Master Thesis

National Crash rates for non-primary road types based on OmniTRANS-Spectrum traffic volumes

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Samenvatting

Introductie

Verkeersveiligheid is een blijvend onderwerp op de agenda van infrastructuurstudies. De verkeersveiligheid is in Nederland aanzienlijk verbeterd ten opzichte van decennia geleden, hoewel de vooruitgang de laatste jaren is gestagneerd. Door de toenemende aandacht voor dit onderwerp komen de discussies en plannen om de maximumsnelheid te verlagen van 50 km/u naar 30 km/u in een stroomversnelling (Amsterdam, 2023). Onderzoek toont aan dat een verlaging van de snelheidslimiet van 50 km/u naar 30 km/u gepaard gaat met een verlaging van het aantal ongevallen (20 tot 30%), met een 10% hogere kans op overleving bij een ongeval (Yannis & Michelaraki, 2024). Deze ontwikkelingen brengen echter ook nieuwe uitdagingen met zich mee. Een belangrijke uitdaging is de kwantitatieve beoordeling van de verkeersveiligheid, om beter inzicht te krijgen op de impact van nieuwe maatregelen van de infrastructuur. Dit roept de vraag op of deze maatregelen de algehele veiligheid van het netwerk verbeteren, aangezien ze de routekeuze kunnen beïnvloeden en mogelijk verkeersrisico's kunnen verplaatsen.

Onderzoeksdoel en Vragen

Om de verkeersveiligheid voor verschillende wegtypes binnen het primaire wegennet te kwantificeren, heeft Rijkswaterstaat risicocijfers berekend op basis van geregistreerde ongevallen op het primaire wegennet en verkeersvolumes op basis van nauwkeurige tellingen. Er is echter beperkt onderzoek gedaan naar risicocijfers voor het onderliggend wegennet (gebiedsontsluitingswegen en erftoegangswegen). Deze wegen zijn complexer dan het primaire wegennet, met een minder gestandaardiseerd wegontwerp, meer kruispunten, verschillende vervoersmodaliteiten en hogere algehele verkeersinteracties, vooral in sterk verstedelijkte gebieden. SWOV heeft recentelijk risicocijfers voor het onderliggend wegennet geschat door gebruik te maken van ongevallendata uit het “Bestand geRegistreerde Ongevallen in Nederland” (BRON) en beschikbare verkeerstellingen (Schermers & Gebhard, 2023). Echter, nauwkeurigere risicocijfers kunnen mogelijk worden verkregen door het gebruik van verkeersmodellen.

In een eerdere studie is een begin gemaakt met het berekenen van risicocijfers op basis van verkeersmodellen (Goudappel, 2023). Echter, er zijn verschillende uitdagingen die verdere onderzoeken en kritische evaluatie vereisten om betrouwbare ongevallendata voor elke wegkenmerk te presenteren. Deze uitdagingen omvatten de complexiteit van verkeersvolumes van verschillende voertuigtypesop een wegvak, die de totale blootstelling tot ongeval en dus de risicocijfers vertekenen; de complicaties van wegen met meerdere wegkenmerken, waar verschillende combinaties van wegkenmerken in het netwerk worden waargenomen; en de omvang en diversiteit van het Nederlandse wegennet, dat een breed scala aan ruimtelijke verschillen vertoont.

Dit onderzoek presenteert een methodologie om deze uitdagingen aan te pakken. Het onderzoeksdoel dat is geformuleerd is:

Dit onderzoeksproject heeft als doel om risicocijfers voor onderliggende wegen met verschillende wegkenmerken in Nederland vast te stellen door gebruik te maken van ongevallen- en blootstellingsdata om de verschillen en de toepasbaarheid van nationale risicocijfers op regionaal niveau te onderzoeken.

