffic flows in different software, but no models accurately represent Swedish driver behavior at work zones. This is a key research gap considering that accidents related to roadwork design and driving behavior are a major issue (Ihs, 2020; Liljegren, 2023). Simulations are an effective tool for analyzing traffic situations, where it is crucial to extract and calibrate the model's parameters according to the chosen case study area (Bång et al., 2014). The importance of creating a safe environment for both drivers and workers on the project site, combined with the lack of research on the subject, forms the aim of this report: to calibrate and adjust a simulation software tool to capture Swedish driving behavior on road work sites. This calibration will help present a realistic representation of Swedish driving behavior, identify safety risks, and therefore be useful in supporting future decisions regarding the design of the work zone.

1.1 Aim and objectives

The purpose of this study is to investigate the impact of work zones on traffic flow and road safety, with a focus on Swedish driving behavior and regulations.

- Conduct a literature study to understand the current situation of road safety in Sweden.
- Present the Swedish traffic regulations and frameworks that govern decision-making and design related to work zones and traffic safety.
- Identify key parameters needed to analyze traffic flow in work zones.
- Develop a code that uses object detection.
- Extract relevant traffic parameters from the object detection code for a specific case study area within the scope.
- Model the work zone in the case study area in VISSIM and run with default values as an uncalibrated scenario.
- Use the extracted parameters and the work zone design to calibrate and adjust the model in VISSIM to correlate with the Swedish driving behavior.
- Propose and analyze improvements by changing the design of the work zone aimed at enhancing road safety in correlation with traffic flow.
- Identify limitations in this study and recommend further research.

1.2 Research questions

The research questions answered in the study are the following:

- Which specific regulations and frameworks are essential to ensure the design and safety of the work zone in Sweden?
- How does the work zone affect the safety of road users and workers, and how are they influenced by driver behavior?
- Which VISSIM parameters need to be calibrated to reflect a Swedish driving behavior in a work zone?
- How can the design of the work zone be improved from efficiency and safety perspectives?

1.3 Scope and limitations

The spatial boundaries of the study are confined to the case study area detailed in Chapter 5. Hence, the study was limited to one highway segment in the Gothenburg region. The study focused on a small segment of the road, i.e., on a micro-level, and therefore did not consider the road network. The data were gathered during the peak hours of one weekday and therefore will not concern other types of traffic flow.

The case study area is a public road owned by the Swedish Transport Administration, and therefore, regulations and frameworks relevant to this type of road were considered. The study focused exclusively on the work environment related to safety, excluding other aspects such as dust and noise disturbances. The economic factors related to working on the road were mentioned, but no calculations were performed.

The simulations were limited by the boundaries of the software VISSIM and therefore are not an entirely accurate representation of reality (Haas & Myers, 2025). How the simulation was designed can be seen in Section 3.5. Pedestrians and cyclists were not considered as the chosen road segment is a highway. Heavy vehicles such as trucks were not considered when extracting parameters from the traffic video survey to minimize the complexity of the code (see Section 5.2).

2 Literature Study

The objective of this review is to examine the safety associated with road work and specifically work zones in Sweden. Additionally, an understanding of the key aspects of simulation tools and methods in relation to the work zone and Swedish driving behavior, particularly the simulation software VISSIM, will be provided.

2.1 Road safety in Sweden

Several factors contribute to the uncertainties of working on the road. For example, speed limits are not respected, and the design of the work zone is not planned and applied safely (Liljegren, 2023; Wikström Melin, 2024). A study was conducted to investigate perceived safety from the perspective of a road worker, revealing that the majority believe that drivers do not respect their work environment (Wikström Melin, 2024). Most participants expressed concerns about working on the road due to safety concerns, with the primary concern being the high speeds of passing traffic. An interview with a focus on QEHS (Personal communication, March 26, 2025) stated that the perceived risks for road workers include a lack of respect from drivers regarding speed, as well as an increase in threats and violence.

Obstacles such as chicanes or mobile speed cameras and increasing fines could be implemented in the work zone to prevent speeding in the work zone (Säterdahl, 2020; Wikström Melin, 2024). In addition, raising awareness that the time saved by a higher speed is minimal compared to the risks of such behavior. A development leader (Personal communication, March 17, 2025) mentions that other important preventive measures include informing drivers in advance to minimize the frustration of change, as well as working at times with lower traffic flow and avoiding rush hours.

Preventive measures of road safety could be taken in the procurement phase (Wikström Melin, 2024). Clients could be better at following up on the entrepreneur's work and be more demanding of the entrepreneur's safety management. This is supported by a person in the field with a focus on QEHS (Personal communication, March 26, 2025) which stated that the economy and safety are interconnected regarding the procurement, and that it is not affordable to implement additional safety measures beyond those specified in the procurement, as contracts are picked based on the lowest price.

The Swedish Traffic Administration has presented a report that summarizes traffic accidents in relation to road work in Sweden between 2003-2021 (Liljegren, 2023). Most accidents occur to unprotected road users or rear-end collisions. Minor injuries were the most common (70%), with the remaining accidents being declared serious or fatal. However, minor injuries are stated as physical in the report, but could cause psychological problems. For road workers, the most common types of accidents are "pedestrian-vehicle" accidents, where all personnel outside their vehicles are regarded as pedestrians, and "single-vehicle" accidents.

According to both statistics and observations of a person with QEHS expertise (Personal communication, March 26, 2025), pedestrians, as road users, are sometimes injured in the work zone (Liljegren, 2023). These incidents often occur when pedestrians enter the work zone unconsciously or by removing fencing, or in connection with the establishment and disestablishment of the work zone. Pedestrian incidents are rarely severe and are usually caused by obstacles such as debris on the ground or high curbs.

2.2 Traffic simulation models

The advantage of traffic simulation modeling is that it allows the viewer to visualize the dynamics of vehicles in a specific traffic situation (Bång et al., 2014). Simulation models are commonly classified by their level of detail. Microscopic models are detailed and focus on individual driving behaviors, capturing interactions between vehicles. Therefore, smaller road segments, such as work zones and highways, are usually analyzed using microscopic models (Elefteriadou, 2014), which is also the case for this study. Macroscopic and mesospheric models are less detailed and can be used to analyze larger road segments, such as how a closed road affects a large traffic system, etc.

VISSIM is the most widely used software for microscopic traffic simulations in Sweden (Bång et al., 2014) and was therefore chosen for this project. VISSIM is developed and calibrated based on measurement data for German conditions (Haas & Myers, 2025). However, Bång et al. (2014) state that the parameters of the simulation model should be calibrated to suit Swedish driving conditions when investigating Swedish driving behavior. Therefore, it is necessary to adapt the VISSIM parameters to correspond with Swedish data and generate a more accurate software model that simulates Swedish driving behavior. Several studies have been found where VISSIM or other simulation models have been calibrated to imitate highway lane closures. However, few studies have been written from a Swedish perspective on the subject.

2.2.1 Traffic simulation model calibration

Edara and Chatterjee (2010) have recognized the need to evaluate guidance on calibrating work zones and determining which parameters should be modified to replicate field conditions. A change in driving behavior occurs in the work zones, mainly due to the reduced capacity that comes with the reduction in lanes. The capacity and driving behavior vary across global regions, and these variations contribute to the need to calibrate and evaluate models with respect to the specific area being analyzed.

Strömgren & Olstam (2016) have developed a model based on equations that calculate capacity reduction and how they correlate with traffic flow on a highway with and without work zones in Sweden. Marking and signing, as well as crossover areas, in the work zone design were considered important. However, the equations used in this study are straightforward and less complex than those used in simulation software.

Only a few studies on the use of VISSIM in Sweden have been conducted, and even fewer have focused on calibrating parameters to match the Swedish traffic flow. In particular, no studies have been found that specifically address the calibration of VISSIM parameters at work zones in Sweden.

2.3 Driving behavior

Understanding and identifying driving behavior can lead to better traffic flow and fewer accidents in traffic (Al-Ahmadi et al., 2019). Driving behavior depends on several parameters, for example, human factors (reaction time, aggression, etc.), surroundings, and road designs (Elefteriadou, 2014). Driving behavior varies and depends on driving conditions and geographical location (Al-Ahmadi et al., 2019). Therefore, it is essential to evaluate the behavior based on the local conditions of the case study and adapt the parameters when analyzing a simulation.

Mahmood & Kianfar (2019), Jehn & Turochy (2019), and Durrani et al. (2016) have examined driving behavior in work zones in VISSIM with a focus on heavy vehicles. Compared to cars, heavy vehicles exhibit different driving behaviors, such as a larger space and time gap; therefore, these parameters should be defined separately.

2.4 Car following

Car following algorithms determine the movement of a following vehicle and its relationship to the lead vehicle (Elefteriadou, 2014). Several car-following models have been developed, where the algorithms are based on various predictions, such as acceleration and speed.

The Wiedemann 74 car following model uses psycho-physical perception (Haas & Myers, 2025). The concept is that the faster driver will perceive a slower vehicle ahead and start to decelerate. It will not know the exact speed of the vehicle ahead, and therefore, there will be a slight alteration period of deceleration and acceleration for the faster vehicle. This behavior is represented in Figure 2.1 where the driver (black line) must actively decelerate when approaching the front car and then accelerate and decelerate in an unregulated and unconscious behavior. This method shows a more realistic and natural driving behavior. The Wiedemann 99 model shares the same concept as the Wiedemann 74 model but is more complex, incorporating additional calibration parameters.

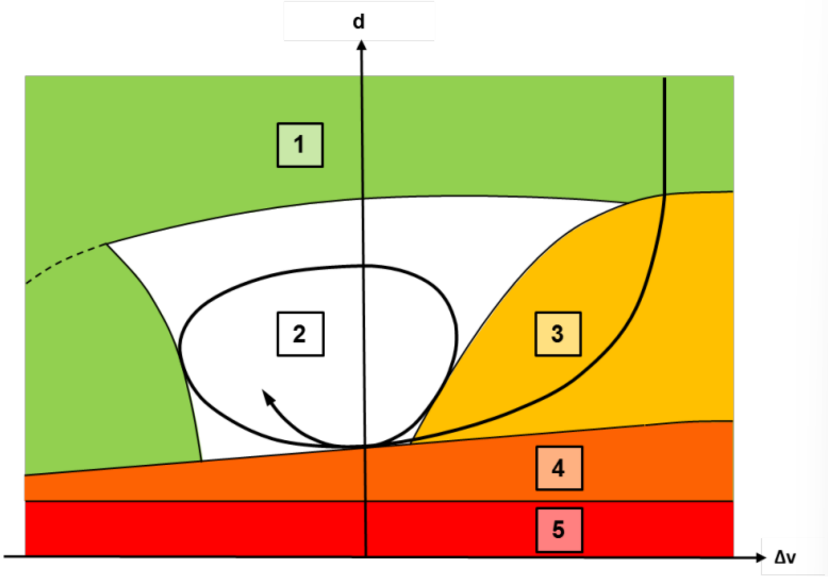


Figure 2.1: Car following model by Wiedemann where, d:Distance to the front car. Δv:Change in speed. 1:“Unregulated behavior” state. 2:Following state. 3:Approaching state. 4:Braking state. 5:Collision state (Haas & Myers, 2025).

Wiedemann’s 74 car following model calculates the safety distance by the square root of the speed and is more suitable at lower speeds, usually below 80 km/h (Haas & Myers, 2025). However, the Wiedemann 99 car-following model calculates the safety distance linearly and is defined as a speed-independent time gap, making it more suitable for roads with higher speed limits, such as highways. Table 2.1 presents the parameters of the Wiedemann 99 model in VISSIM:

Table 2.1: Parameters for the Wiedemann 99 car following model in VISSIM.

parameter	Description	Unit
CC0	Standstill distance	m
CC1	Gap time distribution	s
CC2	Following distance oscillation	m
CC3	Threshold for entering	s
CC4	Negative speed difference	m/s
CC5	Positive speed difference	m/s
CC6	Distance dependency of oscillation	1/ms
CC7	Oscillation acceleration	m/s²
CC8	Acceleration from standstill	m/s²
CC9	Acceleration at 80 km/h	m/s²

Durrani et al. (2016), Edara et al. (2013), Harb et al. (2012), Jehn & Turochy (2019), Mahmood & Kianfar (2019), and Yeom et al. (2016) have examined a highway road segment in VISSIM according to the Wiedemann 99 car following model that is incorporated into the software. The key parameters for traffic flow during highway lane closure with respect to the Wiedemann 99 model are CC1, CC2, and CC0. However, CC0 is only valid when vehicles stand still (Chaudhari et al., 2022). Therefore, the most critical parameters are CC1 and CC2, illustrated in Figure 2.2 (Jehn & Turochy, 2019; Yeom et al., 2016). Increased CC1 and CC2 values lead to a decrease in capacity in work zones (Qawasmeh, 2024). To obtain a realistic model of the Swedish driving behavior, key parameters should be defined from field data to ensure that the simulation replicates the observed behavior (Durrani et al., 2016; Edara & Chatterjee, 2010; Jehn & Turochy, 2019; Mahmood & Kianfar, 2019).

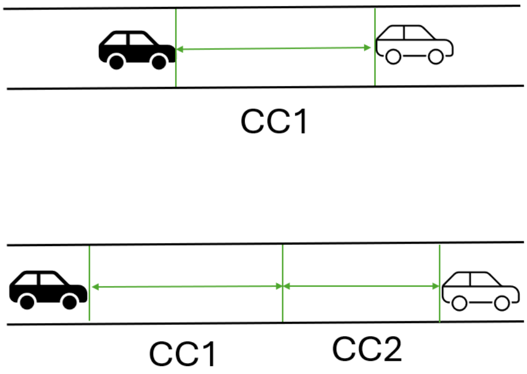


Figure 2.2: CC1 and CC2 illustrated. CC1 is the gap time the driver maintains between the lead vehicle to ensure a safe distance. CC2 is the gap space that the driver maintains to the lead vehicle when close following (Chaudhari et al., 2022).

2.5 Lane changing

Lane changing is generally more complex than car following models because considerations must be made not only of the vehicle in front of the lead vehicle, but also of the rear vehicle, and therefore several decisions influence driver behavior (Elefteriadou, 2014). Due to this complexity, the lane change process is usually modeled in a sequence of decision-making steps:

1. Decision to change lanes
2. Lane choice
3. Gap acceptance
4. Acceleration/deceleration to change lane

In Step 1, the driver decides whether the lane change is mandatory or discretionary (Elefteriadou, 2014). A mandatory lane change is driven by following the assigned route, for example, directions in a work zone. A discretionary lane change is chosen to gain advantages, such as increased speed or improved position, thereby optimizing individual driving conditions. In Step 2, the driver determines the target lane. This becomes more complex when the lane change is discretionary; however, in general, it is assumed that the driver will choose the lane that provides the most utility. In Step 3, the driver evaluates and accepts or rejects the existing gaps in the target lane. This is further discussed in section 2.5.1. Lastly, in Step 4, the vehicle moves into the target lane by accelerating or decelerating.

According to Mahmood & Kianfar (2019), the lane change distance affects driving behavior and is defined as the "earliest distance upstream of a link where drivers are looking for opportunities to change lanes to ensure they are in the desired lane". The default value in VISSIM is 200 m, which indicates that drivers change lanes late and leads to a misrepresentation of the actual traffic flow. A higher value indicates that drivers start to look for a gap and change lane earlier, which is more realistic when modeling a well-marked work zone on a highway.

As stated above, a driver will change lane and merge when the gap is accepted. When reducing the number of lanes on a highway, vehicles are forced to merge into one lane and therefore increase the traffic volume in this lane (Hallmark et al., 2011). An early merge is found to be more effective for traffic flow than a late merge, as drivers tend to "queue jump." Aggressive drivers who cut in line create forced merges and disrupt traffic flow by forcing upstream traffic to brake, which in turn increases congestion. The merging behavior is also influenced by the driver's aggressiveness, where a late merge could be perceived as a more aggressive driving behavior. Due to the effectiveness of an early merge, it is reasonable to adjust the merging parameters in simulations and force drivers to make an early lane change, thereby creating a better traffic flow.

2.5.1 Gap acceptance

According to Elefteriadou (2014), the gap is defined as "the *time* headway between the rear end of the lead vehicle and the front end of the following vehicle", as shown in Figure 2.3. Gap acceptance models aim to predict when a particular gap will be accepted or rejected by the driver performing the maneuver. The minimum gap a driver is willing to accept is called a critical gap and depends on the driver's characteristics and whether the maneuver is mandatory or discretionary. Gap acceptance models usually assume that the drivers act homogeneously and consistently. This is not realistic, but has been proven acceptable.

The gap acceptance is connected to the time headway and is related to the parameter CC1 in the Wiedemann 99 car-following model, but it is also used when defining lane-changing behavior. The parameter CC1 has a major impact on the saturation flow rate and the safety distance, where a large value increases the gap time and reduces the saturation flow (Haas & Myers, 2025).

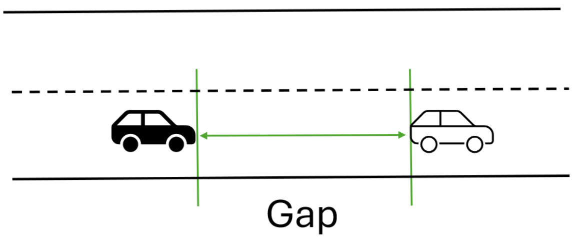


Figure 2.3: Visualization of the definition of the gap between two vehicles.

2.6 Improved work zone design

Ge & Yang (2020) have, with VISSIM, evaluated the relationship between warning zone length and traffic conflicts, such as travel times and safety. Gong & Fan (2016) conducted a study focusing on the main interests related to the jurisdictions of the work zone activities. Impacts are categorized into four main areas: safety, mobility, economics/costs, and environmental concerns. The impacts are usually linked to each other, and therefore, it is hard to evaluate one without considering the others.

3 Method

This section presents the steps taken to answer the research questions. Figure 3.1 presents a flow chart of the main methods used. A literature study and interviews were conducted with a focus on simulation, safety, and Swedish standards that presented understanding of the subject. A vehicle detection code was built to extract collected data on Swedish driving behavior. A model was built in VISSIM where the extracted parameters were implemented to gain a calibrated simulation of the site. Lastly, an improved design scenario was presented and all results was analyzed in a discussion.

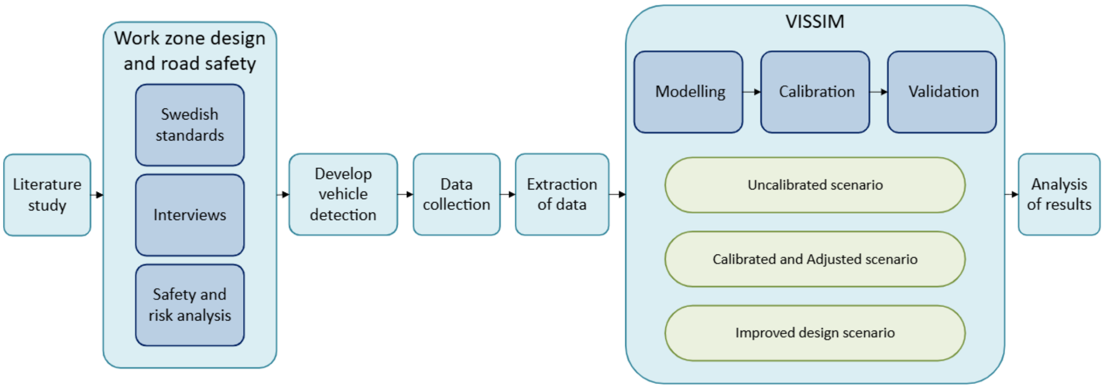


Figure 3.1: Flow chart that is presenting the main methods.

3.1 Literature study

A literature review was conducted to identify relevant studies in the field of research. Swedish frameworks and regulations were examined to gather information on the decision-making process and design choices regarding road closures. In addition, a study of the current state of road safety in Sweden was conducted, as well as an investigation of the use of simulation tools, particularly VISSIM, and how the different parameters were to be implemented.

Interviews were conducted with a development leader, a project engineer with a focus on QEHS, and a skilled worker who performs the work on the road, all Skanska employees. Additionally, a written interview was conducted with experts from the Swedish Transport Administration. All interviewers and their focus areas are shown in Table 3.1. The questions varied depending on the person's expertise in the subject to gather information and opinions of importance. Interviewers were carefully selected due to their expertise in the field and provided qualitative information related to work on the road. The responses provided insight into the perceived safety of the work environment, as well as into regulations and the understanding of the design and management of road work from different perspectives. The interviews were translated from Swedish to English with the respondent's consent.

Table 3.1: Summary of Interviewees.

Role	Organization	Focus area	Interview date	Medium
Development leader	Skanska	Road construction	March 17th	MS Teams
Project engineer	Skanska	QEHS	March 26th	MS Teams
Skilled worker	Skanska	Road construction	April 7th	In person
Project leader	The Swedish Transport administration	Bridge maintenance	April 14th	Email
Project leader	The Swedish Transport administration	Pavement	April 14th	Email
Traffic engineer	The Swedish Transport administration	Road construction	April 14th	Email
Traffic engineer	The Swedish Transport administration	Road construction	April 14th	Email

3.2 Incidents and Accidents

Reports from employees regarding incidents and accidents were examined using Skanska's own portal of work environment-related events called SAI. The events were categorized by region and type of incident. The search was limited to the geographical region *West*, the business branch *Skanska Industrial Solutions* and the classification of events called *fixed work* to align with the scope of this study.

Incident and accident reports are categorized by type of event in SAI. Some statistically relevant events were classified as *other*, making them difficult to locate. In addition, reports are written by Skanska employees or subcontractors, and therefore most reports are from a worker safety perspective and less of a road user's safety perspective. It is also important to note that not all events are registered in SAI due to issues such as a person not realizing an incident or accident occurred.

3.3 Data collection

Data collection involved recording traffic flow in the area of the case study. The recordings were made in the morning and afternoon peak hours on a weekday to assess the impact of capacity, which increases the risk of congestion and contributes to changes in traffic behavior.

Weather conditions could influence the quality of traffic operations and change driving behavior (Elefteriadou, 2014). To obtain a reliable and realistic traffic flow behavior comparable to the simulation results, data collection was performed on a day without rain, snow, or other adverse weather conditions. In addition, there were no incidents or events that occurred in the vicinity that could affect traffic flow.

A camera was set to record the section where the most lane changes occurred, after the warning signs *merging lanes*, but before the start of the chicane. Furthermore, a short data collection was performed, aiming the camera right before the start of the chicane, to identify the number of drivers exhibiting aggressive driving behavior by detecting vehicles that changed lanes at the last minute.

3.4 Traffic detection

Machine learning was used to extract data from the video of the data collection. The data extracted were vehicle speed (km/h), traffic volume (vehicles/h), gap time distribution CC1 (s), following distance oscillation CC2 (m) and lane changes. To extract data from the recordings, the multiple object tracking algorithm *Deep SORT* and the object detection model *YOLOv8* were used (Parico & Ahamed, 2021). YOLO stands for You Only Look Once and is a convolutional neural network (CNN). Deep SORT is based on deep learning and is able to predict what object it is seeing and continue to track its location even if it temporarily moves out of frame (ikomia, n.d.). Deep learning is a subset of machine learning that is used to identify objects and machine learning is a field of study within AI (Lecun et al., 2015). Deep learning algorithms are considered the most robust method for performing object detection, called Multi-Object Tracking (MOT) (Parico & Ahamed, 2021).

YOLOv8 model was imported from Ultralytics, a model development company focusing on AI (Vina, n.d.). The code was modified and developed to suit the needs of this project. The model assigns an ID to each vehicle using vehicle detection, which is written in an Excel file. An area was defined in the code, and when the center point of a vehicle passes this line, the vehicle speed is obtained. Pixels per meter (ppm) were used to calibrate the speed of the vehicles, see 5.2. Input data, combined with data gathered by the program such as frames per second (fps) enables the program to calculate the necessary information. To extract information on which lane the vehicles drove in, the lane coordinates in the region area were defined, and the center point of the vehicle could be sorted in the correct lane. Since each vehicle was given a lane number, the number of vehicles in each direction and the traffic volume could be defined. For each lane, the gaps between vehicles were measured at various points throughout the region. The gap data was sorted and the smallest gap time for each vehicle pair was defined as CC1. CC2 was determined by sorting the maximum gap of the vehicles, subtracting CC1 and converting this number with the velocity to get CC2 in meters.

Since CC1 is a parameter that considers the gap between two following vehicles, a gap that is too large is misleading since these vehicles are not following one another. A gap that is too small is also irrelevant because it represents unsafe and atypical traffic flow, and therefore only the CC1 values between 0.9 and 3 seconds were considered for the analysis (Wisconsin Department of Transportation, 2021). The CC2 parameter is connected to the CC1 parameter, and therefore, the CC2 gap was considered for the vehicle pairs that had CC1 values in the accepted range. Since both too small and too big CC2 distances are irrelevant with the same reasoning as for CC1, only values between 4 and 12 m were considered. The summary of the extracted parameters is found in Table 3.2.

Table 3.2: Summary of extracted parameters from object detection.

Extracted data	Unit	Purpose
Speed	km/h	Obtain the actual speed of vehicles
CC1	s	Obtain the gap between vehicles in a Swedish driving behavior
CC2	m	Obtain the gap between vehicles in a Swedish driving behavior

3.5 Simulation

The simulations were carried out by designing the case study area as seen in Chapter 5 in the multi-model traffic simulation software VISSIM. Figure 3.2 presents the workflow in a flow chart.

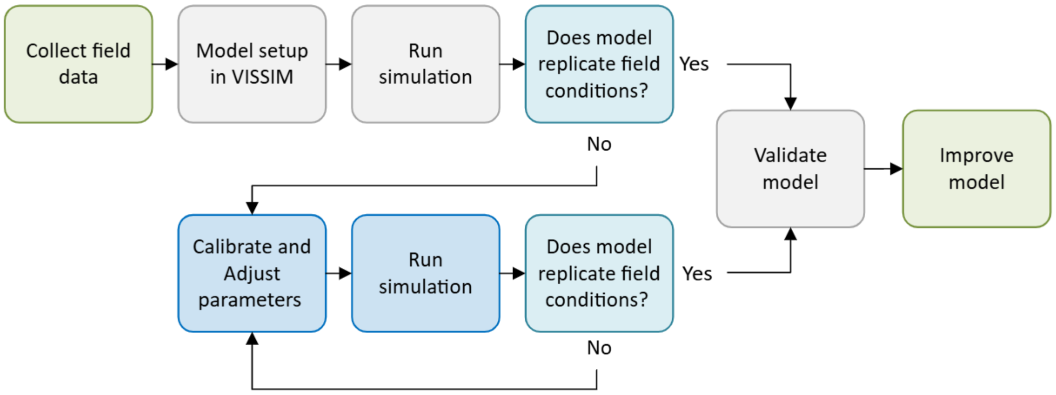


Figure 3.2: Flow chart presenting the simulation process.

First, an uncalibrated scenario was performed to establish a reference point and confirm whether the default values of the simulation tool are comparable to the recorded driving behavior scenario. Later, the simulation was calibrated by implementing the extracted parameters of CC1 and CC2, and further adjusted by modifying additional parameters in VISSIM to adapt the traffic flow to Swedish driving behavior in a work zone scenario. The model was later validated by comparing the results with video recordings. Lastly, modifications were made to the road design and parameters to find an improved work zone design scenario that balances traffic flow and safety.

4 Work Zone Design and Road Safety

When maintenance is required or construction is carried out on or adjacent to the road, it is essential to consider the safety of both workers and road users. In Sweden, several rules and guidelines govern road design and policies aimed at creating a safe environment.

There are two main regulations *TDOK 2012:86: Technical Description for Work on Road* and *TDOK 2012:88: Technical Description for Work on Road - facility management*, both written by the Swedish Transport Administration (The Swedish Transport Administration, 2012, 2024a). *TDOK 2012:86* covers the design and management of the work zone to increase safety and minimize risks, while *TDOK 2012:88* focuses on the planning and implementation of different measures, such as signage and how traffic should be directed.

4.1 Rules and responsibilities

The Swedish transport administration owns the majority of public roads and is responsible for their maintenance (The Swedish Transport Administration, 2024c). There are exceptions where municipalities act as road managers for public roads, as well as municipal roads and streets. Roads owned by private actors or organizations should be managed by their owners.

The regulation *TDOK 2012:86* (2024a) should be followed when the Swedish Transport Administration is the road manager and/or the client. TDOK 2012:86 has been developed to achieve better safety and work environment on road construction sites, for example, by explaining how the work zone should be designed and signed (see Section 4.2. The requirements are at a minimum level for preventive security measures in road operations. Similar regulations apply for municipal road projects and are described in *Road work handbook of the Swedish Association of Local Authorities and Regions* (Berlin & Johansson, 2019).

The construction and operational stage of the work environment should be considered in the planning and design phase of the project, with the developer having responsibility for these considerations (Swedish Work Environment Authority, 2025). The developer is responsible for appointing a principal designer and a principal contractor. The developer is also responsible for obtaining the necessary authorizations and ensuring compliance with the road manager's laws and regulations. According to the Swedish Work Environment Law *SFS 1977:1160*, the employer has the main responsibility for the employee's work safety and is therefore required to take the necessary actions to prevent accidents.

The client performs a traffic analysis to understand the traffic system in the specific area (The Swedish Transport Administration, 2024b). Based on this traffic analysis, decisions are made regarding roadwork. The entrepreneur responsible for performing the work is then provided with the necessary information about the area, such as whether traffic needs to be rerouted due to high traffic volume and the road's capacity.

The entrepreneur must submit a traffic arrangement plan (TA-plan) to the Swedish Transport Administration (The Swedish Transport Administration, 2012). The TA-plan contains information about the project and is sometimes complemented with attachments that describe the placement of traffic and safety devices (The Swedish Transport Administration, 2024a).

Risk management is an essential safety measure regarding road work, requiring an ongoing risk analysis (The Swedish Transport Administration, 2024a). Job planning should be conducted for work stages that the client or the supplier considers critical or if the suppliers perceive that there are risks for their personnel due to passing traffic. A job plan should always be performed for work stages where vehicles are within the safety zone or on the road, with the aim of increasing the safety of the work zone.