Op basis van het onderzoeksdoel zijn de volgende onderzoeksvragen geformuleerd:

1. **Hoe verschillen de risicocijfers tussen en binnen een bepaald voertuigtype(s) op het onderliggende wegennet in Nederland?**
2. **Hoe variëren de risicocijfers afhankelijk van de wegkenmerken op onderliggende wegen in Nederland?**
3. **Hoe verschillen de risicocijfers voor verschillende voertuigtypes en wegkenmerken op niet-primaire wegen in Nederland op regionaal niveau?**

Methodologie

De risicocijfers worden berekend door het aantal ongevallen te delen door het aantal kilometers afgelegd per voertuigtype en wegkenmerk. Vanwege datakwaliteitsproblemen zijn ongevallen met Uitsluitend Materiële Schade (UMS), ongevallen gekoppeld op gemeentelijk niveau en jaren met instabiele ongevallendata uitgesloten. Deze studie richt zich daarom op ongevallen met letsel, dodelijke ongevallen van 2015 tot en met 2019 en 2023. Het berekenen van de risicocijfers vormt het centrale onderdeel van deze studie. Vervolgens zijn deze cijfers geanalyseerd om de onderzoeksvragen te beantwoorden.

Om de complexiteit van verschillende voertuigtypen te behandelen, is een voertuigmatrix opgesteld waarmee de risicocijfers per voertuigtype (motorvoertuigen, vrachtvoertuigen en fietsen) worden verduidelijkt. Hierbij is gebruik gemaakt van het aantal ongevallen waarbij meerdere voertuigtypen betrokken waren en de afgelegde afstand per voertuigtype. Dit biedt inzicht in het risico op ongevallen vanuit het perspectief van elk voertuigtype. Deze aanpak zorgt ervoor dat risicocijfers op een vergelijkbare schaal worden gepresenteerd en eenvoudig te vergelijken zijn.

De tweede uitdaging betreft de veiligheid van wegen met meerdere kenmerken. Het is essentieel om onderscheid te maken tussen wegkenmerken zoals snelheidslimiet, type fietsfaciliteit, mate van verstedelijking, eenrichtingsweg, aantal rijstroken en het aandeel vrachtverkeer. Om de complexiteit van deze wegen aan te pakken, zijn variabele verdelingen en regressiebomen opgesteld die de impact van wegkenmerken op verkeersveiligheid in kaart brengen. De variabele verdelingen bieden inzicht in de algemene invloed van wegkenmerken, terwijl de regressiebomen helpen de meest impactvolle kenmerken en het gedrag van risicocijfers bij combinatie van wegkenmerken te identificeren. Regressiebomen zijn effectief vanwege hun eenvoudige interpretatie (Polzer, 2024).

Om te onderzoeken of de risicocijfers verschillen tussen regio's en of nationale cijfers ook op regionaal niveau gelden, zijn voertuigmatrices en provinciale risicocijfers voor de eerste drie lagen van de regressiebomen berekend. Deze zijn vervolgens getest op significante verschillen tussen nationale en provinciale cijfers.

Resultaten

De voertuigmatrix laat zien dat fietsers het grootste risico lopen betrokken te raken bij een ongeval per afgelegde afstand, vergeleken met motor- en vrachtvoertuigen. Motorvoertuigen vormen voor fietsers de grootste risicofactor, met een drie keer hoger risico dan bij eenzijdige fietsongevallen. Verder blijkt dat vrachtverkeer relatief minder betrokken is bij ongevallen per afgelegde afstand dan fietsers en motorvoertuigen.

De variabele verdelingen en regressiebomen tonen aan dat hogere snelheidslimieten niet per se leiden tot hogere risicocijfers. De regressiebomen geven aan dat combinaties van wegkenmerken hoge of lage risicocijfers kunnen veroorzaken, afhankelijk van het voertuigtype. De hoogste risicocijfers voor aanrijdingen tussen motorvoertuigen en fietsers zijn vooral zichtbaar op wegen met een snelheidslimiet van 50 km/u in sterk verstedelijkte gebieden, waar fietsers en motorvoertuigen de rijbaan delen. Belangrijke wegkenmerken die de risicocijfers beïnvloeden zijn de snelheidslimiet, mate van verstedelijking, type fietsfaciliteit en het aandeel vrachtverkeer.

Uit de provinciale voertuigmatrices blijkt dat de nationale en provinciale risicocijfers in de meeste gevallen significant verschillen. De provinciale regressiebomen bevestigen eveneens dat de risicocijfers vaak aanzienlijk afwijken van de nationale cijfers.