A certified person is responsible for the placement of the road signs in the assigned work zone (The Swedish Transport Administration, 2012). In addition, a safety device manager is appointed in the project that is responsible for the devices being in place as well as checking their function and documenting the quality controls (The Swedish Transport Administration, 2024a). Several signs must be used when designing a road work, some of the most common are, for example, A20 - Warning, road work ahead, and C31 - Speed limit sign (The Swedish Transport Administration, 2020a).

High-visibility clothing and other personal protective equipment should be used to increase the safety of road workers (The Swedish Transport Administration, 2024a). The employer is responsible for providing the appropriate equipment to the workers.

The rules that apply on the specific road where the road work will be carried out can be determined by the classification of the road (The Swedish Transport Administration, 2025a). There are three different classes: protection-classified, normal-classified, and low-classified roads. The classification is determined by the volume of traffic and states the suitable speed limit of the traffic flow and the time at which the road work should be carried out.

Depending on the variation in requirements and layouts of roadworks, there are different methods to organize and execute these tasks. Fixed work is defined as "work carried out in a specific location or road segment with deployed traffic and protective devices in the road area" (The Swedish Transport Administration, 2024a). Intermittent work is road work that progresses in phases and typically utilizes work vehicles, such as those used to construct road markings. Mobile work is performed by vehicles that continuously move throughout the task, such as snow plowing and sanding the road.

4.2 Design of road work

The execution of road work is influenced by several factors, especially the conditions of the work zone. The speed limit is adapted due to the distance of the working personnel and direct traffic. The regulations of the Swedish Transport Administration (2024a) are found in Table 4.1.

Table 4.1: Summary of the regulations regarding speed limits, the safety design measures, and the distance to passing traffic.

Required safety design measure	Speed limit [km/h]
Personnel less than 2.5 m from a lane with passing traffic	30
Personnel more than 2.5 m from a lane with passing traffic	50
Personnel less than 2.5 m from a lane with passing traffic and a longitudinal protection device	50
Personnel working on a road with longitudinal protection device	50-70

A safety zone is defined as "the width of the area outside the road edge that must be kept clear of objects that could harm road users" and aims to minimize the risk of severe injuries and damage if road users drive off the road and collide (The Swedish Transport Administration, 2024a). A visualization is found in Figure 4.1. The size of the safety zone varies depending on the speed limit at the site. The required equipment and material could only be placed during, but not outside, the work shift hours within this zone. The safety zone is not necessary if a longitudinal protection device is implemented, since its function is rendered unnecessary.

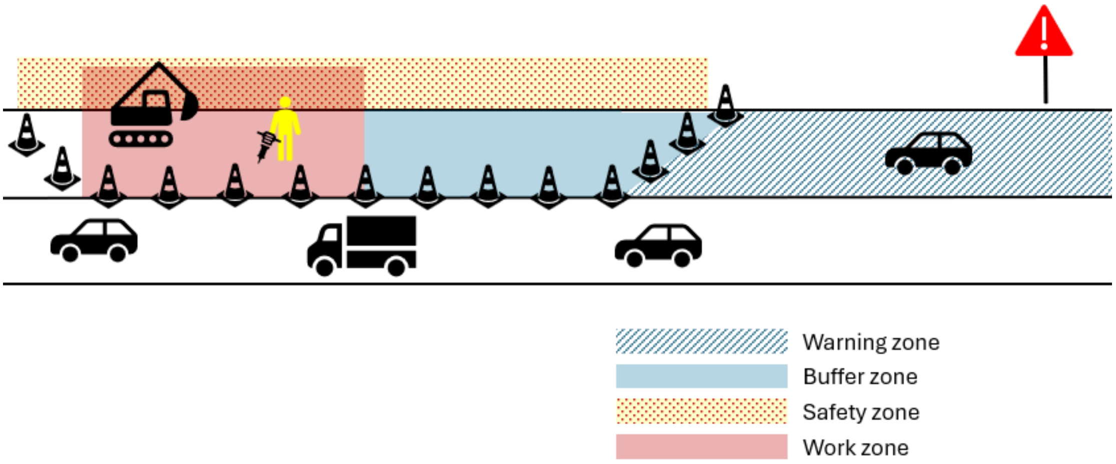


Figure 4.1: An overview of the different safety areas at a road closure.

Road signs are placed at road work to warn drivers about reduced speed limits, but also to inform what to expect and how to act in the traffic situation. Most road signs are placed in the warning zone, see Figure 4.1, to alert drivers about the upcoming traffic disruption. Information about signs and other similar devices and how they should be placed and used is stated in TDOK 2012:86 (2024a, Chapter 10.1-10.4).

Transverse and longitudinal energy-absorbing protective devices should be applied to protect road users and prevent accidents such as falling over and entering restricted areas or incorrect lanes. In addition, the devices also protect the working personnel from passing traffic (The Swedish Transport Administration, 2024a).

Transverse energy absorption devices are designed to prevent road users from causing severe accidents by losing control of the car and driving off the road (The Swedish Transport Administration, 2024a). A Truck Mounted Attenuator (TMA) could be implemented as an additional reinforcement. TMA is required on protection-classified roads. A buffer zone is located between the transverse protection device and the work zone, as illustrated in Figure 4.1. The buffer zone is designed to protect workers and drivers from serious injuries in the event of an accident, and it shall be kept clear of objects and personnel. The minimum length of the buffer zone is half the original speed limit + 10 meters. For example, a road with an initial speed of 80 km/h needs a 50-meter-long buffer zone. A transverse protection device can be replaced with a longitudinal protection device with a maximum angle of 1:10, see Figure 4.2. The maximum distance from the start of the buffer zone to the end of the work zone is 250 meters, provided the work zone is visible to the road user.

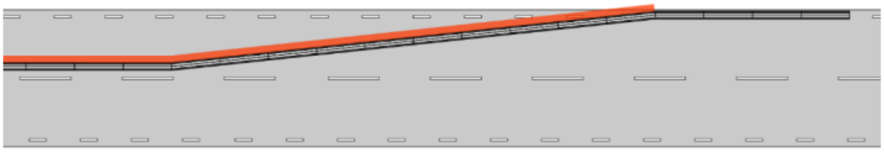


Figure 4.2: Longitudinal protection device used as transverse protection devise (The Swedish Transport Administration, 2024a).

Longitudinal energy absorption protection devices should be used when personnel work on the road with a speed limit greater than 50 km/h (The Swedish Transport Administration, 2024a). In addition, longitudinal safety devices are needed if there is a deep shaft or a steep slope on or near the road. When the original safety devices, such as the cable barrier, are temporarily removed, longitudinal protection devices are needed to ensure safety. The capacity classification of the protection device depends on the classification of the road. Between the protection device and the work zone, a clear protective area must be maintained that is free from objects and personnel.

4.3 Rerouting and diversion of traffic

If road work blocks the lanes in one direction, the traffic must be rerouted to another road, or it can be diverted onto the lanes in the opposite direction. It is the client that presents the results of rerouting or diverting traffic, which are then coordinated by a project leader and a traffic engineer to make the best decision (The Swedish Transport Administration, Personal communication, May 14, 2025). The entrepreneur shall evaluate and confirm the options for rerouting and diversion, usually by examining traffic flow statistics to identify annual average daily traffic, AADT and maps to understand the road design (Development leader, personal communication, March 17, 2025).

According to the regulation TDOK 2012:88, published by the Swedish Transport Administration (2012), the decision making about rerouting or diverting traffic shall be considered in the following order:

- The traffic shall be directed so that the work is not affected (rerouted)
- The traffic shall be directed where vehicles pass at a safe distance from the work zone
- The traffic shall be separated from the work zone and follow the guidelines of the design of road work. To the extent necessary, there should be protective arrangements.

According to the regulation TDOK 2012:86, published by the Swedish Transport Administration (2024a), there are several parameters to be considered when analyzing the feasibility of rerouting the traffic:

- Safety
- Accessibility
- Mobility
- Environment
- Need for actions

- Presence of permanently marked diversion route

Taking these parameters into account, it is not always possible to reroute the traffic. For example, if the traffic flow and AADT is too large and therefore will result in major disturbances on the detour road or that the travel time of the detour road is increasing the travel time excessively (The Swedish Transport administration, Personal communication, April 14, 2025). In addition, the economic (and environmental) value in rerouting should be considered, and it is not reasonable to build a temporary road for a short period of time (Development leader, personal communication, March 17, 2025).

Instead of rerouting, it is possible to manage a high AADT by adapting the work to the right season and time, avoiding road closures during events and rush hours, among other measures (Development leader, personal communication, March 17, 2025). Therefore, a solution to create less disruption in the road network is to close the road at night. This has positive effects on several of the parameters mentioned above, but will also put strain on the body of the worker and cause fatigue according to the experiences of a development leader and a skilled worker (personal communication, March 17 & April 7, 2025). Night shifts are also less valuable economically because labor is more expensive, and also due to the short time windows during which setup takes place (The Swedish Transport Administration, personal communication, April 14, 2025).

When rerouting is not possible, diversion to another road could be an option. To ensure safety, traffic signals or traffic controllers could be used. The advantage of a traffic controller is that it forces passing traffic to maintain a low speed. A traffic controller should not be implemented if the delay of passing vehicles is greater than 10 minutes (Persson, 2011). An experienced development leader notes that, based on their experience, the maximum number of vehicles a traffic controller can maintain is approximately 130 vehicles per hour to meet the guideline of a minimum 10-minute wait (personal communication, March 17, 2025).

When traffic in both directions should share the operable, signs and barriers should be implemented in a clear and correct way to ensure the safety of road users and personnel (The Swedish Transport Administration, 2024a). An example of how signs should be placed can be seen in Figure 4.3.

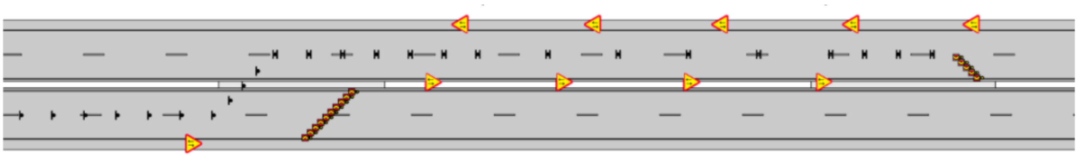


Figure 4.3: Signage at roadwork with diversion of traffic (The Swedish Transport Administration, 2024a)

A skilled worker (personal communication, April 7, 2025) states that rerouting is the optimal decision from a safety perspective, and it feels more unsafe the closer the traffic is diverted with regard to the work zone. In the interview with the development leader (personal communication March 17, 2025) it is mentioned that the amount of traffic that is redirected has increased, where the main reason is that there is a larger basis of reports regarding what is safe from a worker perspective.

4.4 Summary of design and safety

The Swedish guidelines and regulations are well developed and present defined directives on responsibility and design related to road work safety. All work zones in Sweden follow the same regulations, *TDOK 2012:86* and *TDOK 2012:88*. By following these regulations when modeling the setup in VISSIM, the scenario will accurately reflect the Swedish driving behavior. VISSIM settings and parameters were adjusted to replicate the Swedish regulatory standards, taking into account speed limits, roadwork signage, and road design.

5 Case Study Area

When choosing the case study area, the Swedish Transport Administration traffic information website was used where the ongoing road work can be seen (The Swedish Transport Administration, n.d.-a). A case study area on a highway near Gothenburg was chosen where a pedestrian and cycle path will be built and therefore one direction of lanes on the highway is closed to make room for the construction work. The design of the work zone is typical for a highway work zone in Sweden. The case study area is located on highway E20 north-east of Gothenburg at junction Högelidsmotet (91) between Tollered and Ingared, see Figure 5.1. . The designated speed limit is 100 km/h on the highway and is reduced to 70 km/h in the work zone. The decreased capacity and speed were assumed to have an impact on road accessibility (The Swedish Transport Administration, 2025b), data gathered on the 25th of March 2025. The site was also chosen because the high speeds make the workers more vulnerable and therefore a typical work zone with high speeds is suitable to investigate.

Figure 5.1: The location of the case study area in relation to Gothenburg. Modified map from (The Swedish Transport Administration, 2025b).

The road work closed the two lanes in the southbound direction of the highway. Traffic was diverted to the opposite side of the road by creating crossover areas in the median barrier, as illustrated in Figure 5.2.

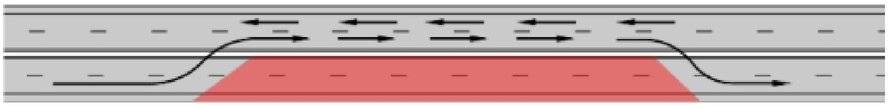


Figure 5.2: The general structure of a traffic diversion into another lane at a highway work zone (The Swedish Transport Administration, 2024c).

The Marking, signing and design of the work zone comply with the framework TDOK 2012:86. To notify the chicane, signage is placed at the area as a combination of the signage D2 "Mandatory direction arrow" and X2 "Barrier marker" as illustrated in figure

5.3 (Ramudden AB, 2019). Together, these signs indicate that the road accessibility is restricted and explain where the vehicle should pass. The signs and barriers affect the driving behavior of the vehicles and make it clear for the drivers where they should merge.

Figure 5.3: A combination of the signage D2 (Mandatory direction arrow) and X2 (Barrier marker) to notify drivers of a chicane.

5.1 Traffic survey video at work zone

Statistics from the Swedish Transport administration (n.d.-b) indicates that the main traffic flow is between 06:00-9:00 and 16:00-18:00 on a weekday. Data were collected in the case study area on 31th of March between 06:30-09:00 and 16:00-18:00 by recording the traffic flow. The weather on this day was sunny and calm with a temperature that varied from 3°C and 12°C and was therefore assumed to not affect the traffic flow. There were no known events or accidents in the area that affected the traffic flow. The camera was set up as shown in Figures 5.5 and 5.4 to catch the majority of the lane changing behavior that occurred at the reduced lane sign and the 70 km/h in 300 m sign. Since most of the lane change occurs in this road segment, it is interesting to quantify the lane change to analyze the driving behavior.

Figure 5.4: Camera set up at the case study area recording the traffic from the bridge over junction 91 pointed at the south west direction.

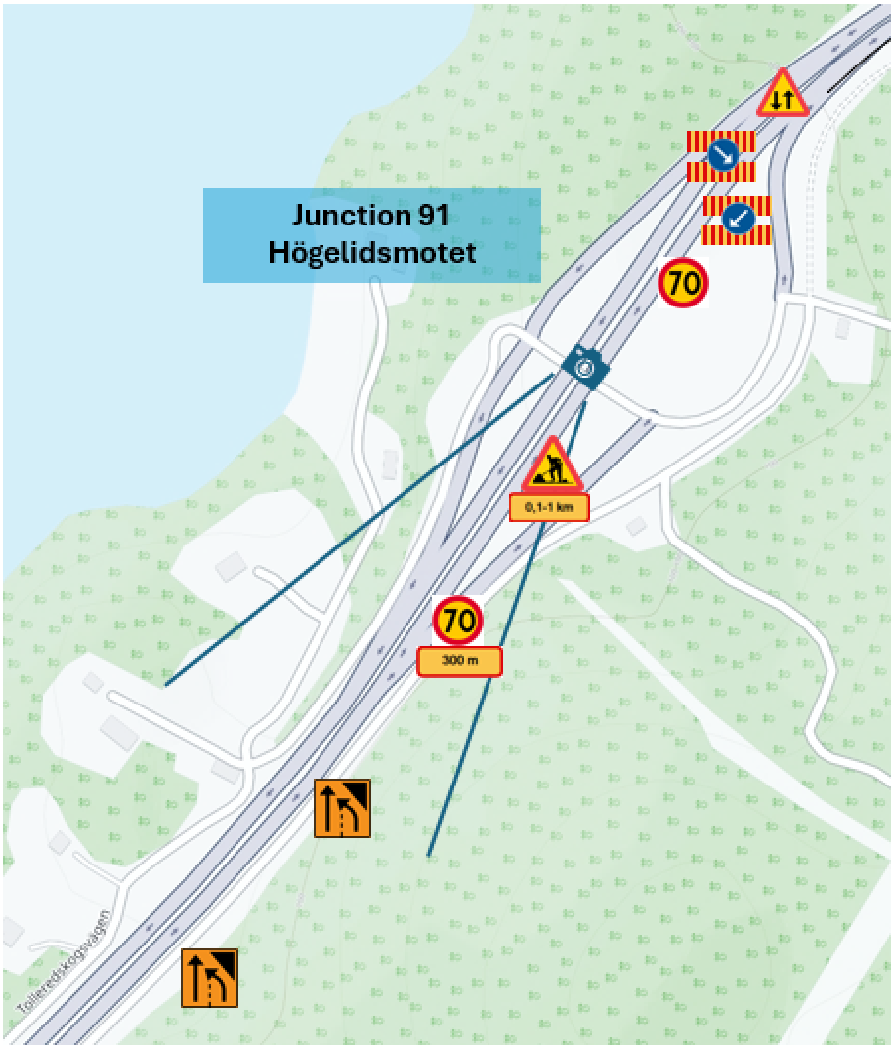


Figure 5.5: The design of the sign locations the and main the recording spot. Modified map from Openstreetmap.org.

Another camera was aimed right before the chicane, recording for 15 minutes in the morning and 15 minutes in the afternoon, the camera angle can be seen in Figure 5.6. The video was used to analyze the number of vehicles showing aggressive behavior and being forced to merge. The count was done visually from the recording. Recorded from: 06:45-07:00 and 16:15-16:30 31th of March.

Figure 5.6: Camera set up at the case study area recording the traffic from the bridge over junction 91 pointed in the northeast direction.

One of the parameters of aggressive driving behavior is unsafe overtaking such as forced late merging (Alonso et al., 2019). Therefore, the aggressiveness of driving behavior was categorized into three zones that were determined based on the distance from the road closure to the location where vehicles merged, as illustrated in Figure 5.7. Zone 1 represented non-aggressive driving, with early merges occurring before the final "lane ends/reduction of lanes" sign, roughly 400 meters before the chicane. Zone 2 indicated semi-aggressive driving, where merging took place between 200 and 400 meters before the chicane. This zone was recorded for data extraction. Zone 3 identified aggressive driving, characterized by late merges that would be considered forced merging.

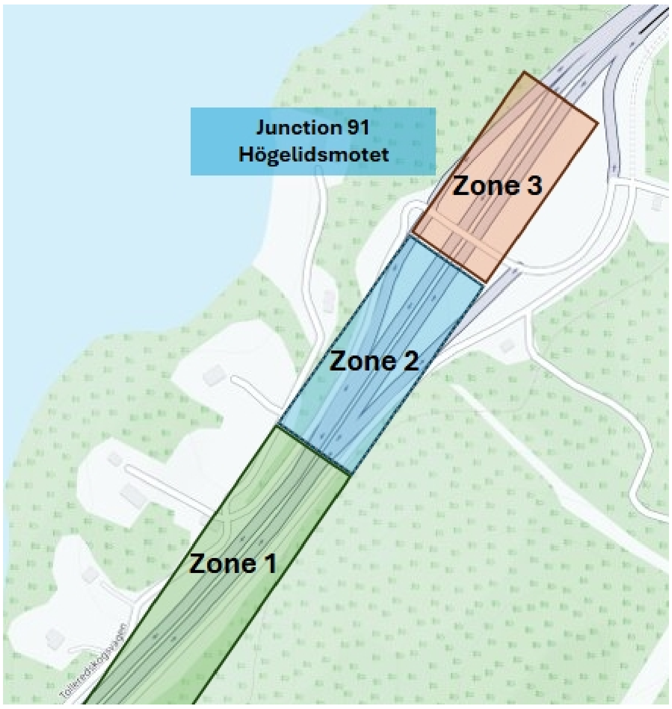


Figure 5.7: Definition of the driving behavior zones: Zone 1 is defined as non-aggressive driving behavior, Zone 2 as semi-aggressive driving behavior, and Zone 3 as aggressive driving behavior. Modified map from OpenStreetMap.org.

5.2 Data extraction from traffic survey video

The code used for data extraction can be seen in Appendix A. When determining the lanes that the vehicles drove in the coordinates in pixels at the top of the region area where the lanes ended, where extracted, see Figure 5.8

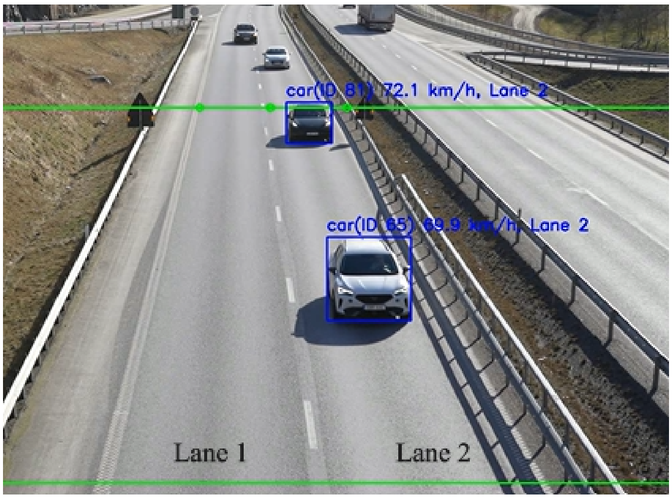


Figure 5.8: Video frame where the region area and lane boundaries can be seen.

To calibrate the speed of the vehicles and the distances in the video frames, a reference vehicle was used. During the recording, the team drove by the filmed area in a car at a constant speed. This together with information about length of road segments and frames per second, the pixels per meter (PPM) to be determined. Since the camera is at an angle, the PPM cannot be determined simply by using pixels in the frame and a known distance, and therefore calibration was necessary. The calibration process was performed for the morning and afternoon recordings since the angle and placement of the camera varied. The code can be seen in Appendix A. To validate the speed and distances, samples were taken and hand calculated to see if the speed and distances matched the output data.

The vehicles were usually detected by the model, but sometimes when for example cars were blocked by other cars in the video frame the calculations became incorrect. To handle this problem vehicles with a speed less than 10 km/h and higher than 110 km/h were excluded. These speed limitations were picked since no vehicles were driving so slowly or standing still and no vehicles were driving so fast during the recordings.

The object detection model could detect cars, but detecting trucks, buses, or other large vehicles proved more challenging. Sometimes, cars were detected as large vehicles and vice versa, and therefore, the decision to exclude large vehicles from the data collection was made. Since these vehicles are long, the gaps between the car in front to the car coming after the truck were automatically excluded from the data because of the extraction of CC1, see Section 3.4. Additionally, vans were misclassified as cars in object detection.

5.3 Simulation in VISSIM

As mentioned in Section 2.2, the simulation software VISSIM was used to model the case study area. Three different scenarios were analyzed; uncalibrated, calibrated and adjusted, and improved design scenario. Data were extracted from these simulations by measuring the individual, average, and median speed at a fixed point that was correlated with the data extraction point. In addition, data on the number of vehicles driving in each lane were extracted and analyzed to determine the percentage of vehicles that merge in each lane. The data points are shown in Figure 5.9. For calibrated and improved scenarios, vehicle travel time was measured from the first merging sign to the end of the work zone to assess the impact of road design changes on drivers.

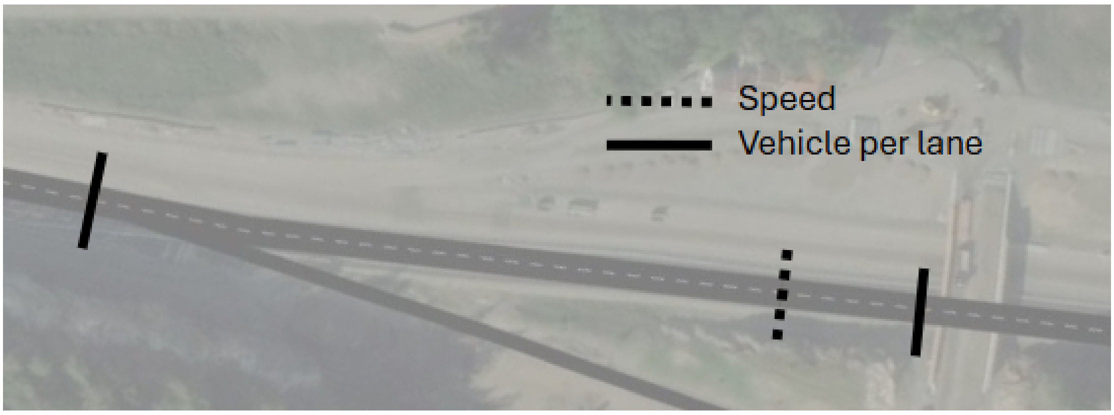


Figure 5.9: Location of the data collection points in VISSIM, for measures of speed and amount of vehicles in each lane at two different locations.

There are no tools in VISSIM that directly simulate a traffic work zone or road closure. To duplicate the chicane design in VISSIM, the road was reduced from two lanes into one at the position of the D2/X2 signs at the chicane, see Figure 5.10. The road was implemented with two connectors, one for an early merge and one for a late merge as shown in Figure 5.11. A partial vehicle route was established for vehicles entering the different connectors.

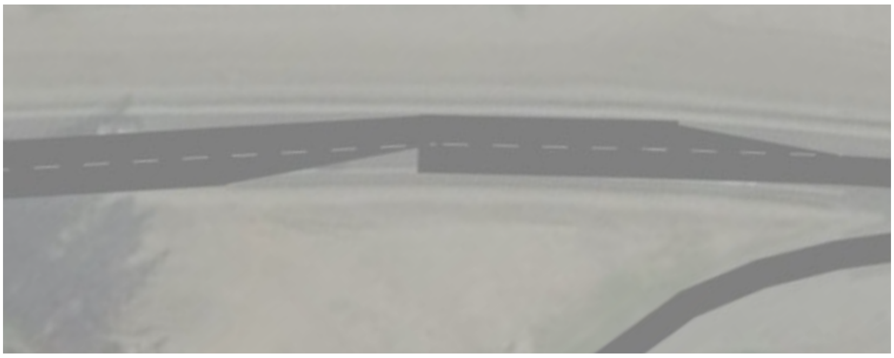


Figure 5.10: Design of the chicane in VISSIM.

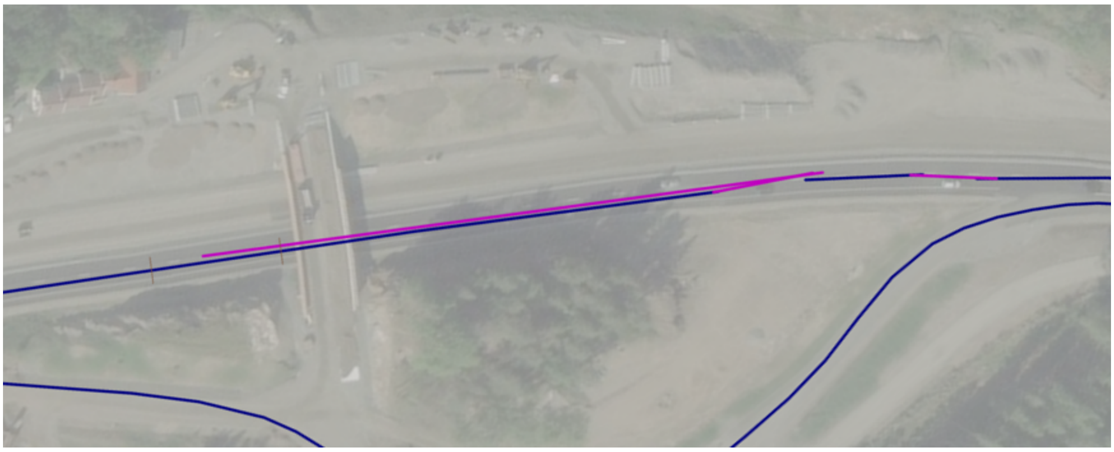


Figure 5.11: Design of the road in VISSIM. Purple lines are connectors and blue lines are nodes.

Some changes were made to the default settings during the design phase to achieve a more realistic simulation, which can be found in Table 5.1. *Jerk limitation* was unboxed because it was found that the vehicles got a more realistic driving behavior. The *Vehicle waiting time before diffusion* was increased so that no vehicles were dissolved due to traffic flow and queuing. For better imitation of traffic flow, a *Cooperative lane change* was implemented where vehicles merge in symbiosis whenever possible. The *desired position at free flow* was set to *any* to mimic the lateral position behavior of the vehicles. Each simulation had a duration of 3600 seconds. The vehicle input was extracted from the field data and the amount of heavy vehicles was set according to Table 5.2.

Table 5.1: Settings changed from default in VISSIM for all scenarios.

Parameter	**Description**	**Default**	**Changed to**
Jerk limitation	Limitations of acceleration	On	Off
Waiting time before diffusion [s]	Time when vehicles are removed from network	60	3600
Cooperative lane change [-]	Vehicles adjusting positions to let other vehicles merge	Off	On
Desired position at free flow [-]	Vehicles can change lateral position freely	Middle	Any

Only one road segment is modeled in VISSIM, which means that interactions between different parts of the network are not included and that vehicles that choose alternative routes are not considered. It was observed that very few vehicles exited the junction and it was concluded that these vehicles do not significantly affect merging and driving behavior and were excluded from the VISSIM model.

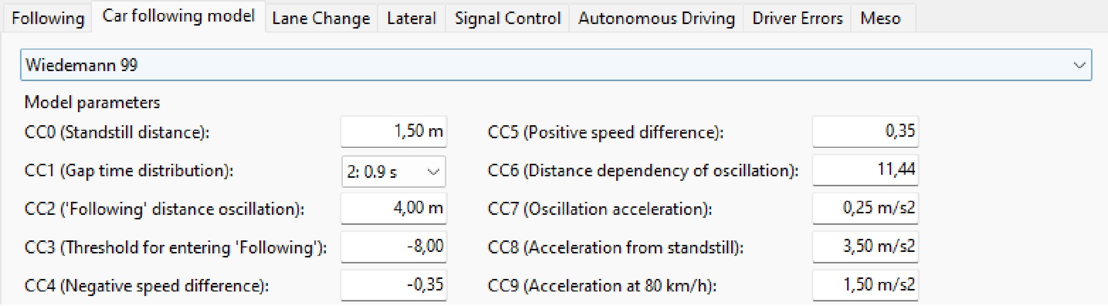
To simulate traffic flow, the number of heavy vehicles on the road was needed. The proportion of heavy vehicles can be seen in Table 5.2 and was gathered from the latest measurement of the Swedish Transportation Administration on the road segment, which was a weekday without events out of the ordinary. The proportion of heavy vehicles has been validated by counting the proportion of heavy vehicles in the traffic survey video.