Discussie

Verschillende resultaten gaan gepaard met complicaties. De afgelegde afstand van tegenovergestelde voertuigen worden bijvoorbeeld niet meegenomen, wat de uitkomsten aanzienlijk kan beïnvloeden. Voertuigen hebben daarnaast uiteenlopende kenmerken: fietsers zijn bijzonder kwetsbaar vanwege hun balansbehoefte, wat de kans op valpartijen vergroot, terwijl bestuurders van motorvoertuigen profiteren van fysieke bescherming. Vrachtwagenchauffeurs zijn relatief gezien het meest ervaren, en de grootte van de voertuigen kan zorgen voor duidelijke aanwezigheid wat kan bijdragen aan een lager aantal ongevallen.

Het is belangrijk te erkennen dat wegkenmerken vaak gecorreleerd zijn. Wegen met lagere snelheidslimieten bevinden zich meestal in sterk verstedelijkte gebieden, waar meer conflictpunten zijn vanwege het grotere aantal kruispunten. Dit onderstreept de complexiteit van het beoordelen van afzonderlijke wegkenmerken. De regressiebomen identificeren zowel invloedrijke als minder invloedrijke kenmerken, zoals de snelheidslimiet, mate van verstedelijking, type fietsfaciliteit en aandeel vrachtverkeer als belangrijke factoren, en aantal rijstroken en rijrichtingen als minder invloedrijk.

Conclusie

Deze studie benadrukt de verschillen in verkeersveiligheid tussen voertuigtypen. Voor fietsers vormen motorvoertuigen de grootste risicofactor, met een drie keer grotere kans op ongevallen dan bij eenzijdige enkelvoudige fietsongevallen. Dit verhoogde risico kan het gevolg zijn van het grote aantal conflictpunten, aangezien motorvoertuigen doorgaans langere afstanden afleggen. Daarnaast dragen enkelvoudige fietsongevallen significant bij aan de hoge risicocijfers, omdat fietsers hun evenwicht moeten bewaren, wat de kans op valpartijen vergroot. Vrachtverkeer blijkt daarentegen minder vaak betrokken bij ongevallen per afgelegde afstand.

De bevindingen suggereren dat een hogere snelheidslimiet niet per definitie leidt tot meer ongevallen. De wegkenmerken gezamenlijk bepalen het ongevallencijfer, en er is sprake van sterke correlatie tussen kenmerken. Desondanks laat de analyse zien dat een hoger verstedelijkingsniveau vanuit alle perspectieven samenhangt met een hoger ongevallencijfer. Tot slot toont deze studie aan dat nationale risicocijfers vaak significant afwijken van regionale cijfers, wat hun bruikbaarheid voor gedetailleerde analyses, met name op provinciaal niveau, beperkt.

Summary

Introduction

Road safety is an enduring topic on the agenda of infrastructure studies. Road safety has improved considerably in the Netherlands compared to decades ago, although it has stagnated in recent years. Due to the increasing focus on this topic, discussions and plans to reduce the speed limit from 50 km/h to 30 km/h are gaining momentum (Amsterdam, 2023). Research indicates that reducing the speed limit from 50 km/h to 30 km/h lowers the number of crashes by 20-30%, with a 10% higher chance of surviving an accident (Yannis & Michelaraki, 2024). However, these developments also present new challenges. An important challenge is the quantitative assessment of road safety to better grasp the impact of new measures on the infrastructure. This raises the question of whether these measures enhance the overall safety of the network, as they could influence route selection and potentially shift traffic risks.

Research Objective and Questions

To quantify road safety for different road types on the primary road network, Rijkswaterstaat has calculated crash rates, utilising crashes that took place on the primary road network and traffic volumes based on accurate traffic counts. However, limited research has been done on crash rates for non-primary road types (rural and urban distributor roads and residential roads). These roads are more intricate than the primary road network, featuring a less standardised road design with more intersections, different modes of transport and higher overall traffic interactions, especially in strongly urbanised areas. SWOV has recently estimated crash rates for the non-primary road network to address this by utilising crash data from “*Bestand geRegistreerde Ongevallen in Nederland*” (BRON) and available traffic counts (Schermers & Gebhard, 2023). However, more accurate crash rates may be achievable by utilising traffic models.