Table 5.2: Number of vehicles on E20, Wednesday (25th) and Thursday (26th) October 2023 at point 7120401 (The Swedish Transport Administration, n.d.-b).

Time	All Vehicles	Heavy Vehicles	Heavy Vehicles proportion
2023-10-25 16:00	801	69	0.09
2023-10-25 17:00	779	73	0.09
2023-10-25 18:00	521	55	0.11
2023-10-26 06:00	1037	72	0.07
2023-10-26 07:00	1117	55	0.05
2023-10-26 08:00	756	76	0.1
2023-10-26 09:00	503	63	0.13
Mean During Peak			**0.09**

5.3.1 Uncalibrated scenario

The uncalibrated scenario of the case study was modeled in VISSIM by designing a road segment that corresponds to the work zone described in the case study. The scenario was run with the default values of the VISSIM Wiedemann 99 model parameters, shown in Figure 5.12.



Wiedemann 99

Model parameters

CC0 (Standstill distance): 1,50 m
CC1 (Gap time distribution): 2: 0.9 s
CC2 ('Following' distance oscillation): 4,00 m
CC3 (Threshold for entering 'Following'): -8,00
CC4 (Negative speed difference): -0,35
CC5 (Positive speed difference): 0,35
CC6 (Distance dependency of oscillation): 11,44
CC7 (Oscillation acceleration): 0,25 m/s2
CC8 (Acceleration from standstill): 3,50 m/s2
CC9 (Acceleration at 80 km/h): 1,50 m/s2

Figure 5.12: Default parameters for Wiedemann 99 car following model in VISSIM. Figure taken from PTV VISSIM software.

To mimic the speed reduction, a *desired speed decision* was implemented at the point of the speed reduction signs in the case study area, approximately 30 m before the start of the chicane. The lane change settings *Lane change distance*, *look ahead distance*, *necessary lane change* and *partial vehicle routing* were simulated with VISSIM default settings for the uncalibrated scenario.

5.3.2 Calibrated and adjusted scenario

As stated in Section 2, the most critical parameters of road work simulations are CC1 and CC2. The extracted parameters from the video survey data were implemented in VISSIM using the mean value of CC1 and CC2, which is explained further in Section 6.2. Table 5.3 presents the difference from the default value of CC1 and CC2 in VISSIM, used in the uncalibrated scenario, and the calibrated value of CC1 and CC2 that was implemented in the calibrated and adjusted scenario as well as the improved design scenarios. CC1 and CC2 were extracted seperatly from the morning and afternoon video survey and the average from the data collection was used in the calibrated and adjusted and the improved design scenarios.

Table 5.3: Calibrated values from default in VISSIM for calibrated and adjusted scenario and Improved design scenarios.

Parameter	Default value	Calibrated value
CC1 [s]	0.9	1.9
CC2 [m]	4	6.8

Several design settings were changed from the default values (used in the uncalibrated scenario) of the calibrated and adjusted scenario. These changes were made to replicate the design field conditions and are presented in Table 5.4. The *partial vehicle routing* was set to 0.99 because the counted number of vehicles that merged in zone 3 was approximately 1% according to the video recordings, further information can be found in Table 6.1. Further, the *speed decision* was moved to the speed restriction + distance sign (C31/T2), approximately 300 m before the chicane. From the field data, it was observed that the drivers chose to lower their speed here, rather than continuing to do so further ahead.

Table 5.4: Settings changed from default in VISSIM for all scenarios.

Parameter	Default settings	Changed settings
Partial vehicle routing [%]	1	0.99
Desired speed decision [km/h]	70	70
Desired speed decision, position from chicane [m]	30	300
Look ahead distance [m]	250	700
Necessary lane change [-1m/s per distance]	200	700
Lane change distance (Early merge) [m]	200	250
Lane change distance (Late merge) [m]	200	350

To obtain an accurate merging behavior, *necessary lane change* and *maximum look ahead distance* was set to 700 m, matching the merging signs. This adjustment replicates the driving behavior where the driver tries to find a gap and merge more realistically when they see the sign and are notified of the change in the road design. The *lane change distances* were adjusted for similar reasons since drivers actively find a gap around the second "warning of lane reduction" sign, approximately 400 m upstream. The input values are varying because the early merge connector was approximately 100 m longer than the late merge connector with the purpose of having lane changes begin at the same point. These changes are visualized in Figure 5.13.

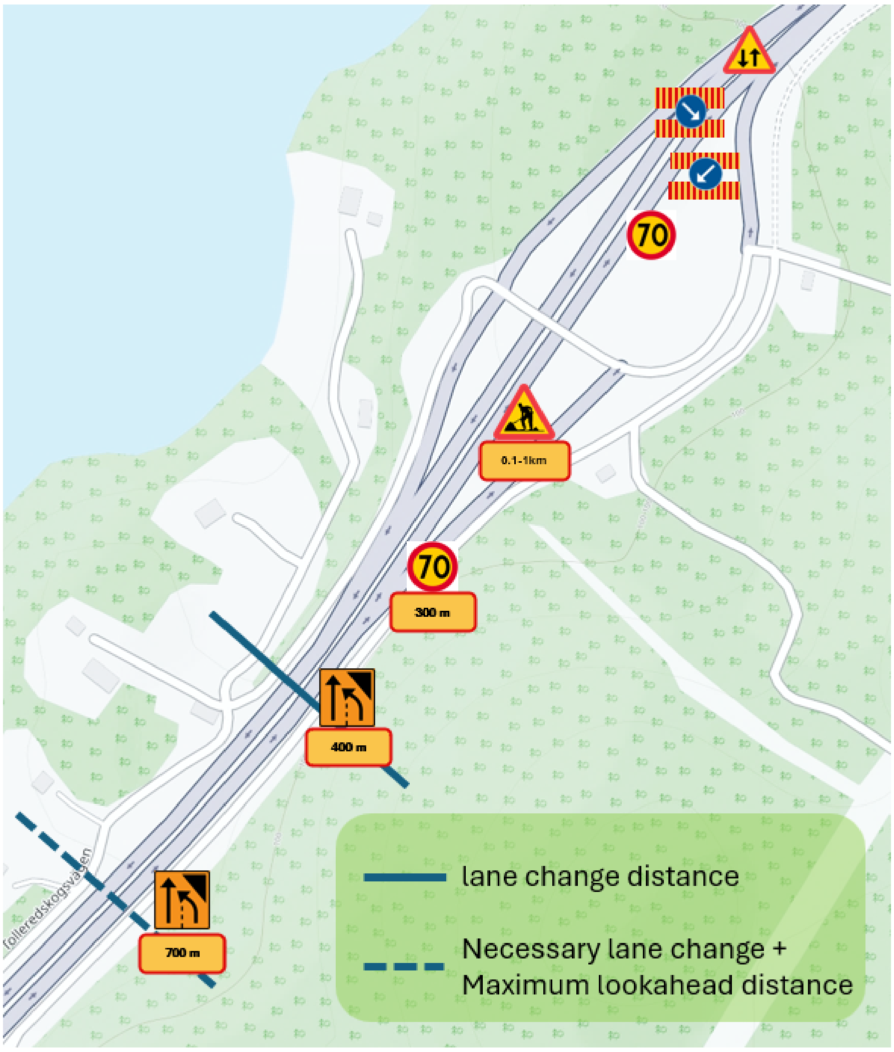


Figure 5.13: An illustration of how the *Necessary lane change*, *Maximum look ahead distance* and *lane change distances* are adjusted.

5.3.3 Validation

The model was validated to ensure accuracy. According to the Swedish Transport Administration, the ideal case is to have enough data in which one part is used for calibration and one part is used for validation (Bång et al., 2014). A less secure validation process requires a higher level of sensitivity analysis. If the models show unacceptable differences, the initial model should be recalibrated. According to Mathew & Radhakrishnan, (2010), an error of maximum 15% is acceptable between the simulated and observed data. The validation was performed visually by comparing the simulated and observed merging behavior at a random time with the result of a real-life scenario. If the error is below the acceptable value (here 15%) the simulation and real-life scenario are thought to replicate reality.

5.3.4 Sensitivity analysis

According to the Swedish Transport Administration, a sensitivity analysis should be conducted to assess the sensitivity of the results to changes in parameters and input data (Bång et al., 2014). The model could be considered unstable if small parameter changes create a large impact on the results. The sensitivity analysis was conducted after the model's validation. The parameters CC1 and CC2 were extracted from the traffic survey and are found in Table 6.2, these parameters were analyzed for the increase and decrease in the mean extracted values of CC1 and CC2 with respect to both the speed of the vehicles and the number of vehicles as seen in Table 5.5.

Table 5.5: Change in parameter values for the sensitivity analysis.

	CC1 [s]	**CC2 [m]**
Default	0.9	4
Calibrated	1.9	6.8
+ 10%	2.1	7.5
- 10%	1.7	6.1
+ 20%	2.3	8.2
- 20%	1.5	5.4
+ 30%	2.5	8.8
- 30%	1.3	4.8

5.3.5 Improved design Scenario

The improved scenario focuses on design improvements and not directly on safety assessments. However, a better design will create a safer road environment. For example, Zhang et al. (2023) mention that there is a statistical correlation with speed and crash risk in the work zone scenario, and it is commonly known that a lower speed reduces the severity of the crash. Therefore, changes were made to the design of the work zone by lowering the *desired speed decision* from 70 km/h to 60 km/h.

In addition, a traffic flow in which drivers do not have to brake heavily is important to reduce the statistics of vehicles hitting other vehicles in the rear (Ihs, 2020). Hallmark et al. state that (2011) an early merge is preferred over a late merge. Therefore, the *lane change distance* was increased to simulate an earlier merging. In reality, this could be implemented by placing the lane closure signage earlier. Lastly, a combined scenario of a decreased *desired speed decision* and an increase *lane change distance* was simulated. All improved design scenarios were analyzed with respect to the mean and median speed, the vehicles changing in each lane, and the travel time. Table 5.6 presents the parameter changes for each improved scenario.

Table 5.6: Changed parameters for the improved design scenarios.

Parameter	**Improved Speed**	**Improved Lane change distance**	**Improved Combined**
Desired speed decision [km/h]	60	70	60
Lane change distance (Early merge) [m]	250	350	350
Lane change distance (Late merge) [m]	350	450	450

6 Result

The results are presented in relation to the purpose of this study and are based on collected data and simulations. Since the most common accident in work zones is rear-end collisions, it is essential to analyze the gap between the vehicles, specifically CC1 and CC2. If vehicles have a larger gap between each other, it decreases the risk of collisions. An earlier lane change indicates that vehicles are more aware of the traffic situation coming up ahead and are prepared for the upcoming work zone. When vehicles change lanes earlier, it also lowers the risk of collisions, as less pressing situations occur because the vehicles have more time to find a suitable gap to merge into. The speed at which vehicles travel is also important to see if the speed limit is respected or if dangerous situations occur when vehicles speed past the work zone.

6.1 Incidents and Accidents

The incidents and accidents recorded in a fixed work zone between September 2021 and March 2025 for Skanska Industrial Solutions employees and their subcontractors are presented in Figure 6.1. Most accidents and incidents have occurred in pavement operation projects.

The category with the highest number of incidents and accidents in the work zone is *slip and fall accidents*. A typical fall accident occurs when a worker steps out of a work vehicle and trips. *Work Vehicle/Equipment Collision* includes collisions between work vehicles or with equipment, work vehicles slipping off the road, or overturning. Road users *speeding or driving too close to the work zone* is also a problem where road users do not respect the speed limit or the space where personnel work. The category *Equipment injury* includes burns from chemicals and hot materials, cuts from handling materials and equipment, etc. *Work vehicles malfunction* is, for example, failure of truck brakes. *Unauthorized work zone entry* includes road users in the work zone or drivers who pass the traffic controller and therefore enter the work area without permission. *Threats and violence against personnel* in the work area include road users who threaten, hurt, or fight workers. *Road user colliding with traffic devices* where road users drive into traffic devices, such as barriers, and *Road User colliding with work vehicles* is where road users drive into work vehicles. *Road user collides with road user* is where the road user is driving into the vehicle ahead in a queue at the traffic controller.

Unauthorized work zone entry has a relatively small report statistic, but is mentioned as an increasing problem by the QEHS-focused interviewer (Personal communication, March 26, 2025). This poses a safety risk to both road users, who may be injured, and workers, who may experience increased stress. All interviewees had experienced that *Personnel threats and Violence* towards personnel is increasing. The main reason is believed to be that road users experience stress when realizing that their travel time will increase. This could be mitigated by informing drivers about road closures in advance, as well as by implementing appropriate measures. For example, avoid using traffic controllers if the waiting time exceeds 10 minutes. In addition, it is recommended to avoid working alone. *Speeding/Driving to close work zone* is agreed to be a main issue of road safety by all interviewers. A skilled worker (Personal communication, April 7, 2025) agrees that speeding is a factor in feeling unsafe at work. One solution is to require vehicles to reduce their speed, such as by using chicanes and speed bumps. A

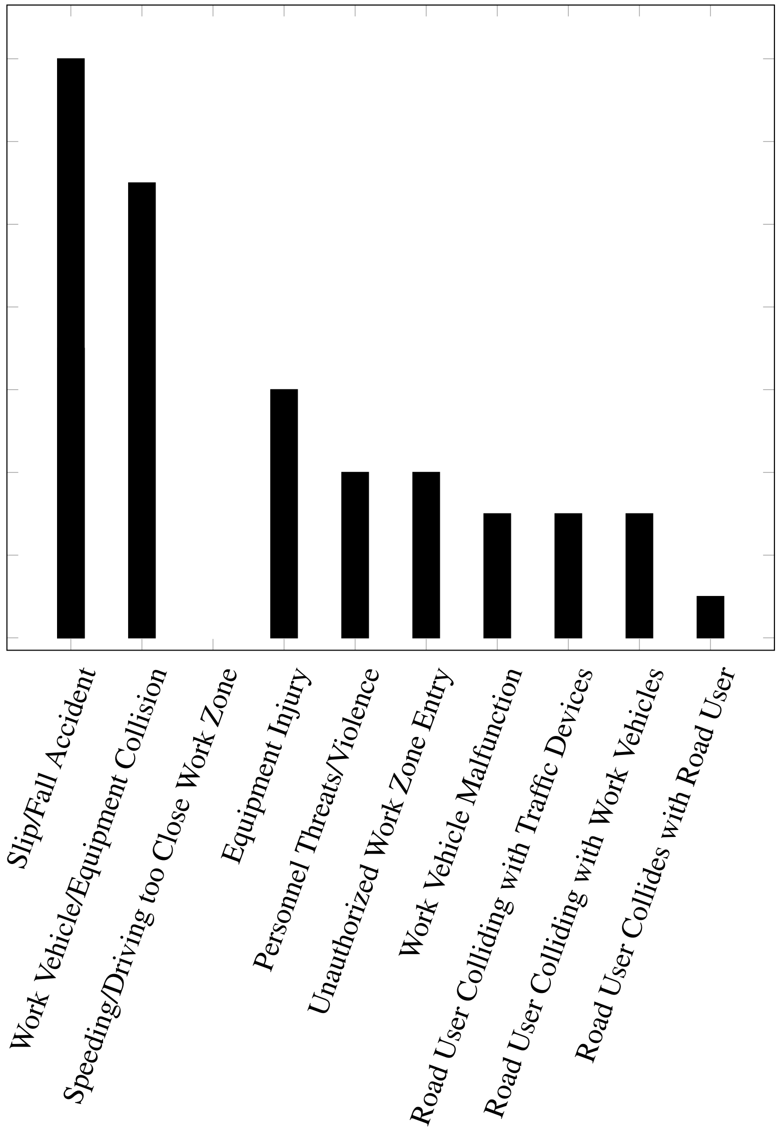


Figure 6.1: Incidents and Accidents at fixed work zones between September 2021 and March 2025, reported in SAI

skilled worker suggested that an effective solution would be to have the traffic controller move along the work zone when the work is variable, such as paving.