In a preliminary study, an initial effort was made to calculate the crash rates based on traffic models (Goudappel, 2023). However, several challenges require further investigation and critical evaluation to present reliable crash data for each road characteristic. These challenges include the complexity of traffic volumes of different vehicle types on a single road segment, which distorts the total exposure of crashes and, therefore, the crash rate; the intricacy of roads with multiple road characteristics, where various combinations of road characteristics are observed in the network; and the size and variety of the Dutch road network, which shows a wide range of spatial differences.

This study presents a methodology to address these challenges. Therefore, the research objective that has been constructed is:

> This research project aims to determine crash rates for non-primary roads with various characteristics in the Netherlands by utilising crash and exposure data to investigate the differences and the applicability of the national crash rates on a regional level.

Based on the research objective, the following research questions have been formulated:

1. ***How do crash rates differ across and amongst vehicle types on non-primary roads in the Netherlands?***
2. ***How do crash rates differ depending on road characteristics on non-primary roads in the Netherlands?***
3. ***How do crash rates for different vehicle types and road characteristics on non-primary roads in the Netherlands vary at the regional scale?***

Methodology

Crash rates are calculated by dividing the number of crashes by the number of kilometres travelled per vehicle type and road characteristic. As a result of data quality issues, it has been decided to exclude Property Damage Only (PDO) crashes, crashes registered at the municipal level and years of crash data that do not reflect a stable situation. Therefore, this study focusses on injury crashes, fatality crashes and crashes in the years 2015 to 2019 and 2023. Calculating the crash rate is central to this study. Subsequently, these crash rates were analysed to answer the research questions.

To address the complexity of different types of vehicles, a vehicle matrix was used to clarify the crash rates across and amongst vehicle types (motor vehicles, freight vehicles and bicycles). To facilitate this the number of crashes involving multiple vehicle types and the distance travelled by one vehicle type was utilised. This approach clarifies the risk of an accident involving both vehicles from a certain perspective. As a result, crash rates will be on a similar scale and, therefore, easy to compare.

The second challenge concerns the safety of complex roads with multiple road characteristics. It is therefore important to distinguish between different road characteristics: speed limit, type of bicycle facility, degree of urbanisation, one-way road, number of lanes and proportion of freight traffic. To address the issue of complex roads, variable distributions and regression trees are created that consider road characteristics that affect road safety, according to the literature. The variable distributions provide more insight into the general influences of road characteristics. Regression trees are utilised to determine the most impactful road characteristics and accident rate behaviour when road features are combined. This method is used because regression trees have proven to be very effective in solving problems and the ease with which they can be interpreted (Polzer, 2024).

To see whether the accident figures differ between different regions within the Netherlands, and whether national accident figures apply at the regional level. Vehicle type matrices were determined for these provincial accident incidents, and the provincial accident rates for the first three national layers of the regression trees were calculated. These two products were tested for significant differences between national and provincial accident rates.

Results

The vehicle matrix shows that cyclists face the highest risk of being involved in a crash per distance travelled compared to motor and freight vehicles. For cyclists, motor vehicles are the highest risk factor, with this risk being three times higher than the second highest crash rate, which is for one-sided bicycle crashes. The results also show that freight traffic is the least involved in crashes per distance travelled compared to cyclists and motor vehicles.

The variable distributions and regression trees have shown that higher speed limits do not necessarily lead to higher crash rates. The results of the regression trees show that road characteristic combinations cause a high or low crash rate, depending on the perspective of the vehicle type. For crashes between motor vehicles and cyclists per billion bicycle kilometres, the highest crash rates can be seen, especially on roads with a speed limit of 50 kph, within a strongly urbanised area where cyclists and motor vehicles share the roadway. Furthermore, the regression trees also show impactful road characteristics on the crash rate, based on their position in the tree. These are the speed limit, the degree of urbanisation of an area, the bicycle facility type and the freight traffic share.

The results of the provincial vehicle type matrixes showed that the national and provincial crash rates differ significantly in most cases. Most regional combinations of vehicle types are significantly different from the national average. The results of the provincial regression trees also show significantly different crash rates from the national figures.

Discussion

Many results come with a number of complications. The distance travelled by opposing vehicles is not considered; however, it can substantially impact the outcomes. Furthermore, vehicles possess varying characteristics, cyclists are particularly vulnerable due to their need to maintain balance, which increases the likelihood of falls that can lead to serious injuries or even fatalities. In contrast, drivers of motor vehicles benefit from physical protection. This holds true for freight vehicles as well, where drivers are typically more experienced, and the presence of larger vehicles can contribute to a lower incidence of accidents.