6.2 Data extraction from traffic survey

After running the code on the traffic survey videos, the data were extracted. The data is presented in Table 6.1 - 6.2 and Figure 6.2 - 6.4. To show the distribution of the extracted data in a clear way, histograms were plotted when relevant (Xu et al., 2015). The lane change in the different zones can be seen in Table 6.1. Vehicles that have not changed lanes in Zone 2 or 3 are assumed to have changed lanes in Zone 1. In zone 3, less than 1 % changed lanes because most of the vehicles have already changed in zone 2 or 1. In the afternoon, more vehicles merge in zone 1 because there is a higher traffic flow, see Table 6.2, and therefore drivers want to merge earlier to get a guaranteed spot in lane 2. The percentage of vehicles merging in zone 3 is lower in the afternoon due to queue dynamics; there is more queuing in the afternoon, and therefore, vehicles create a queue in lane 2 earlier.

Table 6.1: Driving behavior at the case study area, in which zone the vehicles change lanes from the traffic survey footage.

Time	**06:45-07:00**	**06:45-07:00**	**16:15-16:30**	**16:15-16:30**
Zone	**2**	**3**	**2**	**3**
Vehicles changed from lane 1 to 2	62	1	68	1
Total amount of vehicles in both lanes	152	152	390	390
Percentage of vehicles changing lanes	40.8%	0.66%	17.4%	0.26%

Figure 6.2 presents the extracted speeds of vehicles. In the afternoon, the speed has a broader distribution, with more vehicles driving slowly, as well as more drivers going fast. This could be because the higher traffic flow creates congestion, which leads to slower speeds for vehicles. The speed increase compared to the morning could be vehicles driving fast in lane 1 to get further ahead in the queue.

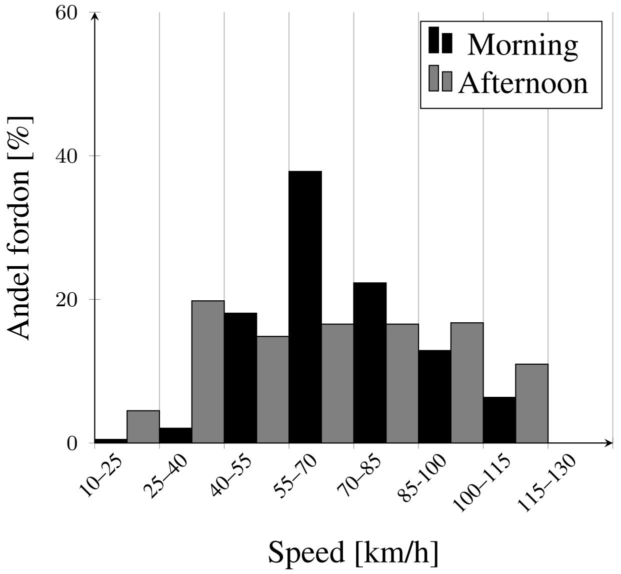


Figure 6.2: Speed in the region area, which is located in zone 2, in the morning and afternoon, illustrated in a histogram.

In Table 6.2 and Figure 6.3-6.4, CC1 and CC2 of the video survey can be seen. The parameters do not vary significantly from morning to afternoon. The average value of CC1 and CC2, found in Table 6.2, is considered representative of the Swedish driving behavior in a work zone.

Table 6.2: Average values from data extraction used in simulation in VISSIM.

Parameter	**06:30-09:00**	**16:00-18:00**	**Average**
Average CC1 [s]	1.97	1.89	1.93
Average CC2 [m]	7.17	6.42	6.80
Traffic volume [veh/h]	1157	1425	1291

The histograms in Figure 6.3 and 6.4 show the distribution of CC1 and CC2 from the video survey data. The distance between the vehicles is quite evenly distributed in the 0.9-3 second span, but the majority is between 1.7-2.2 seconds. Since the data is from a video survey with varying traffic flow, the distance between the vehicles will vary. CC2 is mostly represented in the 4-5.6 m span, which means the gap between the vehicles is mostly only a few meters. When there is some congestion, the vehicle pairs can vary when the speed changes of the lead vehicles, which can explain the higher CC2 values.

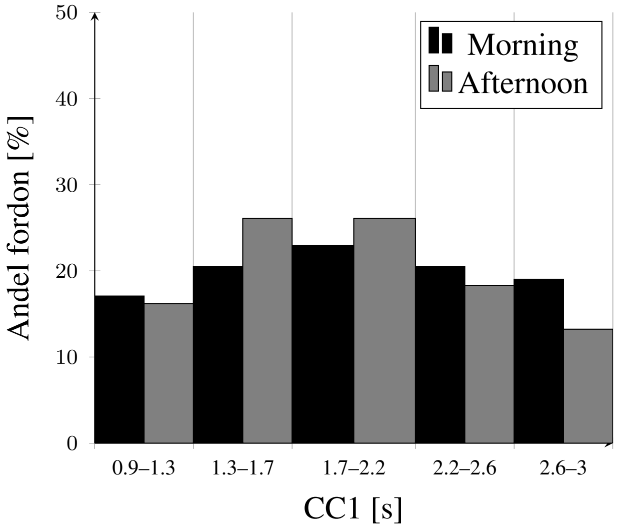


Figure 6.3: CC1 in region area in the morning and afternoon from data collection in zone 2, illustrated in a histogram.

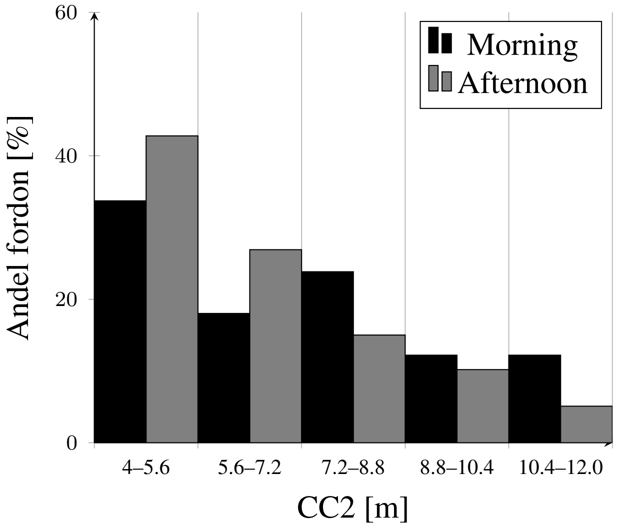


Figure 6.4: CC2 in region area in the morning and afternoon from data collection in zone 2, illustrated in a histogram.

6.3 VISSIM Traffic Simulation

What parameters are used to simulate each scenario can be seen in Chapter 5. For the uncalibrated scenario, the parameters are set to the default values defined in VISSIM, except for the desired speed decision, which is set to the speed limit in the work zone. The calibrated and adjusted scenario has CC1 and CC2 values set to the mean value collected from the video survey (see Table 6.2). The described speed is the same as the uncalibrated scenario, since the speed limit at the work zone is the same. The look-ahead distance and lane-change distance were set to 700 m because this is the position of the lane closure sign, and the majority of vehicles consider the surrounding traffic and switch lanes. For the improved scenario, CC1 and CC2 remain the same as in the calibrated and adjusted scenario, as the improved scenario should be based on how Swedish drivers behave in traffic.

6.3.1 Uncalibrated, Calibrated and Adjusted Scenario

The uncalibrated, calibrated, and adjusted scenario vehicle speed data were gathered from VISSIM simulations. The data is shown in a histogram in Figure 6.5. In the uncalibrated scenario, vehicles drive much faster compared to the calibrated and adjusted scenario. The calibrated and adjusted scenarios' speed output is much closer to the video survey data.

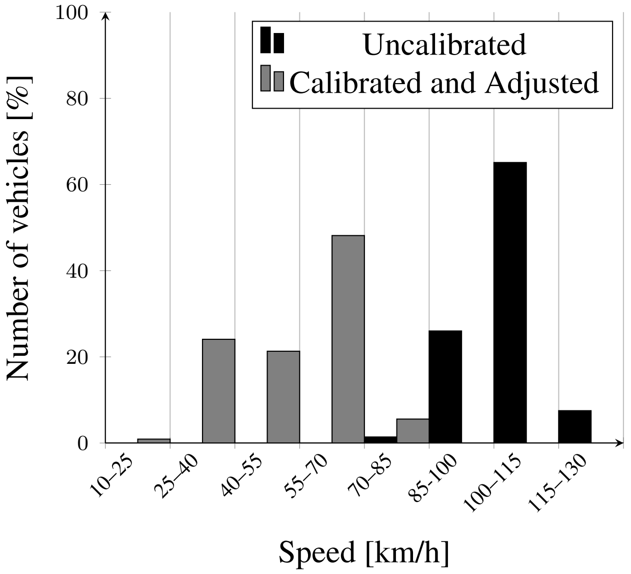


Figure 6.5: Speed in uncalibrated, calibrated, and adjusted scenarios gathered from the VISSIM simulation in zone 2, illustrated in a histogram.

6.3.2 Improved design scenario

The improved design scenario vehicle speed data was gathered from the VISSIM simulation. The data is shown in a histogram in Figure 6.6. When the speed decision was changed, the speed decreased somewhat compared to the calibrated and adjusted scenario. The speed increased somewhat compared to the calibrated and adjusted scenario when the lane change distance was changed. With both the lane change distance and the speed decision changed, the mean speed was lowered by about 6 km/h.

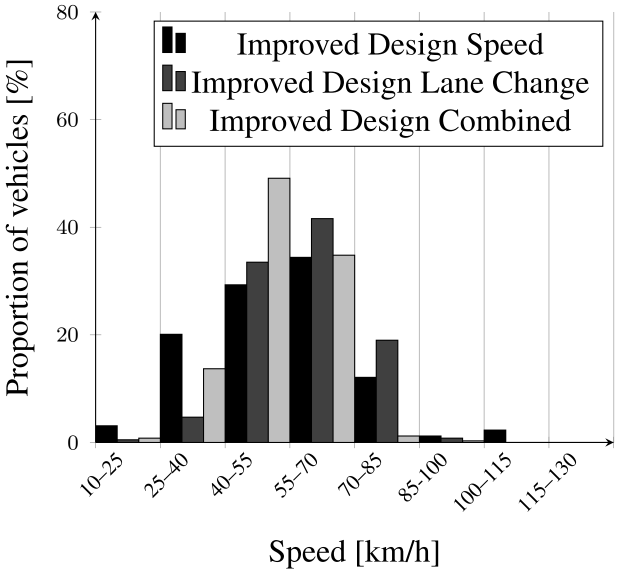


Figure 6.6: Speed in improved design scenario gathered from the VISSIM simulation in zone 2, illustrated in a histogram.

6.4 Validation, Sensitivity Analysis and Summary of Results

Results from the simulation validation and sensitivity analysis are presented. Additionally, a summary of the simulation results is compiled in a table.

6.4.1 Validation

By validating the data from the calibrated and adjusted simulation with the video survey data, a clear assessment can be made of whether the results are valid or not. As seen in Table 6.3, the absolute error, the largest difference in results, is 9%, which falls within the acceptable range; therefore, the calibrated and adjusted scenario can be deemed correct.

Table 6.3: Validation of calibrated and adjusted scenario, done by comparing the proportion of vehicles changing lanes in zone 2 from the video survey with the calibrated and adjusted scenario data from VISSIM.

Scenario	**Lane Change Zone 2**
Calibrated and Adjusted	48 %
Validation 07:45-08:00	38%
Validation 16:30-16:45	42 %
Average Absolute error	9 %

6.4.2 Sensitivity analysis

Figure 6.7 illustrates how variations in the CC1 parameter affect the mean speed in the region area, as well as the lane change in zone 2. The y-axis represents the deviation of the output parameter, either mean speed or lane change in zone 2, from the calibrated and adjusted scenario. The same analysis was performed for CC2 in Figure 6.8. Change in CC1 affects the mean speed and lane change in zone 2 significantly, where a 30 % increase of the calibrated CC1 value results in a 60% decrease in mean speed and can therefore be said to be a dominant sensitivity factor with quantifiable impacts on both speed and merging. The calibrated value for CC1 is 1.9 seconds, compared to the default value in VISSIM, which is 0.9 seconds, representing a significant change. CC2 does not affect the results as much as CC1, but still contributes to changes in the results. CC2 was also changed significantly from 4 m to 6.8 m It can therefore be stated that the calibrated and improved scenario changes the traffic conditions drastically compared to the uncalibrated scenario because two influential parameters are calibrated.

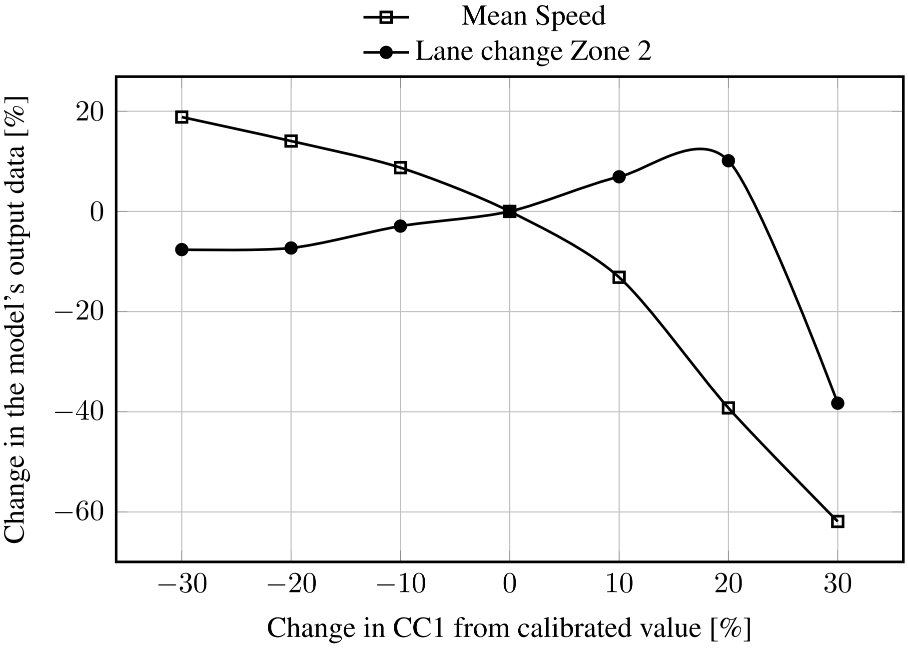


Figure 6.7: Sensitivity analysis of CC1: Impact of changes in CC1 on model outputs for mean speed and lane changes in Zone 2.