It is important to note that road characteristics are often correlated. For example, roads with lower speed limits are typically located in strongly urbanized areas, which tend to have more conflict points due to the greater number of intersections compared to moderately urbanized and non-urbanized regions. This observation underscores the complexity of assessing the safety of individual road features. The findings from the regression trees identify both impactful and less impactful road characteristics. The characteristics deemed impactful include speed limits, the degree of urbanity, the type of bicycle facilities, and the share of freight traffic. Conversely, characteristics considered less impactful are the number of lanes and the number of directions of the road.

Conclusion

In conclusion, this study highlights distinct differences in road safety among various vehicle types. For cyclists, motor vehicles present the highest risk factor, with the likelihood of crashes being three times greater than that associated with the second highest risk. This elevated risk may originate from the numerous conflict points, as motor vehicles typically travel longer distances. Additionally, single-vehicle bicycle crashes significantly contribute to high crash rates, likely due to the need for cyclists to maintain balance, which raises the potential for falls and injuries. Furthermore, the findings indicate that freight traffic is involved in fewer crashes per distance travelled compared to both cyclists and motor vehicles.

This study also suggests that increasing the speed limit does not inherently result in a higher rate of accidents. However, a road's characteristics collectively contribute to determining its accident rate, and road characteristics are substantially correlated. Nevertheless, the variable distributions reveal that a greater level of urbanisation is associated with a higher accident rate from all perspectives. Lastly, this study highlights that national crash rates differ significantly from regional crash rates, both for vehicle types and road characteristics. This shows that national crash rates could be less useful for a lower level of detail, especially provincial.

1. Introduction

Ensuring traffic safety by minimising the number of crashes is a fundamental objective in infrastructure studies. While aiming for zero fatal crashes may seem ambitious, comparing current statistics with those from previous decades suggests that progress is being made (eurostat, 2023). Statistics from the Netherlands (CBS) indicate a reduction of 50% in traffic-related deaths between 1996 and 2010 (CBS, 2023). This trend is the result of continuous innovation in various traffic factors, such as prescribed road designs emphasising traffic safety (CROW, 2018), improvements in vehicle safety standards (NHTSA, sd) and stricter regulations for obtaining driver's licenses (Kiss, 2023). However, the number of traffic fatalities has been fluctuating around 600 since 2010, with 2022 recording the highest number of fatalities since 2007 (745 fatalities) (CBS, 2023).

Nevertheless, the Netherlands is ranked as one of the safest countries in the EU and OECD regarding road safety, with low deaths per capita and distance travelled (SWOV, 2021). Still, traffic fatalities for cyclists are more common in the Netherlands than in other countries, with double the number of traffic fatalities compared to the second-highest country, Denmark (SWOV, 2021). This can be attributed to the Netherlands' high number of cyclists per capita. The Netherlands scores slightly better when considering road deaths for cyclists per distance travelled (SWOV, 2021). This immediately shows that countries differ a lot in terms of traffic, several factors can explain this, such as the difference in the level of prosperity and culture in a country (Berghe, Schachner, Sgarra, & Christie, 2020), the difference in mobility and travel behaviour (Wegman, Eksler, Hayes, & Lynam, 2005), road safety policy differences (Bliss & Breene, 2009; Chen, Wu, Chen, & Wang, 2016) and the difference in performance indicators (Wegman, et al., 2008; Shen, Hermans, Bao, Brijs, & Wets, 2020; Aarts & Bax, Benchmarking van verkeersveiligheid, 2014).

There is a growing focus on road safety in the Netherlands, with discussions and plans regarding reducing the speed limit of urban roads from 50 km/h to 30 km/h (Amsterdam, 2023). This trend is also evident in other European countries (Wagenaar, 2023). One of the primary reasons behind this initiative is to protect vulnerable road users from the high speeds of motor vehicles. Research shows that driving at slower speeds could result in 20-30% fewer crashes, with a 10% higher chance of survival in crashes at 30 km/h compared to 50 km/h (Yannis & Michelaraki, 2024). This demonstrates how the infrastructure continues to develop into a safer network. However, these ongoing developments also present new challenges. One significant challenge is quantitatively assessing road safety to gain more control over the impact of new measures on the infrastructure. This raises the question of whether the new infrastructure measures ensure the overall safety of the network since this could affect route choices on the network and may relocate traffic risks.

This section introduces the current study by first examining previous studies on road safety measurements in the Netherlands. This approach provides the necessary background and emphasises existing challenges. Following this discussion, the context and objective of this research will be outlined, finishing in presenting the research questions.

1.1 Research Context and Objective

As mentioned, limited research has been done on crash rates for non-primary roads in the Netherlands. The available crash rates are based on a sample of traffic counts. However, no crash rates have been formulated based on traffic models to construct representative crash risk figures. Crash rates based on traffic models would be valuable for accurately evaluating the impact of road characteristics on road safety and making informed decisions regarding infrastructure changes. Before this study, an exploratory study was conducted in which a first attempt was made to determine the crash rates per road type by dividing traffic crashes by the distances travelled per road type based on the traffic model (Goudappel, 2023). However, several challenges require further exploration and critical evaluation to present reliable crash data per road type. These challenges include the complexity of different types of vehicles involved in a crash, where varying vehicle volumes make calculating integrated crash rates difficult, and the challenge of the heterogeneity of road characteristics of the non-primary road network, which reveals a wide range of spatial differences.

An appropriate study should be conducted to determine new crash rates at a national level to address these challenges. The various road characteristics should be carefully selected while also identifying and statistically analysing the various factors that impact these crash rates. Such an approach contributes to confidence in the presented crash rates, enabling practical application. To address the challenge regarding the size and variety of the Dutch road network, a thorough analysis of the crash rates in different regions of the Netherlands, by a comparison of these regional crash rates and with the national crash rates, is necessary to gain insights into the variations in road safety at the national level.

The research objective that has been constructed is:

> This research project aims to determine crash rates for non-primary roads with various characteristics in the Netherlands by utilising crash and exposure data to investigate the differences and the applicability of the national crash rates on a regional level.

1.2 Research Questions

Based on the research objective, the following research questions have been formulated:

1. ***How do crash rates differ across and amongst vehicle types on non-primary roads in the Netherlands?***

As described in the project context, one challenge that has emerged is determining crash rates for different vehicle types due to complex vehicle volumes. These vehicle types also encounter each other during crashes. For this reason, it is important to determine the crash rate across and amongst different vehicle types on non-primary roads in the Netherlands. This shows a difference in risk between these vehicle types, providing valuable insights.

2. ***How do crash rates differ depending on road characteristics on non-primary roads in the Netherlands?***

To determine crash rates, choosing appropriate combinations of road characteristics is necessary. Essentially, it should be possible to extract these road characteristics using the available data, with the requirement that these road characteristics are nationally representative. Road characteristics that influence traffic safety are initially explored with a literature review and illustrated as a conceptual framework. To facilitate this question, variable distributions and regression trees will be utilised to discover the most impactful road characteristics.

3. ***How do crash rates for different vehicle types and road characteristics on non-primary roads in the Netherlands vary at the regional scale?***

This question examines the challenges posed by the size and diversity of the Dutch road network. By applying the same methodologies used in previous questions, crash rates for different vehicle types and road characteristics will be analysed on a regional level. A significance test will be employed to determine whether the national crash rate is representative for the various regions in the Netherlands. With this question, whether national crash rates are regionally applicable may be clear.

2. Literature Review

This chapter presents the literature review to provide more context for previous research goals and questions. This is done by discussing previous studies on crash rates in the Netherlands, followed by the literature study on factors that affect the traffic crash risk.

2.1 Previous Studies on Crash Rates in the Netherlands

Several studies have examined crash rates in the Netherlands. The most well-known study is conducted by Rijkswaterstaat, which presents crash rates to assess road safety quantitatively based on the speed limit and the number of lanes. These crash rates reflect the risk of an individual road user becoming a victim in a crash (Rijkswaterstaat, 2023). Although used nationwide and reliable, these traffic risk figures only apply to the primary road network, while the non-primary road network presents a different set of challenges. These challenges arise from its intricacy, featuring a less standardised road design with more intersections, different modes of transport, and higher overall traffic interactions, especially in strongly urbanised areas. Crash rates on the non-primary road network can be utilised to quantitatively evaluate the safety of different speed limits, analyse the risk of different vehicle types being involved in crashes and determine if other road characteristics influence the level of risk. Therefore, having crash rates for the non-primary road network would be valuable for accurately evaluating the impact of road characteristics on road safety and making informed decisions regarding infrastructure changes.