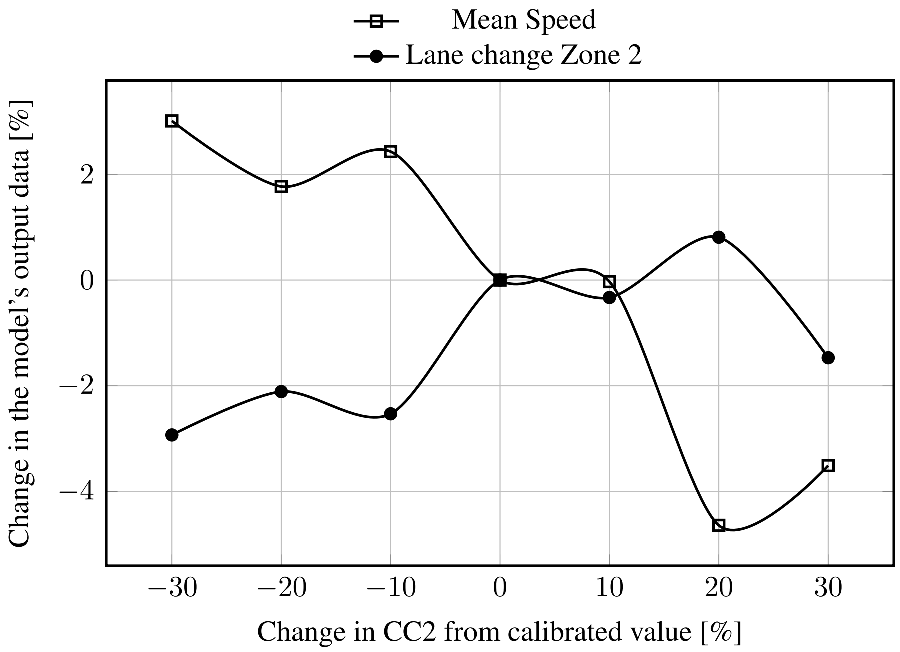


Figure 6.8: Sensitivity analysis of CC2: Impact of changes in CC2 on model outputs for mean speed and lane changes in Zone 2.

Tables 6.4 and 6.5 present how changes in CC1 and CC2 affect mean and median speed, as well as lane changes in Zones 2 and 3. It is observed that speed generally decreases, and a late lane change (in Zone 3) is more common with larger gaps. The percentage of lane change in Zone 3 ranges from as low as 0.15% to as high as 35%, where the tabular format provides a clearer presentation than a graph.

Table 6.4: Sensitivity analysis for CC1, comparison in speed and lane changing.

Change in CC1 from calibrated value [%]	Mean Speed [km/h]	Median Speed [km/h]	Lane Change Zone 2 [%]	Lane Change Zone 3 [%]
CC1 -30	67.2	68.8	44.1	0.2
CC1 -20	64.5	67.5	44.2	0.2
CC1 -10	61.5	64.9	46.3	0.3
CC1 +10	49.1	46.8	51.0	0.5
CC1 +20	34.4	33.0	52.5	6.6
CC1 +30	21.5	19.6	29.4	35.8

Table 6.5: Sensitivity analysis for CC2, comparison in speed and lane changing.

Change in CC2 from calibrated value [%]	Mean Speed [km/h]	Median Speed [km/h]	Lane Change Zone 2 [%]	Lane Change Zone 3 [%]
CC2 -30	58.3	61.9	46.3	0.9
CC2 -20	57.6	61.1	46.7	0.5
CC2 -10	57.9	61.7	46.5	0.6
CC2 +10	56.5	60.8	47.6	1.0
CC2 +20	53.9	56.8	48.1	1.2
CC2 +30	54.6	58.3	47.0	1.5

6.4.3 Summary of Results

In Table 6.6, the travel time for the different scenarios can be seen. The scenario with the longest travel time throughout the work zone is improved design speed decision and improved combined, which is 4 seconds, or 2.2%, longer than the shortest, improved speed decision. It can be stated that travel time is not significantly affected by changing the design of the work zone. A lower speed creates a safer work zone with fewer severe accidents; therefore, the results can be used to argue that lowering the speed can be implemented without a significant impact on travel time.

Table 6.6: Travel time throughout the work zone for the different scenarios.

Scenario	Mean Travel Time [s]	Median Travel Time [s]
Calibrated and adjusted	138	136
Improved Design Speed Decision	141	139
Improved Design Lane Change Distance	137	136
Improved Design Combined	141	140

In Table 6.7, the most critical results from the data collection and VISSIM scenarios are presented with regard to the main speed, median speed, and lane change. The lowest mean speed is achieved in the improved design combined scenario. In the uncalibrated scenario, lane change in zone 3 was the highest and differed the most from the traffic survey data.

Table 6.7: Summary of results from the different scenarios.

Scenario	Mean Speed [km/h]	Median Speed [km/h]	Lane Change Zone 2 [%]	Lane Change Zone 3 [%]
Traffic Survey Morning	69.0	66.16	40.8	0.66
Traffic Survey Afternoon	64.8	64.8	17.4	0.26
Uncalibrated	105	104	41.3	10.1
Calibrated and Adjusted	56.6	60.3	47.7	0.4
Improved Design Speed Decision	52.7	53.8	50.3	0.9
Improved Design Lane Change Distance	59.1	60.4	11	0.1
Improved Design Combined	50.7	51.2	12.1	0.5

7 Discussion

This chapter will reflect on the findings of this study and link them to the research questions.

7.1 Work zone design and road safety

As presented in Chapter 4, Sweden has several regulations and frameworks regarding design and safety. There are national standardizations such as *TDOK 2012:86* and *TDOK 2012:88*, published by the Swedish Transport Administration. In addition, there are supplementary regulations for municipalities. A development leader (personal communication, 17 March, 2025) stated the importance of planning for risks and safety already in the procurement and development phase. It is essential to follow these regulations to ensure not only a safe work environment but also the safety of road users. The work zone at the case study area follows the guidelines in *TDOK 2012:86* and *TDOK 2012:88*. The improved design scenarios are enhancements that can be added to the regulations to improve traffic flow and driving behavior.

7.1.1 Incidents and accidents

The extraction of the correct data in SAI was complicated due to misclassified reports and the need to sort out which reports were considered work on the road. Therefore, some reports might have been missed. As stated in several interviews, not all events have been reported. Both a QEHS expert and a skilled worker (personal communication, March 26 & April 7, 2025) mentioned that it is possible that the workers have gotten used to their work environment and will therefore underestimate the severity of an event.

Reported events are a good basis for decision-making about a safer work space. A development leader (Personal communication, March 17, 2025) has noticed an increase in rerouting compared to diverting traffic, likely due to incoming reports of road safety concerns. The Swedish Transport Administration (Personal communication, April 14, 2025) is using another reporting tool. The Swedish Transport Administration is gathering information and reports from within the sector to improve national regulations regarding road safety.

Accidents and injuries could appear in many different ways and therefore it is impossible to apply one single uniform solution. According to the result of the interviews, own observations and the quantitative research, most accidents are minor. A skilled worker (personal communication, April 7, 2025) mentioned that the best preventive measure on the worker side is to always be alert and communicate with the team. It is further stated that the headset for talking, mounted on the helmet, is a key tool not only to warn each other about risks but also to work more effectively. Preventive measures that could be implemented in the design and work zone regulations include informing drivers about upcoming road work and enforcing a lower speed limit for vehicles on the project site.

7.2 Uncalibrated and calibrated and adjusted scenario

As expected, the uncalibrated simulation differs significantly from the calibrated and adjusted scenario. VISSIM is a software built on German data and driving behavior and is therefore not applicable to Swedish driving behavior without calibration. For instance, the default value of CC1 is 0.9 seconds in VISSIM, while the extracted CC1 from a Swedish driving behavior was found to be 1.9 seconds, an increase of 111%, which is a first indicator that the Swedish driving behavior is less aggressive.

The parameters CC1 and CC2 were increased in the calibrated and adjusted scenario, resulting in an extension of the allowed distance for vehicles to merge. This influenced lane change behavior, as drivers needed to find larger gaps before merging, where the increased spacing between vehicles could create longer queues. Smaller values of CC1 and CC2 would influence more aggressive driving behavior and lead to fewer vehicles breaking in advance, which is also seen in the large proportion of vehicles in the same speed interval in Figure 6.5.

As seen in Figure 6.5, vehicles behave differently in the uncalibrated vs. calibrated and adjusted scenario. In the uncalibrated scenario, vehicles were unable to notice the sign of reduced speed, and therefore, the mean speed was adapted to the original speed of 100 km/h, where for the uncalibrated scenario, the *desired speed decision* was implemented, where drivers noticed the signage of reduced speed. This created a more realistic speed distribution compared to the speed distribution in the extracted data, as shown in Figure 6.2. The calibrated and adjusted scenario resembles the extracted morning scenario in terms of speed distribution. The morning hours had a lower traffic volume (Table 6.2) and therefore more free flow, allowing vehicles to easily adapt to the speed limit. When traffic volume increases, the speed distribution is equalized between intervals due to a more intense car following. There was some non-standstill queuing, and therefore the vehicles were forced to slow down, especially when other vehicles were merging ahead. The larger amount of increased speed for the afternoon traffic could be due to the stress individual drivers felt in finding an acceptable gap. During the calibrated and adjusted scenario, there were no vehicles that were going above the speed limit of 100 km/h and this is due to the limitations of the software; when implementing a *desired speed decision* of 70 km/h the vehicles will increase their speed as far as 100 km/h.

The lane change, as shown in Table 6.7, simulated morning traffic with regard to the changes in zone 2 for both the uncalibrated and calibrated and adjusted scenarios. However, the number of vehicles changing in zone 3 exceeded the data collected in the uncalibrated scenario. The main impact of the lane change decisions was the modifications of the *lane change distance*. The conclusion is that Swedish drivers exhibit less aggressive driving behavior than the VISSIM default parameters regarding merging, where, in reality, few vehicles are queue-jumping, and almost all vehicles are adapting to early merging. In the afternoon, traffic experienced a small number of lane changes in both Zone 2 and Zone 3, which means that many vehicles will merge in Zone 1. This indicates that driving behavior is, in merging terms, less aggressive when the traffic flow is larger. The drivers would generally adapt to the non-standstill queuing and will merge early to reach the back of the queue, rather than merging into the queue in zones 2 or 3.

The extracted results from VISSIM regarding the calibrated and adjusted scenario more closely correspond to a morning traffic flow with lower traffic volume and less queuing than an afternoon traffic flow. However, even if the afternoon traffic flow had a non-standstill queue, the traffic flow was less aggressive in terms of gap parameters, speed, and lane changes.

A concern is that small changes in the design could lead to significant differences in the result. This simulation closely adapts to reality, requiring minimal changes, such as implementing a gradient for the chicane connectors.

7.2.1 Validation

To obtain a valid Swedish driving behavior simulation result, the simulation should be accurate for all intervals during the day. Table 6.3 shows that the average absolute error is 9% from the two random times chosen for the validation, which is below the maximum acceptable error of 15% found in Section 5.3.3. The validation process could be more accurate if several case study areas were examined and compared to the VISSIM simulation result. The overall errors are within the acceptable limit; however, the simulations may still fail to accurately replicate certain parameters, such as lane changing, vehicle speed, and reaction time. Spatial biases can affect parameters such as reaction time and speed if the road segment with different geometries, for example, a curved section, influences driving behavior. Temporal biases may also influence model accuracy. For example, the simulation's performance during lower traffic flows, such as midday, is unknown. A more detailed valuation would therefore be a good addition to examine these potential biases.

7.2.2 Sensitivity analysis

A sensitivity analysis was conducted by modifying the parameters CC1 and CC2 separately to examine how traffic flow changes in response to changes in traffic behavior. An increase in the parameters will generally result in less aggressive driving behavior. As seen in Figures 6.7 and 6.8, CC1 has a much larger impact on driving behavior, resulting in large differences in speed and the position of lane change. Figure 6.8 has a maximum of 5% change in values compared to the calibrated and adjusted results, and therefore all modified CC2 values are acceptable.

The *mean speed* is generally lowered with a larger input number. This is due to the larger gap acceptance, where drivers will have a larger space between vehicles, making the queue longer and slower. Higher mean and median speeds indicate greater vehicle free flow. The number of vehicles that change lanes in Zone 2 is slowly increasing with a higher input value. The exception is CC1 +30%, where queues are long due to large gaps, and therefore will be considered unstable. This indicates that if a very unaggressive behavior is adopted in Sweden, more implementations will be needed in the work zone area to ensure an adequate traffic flow.

As seen in Table 5.5, the comparison of the default value of CC1 (0.9 seconds) and the SA+30% (2.5 seconds) is 178% and therefore indicates that an increase in CC1 correlates strongly with a less aggressive driving behavior. Since CC1 significantly influences the results and is a sensitive factor, it should be carefully revised in future research on Swedish driver norms in work zone safety modeling."

7.3 Improved design scenario

The calibrated and adjusted scenario was improved by reducing the *desired speed decision* and increasing the *lane change distance*. This simulates a scenario where the speed is reduced due to safety reasons, as lower speeds reduce the risk of serious injury. Additionally, signs indicating merging are located further ahead, with the expectation that drivers will look for a merging gap earlier, thereby increasing the traffic flow. This was expected to improve the safety of workers, and the chosen parameters were determined by reviewing the literature (see Section 2.6) and interpreting the interviews.

As illustrated in Figure 6.6, the speed distribution is lower in the speed decision scenario and higher in the lane change distance scenario. Combining these scenarios results in a speed distribution with the majority of vehicles traveling between 40 and 70 km/h. The combined scenario features few vehicles in the low intervals, traveling at speeds below 40 km/h, indicating that traffic flows freely without the presence of queues. Compared to the calibrated and adjusted scenario in Figure 6.5, the combined improved design scenario has a less scattered distribution in the low intervals that once again indicates a better traffic flow.

As expected, increasing the *lane change distance* results in more vehicles merging in Zone 1 (the remaining values that do not change lanes in Zones 2 and 3), as seen in Figure 6.7. From the same table, it is seen that when *desired speed decision* and *lane change distance* are combined, the result will be that more drivers choose to merge earlier, and the mean and median speed will be reduced.

Table 6.6 presents the travel time throughout the work zone (approximately 2.5 km), where we notice that the lowered *desired speed decision* will only increase the travel time by 3 seconds, or 2.2 %. It is important to inform drivers that speeding will not significantly affect travel time and that the safety of road users and road workers is more important than the few seconds saved.

Due to the time constraints, the improved design scenario will only indicate a direction for a more effective and safer design of the work zone. For further research, these scenarios could be optimized by combining these two parameters until the most effective design is found, considering both speed and travel time. This optimization could be implemented and validated in a case study scenario to compare how Swedish driving behavior changes due to the design parameters.

Rear-end collisions are one of the most common types of accidents. Therefore, it is important to inform drivers about the upcoming speed reduction. In addition, the speed reduction shall not result in forced breaches for vehicles or create large queues.

7.4 Further research

The safety of road work could be further researched by analyzing a larger spatial area in SAI and comparing the results with other accidents and incidents in the sector. Since workers commonly report accidents and incidents, there is also a gap in survey data that prevents a clear understanding of how road users experience road disruptions in terms of safety.

For future research, a developed road network could be examined to collect a larger volume of data and perform a more reliable and applicable traffic simulation. The improved design model could be implemented and studied as a real-life scenario to validate the accuracy of the software. There is also a need to evaluate economic calculations and environmental factors regarding road disruptions.

There is also a need to explore alternative methods of conducting road work. For instance, the sector has recently adopted a strategy of working simultaneously across all parallel lanes during pavement operations to enhance capacity and efficiency for the project. However, this approach warrants further investigation to assess its impact on both safety and traffic throughput. Simulation-based studies should be conducted to evaluate potential trade-offs—for example, comparing scenarios with single-lane closures versus full-lane closures to understand how different strategies affect traffic flow, safety, and driving behavior.

8 Conclusion

The purpose of this study is to investigate the impact of road work zones on traffic flow and safety analysis. Sweden has several regulations and frameworks to ensure the safety of road users and road workers. However, accidents and incidents are inevitable, and it is therefore important to report and analyze these events and adapt the results to improve safety. Interviews were conducted in which the personnel agreed that the road is an unsafe workplace and it is crucial to be aware of the safety risks associated with working on the road.

Object detection was employed for data extraction and successfully extracted data on Swedish traffic flow. The Swedish behavior was found to be less aggressive than the default value of the simulation tool VISSIM, which is based on German data. The calibrated and adjusted simulation yielded a lower average speed, an earlier lane change, and a more realistic traffic flow compared to the uncalibrated scenario. A sensitivity analysis was made on the modeled network, and it shows that the parameter CC1 is more influential and vulnerable than CC2.

The calibrated and adjusted scenario was improved by reducing the *desired speed decision* and increasing the *lane change distance*. This was successful in creating a safer work zone with respect to speed, while also achieving a more compact speed distribution that indicated fewer queues without significantly affecting travel time through the work zone. This suggests that reducing speed and improving merging signs could lead to a better flow and a safer work environment for both road workers and road users.

VISSIM is an adaptive tool for simulating work zone designs. However, there is no general work zone tool in VISSIM; therefore, roads must be closed manually by reducing the number of lanes. In reality, it is not only the design that could be changed to create a safer work zone. In some cases, it is possible to change driving behavior by informing drivers about the risks in traffic.

The design of the road work is closely related to road safety. The regulations must be followed to guide road users to safe decisions, while road workers must be aware of their surroundings and ensure the safety of the work zone. VISSIM, along with object detection, is a functional tool for analyzing and evolving traffic safety, but it comes with some uncertainties.

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Appendix A

```
import cv2
import numpy as np
import pandas as pd
import math
import time
from tqdm import tqdm
from ultralytics import YOLO

##############################
# INPUT AND CONFIGURATION
##############################

VIDEO_PATH = r"C:\E20_Afternoon.MP4" # Path to the input video
    file #Morning: C:\E20_Morning.MP4
OUTPUT_VIDEO = "speed_estimation.avi" #Output video
EXCEL_FILENAME = "vehicle_tracking.xlsx" #Excel file to store
    results

# Region boundaries (vertical band for speed detection)
LINE_REGION_Y_MIN = 500 # Top of region area #Morning: 450
LINE_REGION_Y_MAX = 1060 #Bottom of region area #Morning: 1050
PASSED_LINE_Y = LINE_REGION_Y_MIN

# Video properties
FRAME_WIDTH = 1920
FRAME_HEIGHT = 1080
FPS = 50 #frames per second

# Lane boundaries
LANE1_LEFT = 1050 #Morning: 890
LANE1_RIGHT = 1155 #Morning: 995
LANE2_LEFT = LANE1_RIGHT + 1
LANE2_RIGHT = 1270 #Morning: 1100

# Pixels per meter (calibration factor)
PPM = 2.17 #Morning 1.885

# Detection settings
CONF_THRESHOLD = 0.1 # Lower => more detections, but also
    potential false positives
DETECT_CLASSES = [2] # Only detect ’car’ (COCO ID=2). Use None
    to detect all classes.

# Horizontal band polygon where the calculations are made
REGION_PTS = [
    (0, LINE_REGION_Y_MAX),
    (FRAME_WIDTH, LINE_REGION_Y_MAX),
    (FRAME_WIDTH, LINE_REGION_Y_MIN),
```

```
    (0, LINE_REGION_Y_MIN)
]

# Minimum time tracked for speed estimation (to reduce noise)
MIN_TRACK_TIME = 0.1 # Seconds

# Global dictionary to store bounding boxes for gap calculation
boxes_data = {} # track_id -> list of [(x1,y1,x2,y2), time]

####################################
# HELPER FUNCTIONS
####################################
def draw_region(img, pts, color=(0, 255, 0), thickness=2):
    """
    Draws the horizontal region on the frame for speed
        detection.
    """
    pts_np = np.array(pts, np.int32).reshape((-1, 1, 2))
    cv2.polylines(img, [pts_np], isClosed=True, color=color,
        thickness=thickness)

def draw_points(img, points, color=(0, 0, 255), radius=5,
    thickness=2):
    """
    Draw circle markers at each point in 'points' (e.g., lane
        boundaries).
    """
    for point in points:
        cv2.circle(img, point, radius, color, thickness)

def determine_lane(center_x):
    """
    Determine lane based on user-defined boundaries:
      Lane1: x in [LANE1_LEFT, LANE1_RIGHT]
      Lane2: x in [LANE2_LEFT, LANE2_RIGHT]
      0 if outside these ranges
    """
    if LANE1_LEFT <= center_x <= LANE1_RIGHT:
        return 1
    elif LANE2_LEFT <= center_x <= LANE2_RIGHT:
        return 2
    else:
        return 0


def calculate_vehicle_gaps(unique_lane_vehicles,
    recorded_speed, region_positions, boxes_data):
    """
    Compute gap times by checking 8 sub-lines in the region.
    Avoid 'None' times by skipping lines that don't have both
        lead/follow times.
```

```
"""
gap_records = []
# We have lane_vehicles -> lane -> [(track_id, detection_time, y_pos), ...]
for lane in unique_lane_vehicles:
    # Sort vehicles in the lane by detection time
    sorted_vehicles = sorted(unique_lane_vehicles[lane], key=lambda x: x[1]) # Sort by detection time

    # Process each consecutive pair in the sorted list
    for i in range(1, len(sorted_vehicles)):
        lead_id, _, _ = sorted_vehicles[i-1] # Lead vehicle
        follow_id, _, _ = sorted_vehicles[i] # Following vehicle

        lead_positions = boxes_data.get(lead_id, [])
        follow_positions = boxes_data.get(follow_id, [])

        # Create 8 sub-lines across the region to determine CC2
        gap_lines = [
            LINE_REGION_Y_MIN + j * (LINE_REGION_Y_MAX - LINE_REGION_Y_MIN) / 8.0
            for j in range(8)
        ]

        gap_times = []
        for line_y in gap_lines:
            lead_time = None
            follow_time = None

            # Find time for lead vehicle crossing line_y
            for (x1, y1, x2, y2), t in lead_positions:
                if (line_y - 10) <= y1 <= (line_y + 10):
                    lead_time = t
                    break

            # Find time for following vehicle crossing line_y
            for (x1, y1, x2, y2), t in follow_positions:
                if (line_y - 10) <= y1 <= (line_y + 10):
                    follow_time = t
                    break

            if lead_time is not None and follow_time is not None:
                gap_times.append(follow_time - lead_time)

        if gap_times:
            min_gap_time = min(gap_times)
            max_gap_time = max(gap_times)
```

```
            lead_speed_m_s = recorded_speed.get(lead_id, 0) /
               3.6 # convert km/h -> m/s
            min_gap_distance = lead_speed_m_s * min_gap_time
               #CC1
            max_gap_distance = lead_speed_m_s * max_gap_time
            cc2 = max_gap_distance - min_gap_distance #CC2

            gap_records.append({
                'Previous_Vehicle_ID': lead_id,
                'Current_Vehicle_ID': follow_id,
                'Lane': lane,
                'CC1_s': min_gap_time,
                'Max_Gap_Time_s': max_gap_time,
                'Min_Gap_Distance_m': min_gap_distance,
                'Max_Gap_Distance_m': max_gap_distance,
                'CC2_m': cc2,
            })

    return gap_records

###################################
# MAIN
###################################
def main():
    from ultralytics import YOLO
    from tqdm import tqdm
    import time

    start_time = time.time()

    # Initialize YOLOv8
    model = YOLO("yolov8n.pt")
    model.overrides['conf'] = CONF_THRESHOLD
    model.overrides['classes'] = DETECT_CLASSES
    names = model.model.names

    # Open video
    cap = cv2.VideoCapture(VIDEO_PATH)
    assert cap.isOpened(), f"Error reading video file:
       {VIDEO_PATH}"
    total_frames = int(cap.get(cv2.CAP_PROP_FRAME_COUNT))

    video_writer = cv2.VideoWriter(
        OUTPUT_VIDEO,
        cv2.VideoWriter_fourcc(*"mp4v"),
        FPS,
        (FRAME_WIDTH, FRAME_HEIGHT)
    )

    # Data structures for tracking
    start_positions = {} # track_id -> (x, y, start_time)
```

```
recorded_speed = {}  # track_id -> speed_kmh
recorded_lane = {}   # track_id -> lane
region_positions = {} # track_id -> [(x, y, time), ...]
top_positions = {}   # track_id -> (lowest y so far)
lane_vehicles = {1: [], 2: []}
unique_lane_vehicles = {1: [], 2: []}
speed_records = []
gap_records = []

frame_count = 0

# Lane boundary points for visualization
LANE_POINTS = [
    (LANE1_LEFT, PASSED_LINE_Y),
    (LANE1_RIGHT, PASSED_LINE_Y),
    (LANE2_LEFT, PASSED_LINE_Y),
    (LANE2_RIGHT, PASSED_LINE_Y)
]

# Progress bar
with tqdm(total=total_frames, desc="Processing Video",
    unit="frame") as pbar:
    while True:
        ret, frame = cap.read()
        if not ret:
            break

        # Resize to match your known resolution
        frame = cv2.resize(frame, (FRAME_WIDTH, FRAME_HEIGHT))
        frame_count += 1
        current_time_s = frame_count / FPS

        # YOLO detection + tracking
        results = model.track(frame, persist=True, show=False)

        # if no detection, just proceed
        if not results or results[0].boxes is None:
            video_writer.write(frame)
            pbar.update(1)
            continue

        # Draw region band & lane boundary points
        draw_region(frame, REGION_PTS, (0, 255, 0), 2)
        draw_points(frame, LANE_POINTS, color=(0, 255, 0))

        boxes = results[0].boxes.xyxy
        cls_vals = results[0].boxes.cls
        if results[0].boxes.id is not None:
            ids = results[0].boxes.id
        else:
            ids = np.arange(len(boxes))
```

```
# Collect bounding boxes for gap analysis
for i in range(len(boxes)):
   try:
      track_id = int(ids[i].item()) if
         hasattr(ids[i], "item") else int(ids[i])
   except Exception:
      track_id = i

   x1, y1, x2, y2 = boxes[i]
   if track_id not in boxes_data:
      boxes_data[track_id] = []
   boxes_data[track_id].append(((x1, y1, x2, y2),
      current_time_s))

# Process each detection
for i in range(len(boxes)):
   try:
      track_id = int(ids[i].item()) if
         hasattr(ids[i], "item") else int(ids[i])
   except Exception:
      track_id = i

   x1, y1, x2, y2 = boxes[i]
   center_x = float((x1 + x2) / 2)
   center_y = float((y1 + y2) / 2)

   cls_val = cls_vals[i]
   cls_id = int(cls_val.item()) if hasattr(cls_val,
      "item") else int(cls_val)
   vehicle_type = names.get(cls_id, "unknown")

   # Store first detection
   if track_id not in start_positions:
      start_positions[track_id] = (center_x,
         center_y, current_time_s)

   # If vehicle is within vertical band
   if LINE_REGION_Y_MIN <= center_y <=
      LINE_REGION_Y_MAX:
      # keep region position
      if track_id not in region_positions:
         region_positions[track_id] = []
      region_positions[track_id].append((center_x,
         center_y, current_time_s))

      # track top pos for lane assignment
      if track_id not in top_positions or center_y <
         top_positions[track_id][1]:
         top_positions[track_id] = (center_x,
            center_y, current_time_s)
```

```
               lane = determine_lane(center_x)
               recorded_lane[track_id] = lane
               if lane in [1, 2]:
                  lane_vehicles[lane].append((track_id,
                     current_time_s, center_y))

            # speed calculation
            if track_id not in recorded_speed:
               sx, sy, st = start_positions[track_id]
               dt = current_time_s - st
               if dt >= MIN_TRACK_TIME:
                  disp_px = abs(center_y - sy)
                  disp_m = disp_px / PPM
                  speed_kmh = (disp_m / dt) * 3.6
                  recorded_speed[track_id] = speed_kmh
                  current_lane =
                     recorded_lane.get(track_id, 0)
                  speed_records.append({
                     ’Vehicle_ID’: track_id,
                     ’Time_s’: current_time_s,
                     ’Vehicle_Type’: vehicle_type,
                     ’Center_X’: center_x,
                     ’Center_Y’: center_y,
                     ’Speed_km_h’: speed_kmh,
                     ’Lane’: current_lane
                  })

         # Prepare annotation
         lane_num = recorded_lane.get(track_id,
            determine_lane(center_x))
         if track_id in recorded_speed:
            spd = recorded_speed[track_id]
            label = f"{vehicle_type}(ID {track_id})
               {spd:.1f} km/h, Lane {lane_num}"
         else:
            label = f"{vehicle_type}(ID {track_id}), Lane
               {lane_num}"

         # Draw bounding box & label
         cv2.rectangle(frame, (int(x1), int(y1)), (int(x2),
            int(y2)), (255, 0, 0), 2)
         cv2.putText(frame, label, (int(x1), int(y1) - 10),
                  cv2.FONT_HERSHEY_SIMPLEX, 0.8, (255, 0,
                     0), 2)

      video_writer.write(frame)
      print(f"Frame {frame_count}: Processed {len(boxes)}
         tracks.")
      pbar.update(1)

# Done reading frames
```

```
    cap.release()
    video_writer.release()
    cv2.destroyAllWindows()

    # Sort top position
    unique_lane_vehicles[1] = []
    unique_lane_vehicles[2] = []
    for track_id, (cx, cy, t) in top_positions.items():
        lane = recorded_lane.get(track_id, 0)
        if lane in [1, 2]:
            unique_lane_vehicles[lane].append((track_id, t, cy))
    for lane in [1, 2]:
        unique_lane_vehicles[lane].sort(key=lambda x: x[1]) #
            sort by y

    # Gap records
    gap_records = calculate_vehicle_gaps(
        unique_lane_vehicles,
        recorded_speed,
        region_positions,
        boxes_data
    )

    # Save results
    df_speed = pd.DataFrame(speed_records)
    df_gap = pd.DataFrame(gap_records)
    with pd.ExcelWriter(EXCEL_FILENAME, engine=’openpyxl’) as
        writer:
        df_speed.to_excel(writer, sheet_name=’Speed’,
            index=False)
        df_gap.to_excel(writer, sheet_name=’Gap_Analysis’,
            index=False)

    elapsed = time.time() - start_time
    print(f"\nResults saved to ’{EXCEL_FILENAME}’ in sheets
        ’Speed’ and ’Gap_Analysis’.")
    print(f"Total Processing Time: {elapsed:.2f} seconds")


if __name__ == "__main__":
    main()
```

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