SWOV has already conducted studies to determine crash rates for the non-primary road network. Due to the lack of reliable data in previous years, this has not been done since 2007. With some improvements in data availability, SWOV has made efforts to update these figures. This involved using various datasets, including the National Road Database (NWB) and the Road

Table 1: Summary of Results Crash Density and Risk Rates (Schermers & Gebhard, 2023)

Speed limit	Average daily traffic volume: sample median	Crash density**		Risk rates***			
		Sample road sections	National estimate	Sample road sections		National estimate	
		Injury*	Injury*	Fatal	Injury*	Fatal	Injury*
30 km/h	1,455	0.071	0,0166	2.9	95.9	0.9	31.3
50 km/h	5,779	0.203	0.1149	1.9	54.7	1.9	54.5
60 km/h	3,021	0.130	0.0108	2.6	70.6	1.1	9.8
80 km/h	11,191	0.102	0.0466	2.9	25.1	1.8	11.4

** Crashes with outcomes: fatal, to hospital, and minor injury combined*

*** Average annual number of road section crashes from 2011 to 2020 per road kilometre*

**** Number of road section crashes per year/billion vehicle kilometres per year*

Characteristics Database (WKD), to estimate the road length, traffic intensity data and crash data (BRON). The calculation for the traffic volumes involved the traffic counts since the available traffic models and floating car data (FCD) were not reliable enough, and, based on these traffic counts, the national traffic volumes were determined. The speed limits (30, 50, 60 and 80 km/h) were used to categorise the roads. The crash rate was calculated with the sum of all crashes on the categorised roads and the corresponding traffic volumes (Schermers & Gebhard, 2023).

The study's results indicate a wide range of average 24-hour intensities, and in almost all cases, no significant differences are found. Table 1 shows the crash densities and crash rates from the study. crash densities do not correspond for sample roads to those for the national level, except for a few instances. This can be attributed to short road sections and over-representing busier and/or more dangerous roads. Moreover, there are many differences between the sample road sections and the national estimate for the crash rates (Schermers & Gebhard, 2023).

The findings indicate that traffic counts may not be suitable for determining crash rates (Schermers & Gebhard, 2023). This is probably due to a limited number of counts, resulting in a "limited" crash rate. Additionally, translating sample intensities to the national intensity on the assumption that this is representative is debatable due to unrepresentative sample intensities.

2.2 Factors that affect traffic crash risk

Various road characteristics in the non-primary road network, as well as external factors, can have an impact on road safety. The following sections will review the literature to identify specific factors that significantly impact the crash risk, number of crashes and crash severity. Identifying these factors is crucial for guiding the research in selecting road characteristics that are available in the datasets also supported by the literature. Subsequently, a conceptual framework will visually represent connections between the factors and traffic safety figures. This literature review aims to provide valuable insights into the relationship between road characteristics, external factors, and road safety, contributing to a better understanding of potential interventions and improvement in the non-primary road network.

Several databases were utilised to identify a comprehensive selection of relevant articles. The databases included "Transport Research International Documentation", "Scopus, and "Google Scholar". These databases were selected for their broad coverage of the relevant literature on traffic safety. The first step of the process was to define relevant keywords to be searched for within the databases. The following search terms were used:

> *(Crash OR Accident) AND (Rate OR Risk OR Frequency OR Severity) AND (Factors OR Causes) AND (Time OR Location OR Weather OR (Built AND Environment) OR (Road AND (Characteristics OR Properties)))*

2.2.1 *Time and Location Factors*

The time of a crash can be subdivided into different parts, namely the time of day, day of week and month/season of the year. Research has extensively explored the impact on the first two time scales, time of day and day of week. It appears that the time of day may not significantly affect the number of crashes (Martin, 2002), but it does seem to influence the severity of crashes (Pape-Köhler, Simanski, Nienaber, & Lefering, 2014; Song, Li, Fan, & Liu, 2021; Martin, 2002; Asgarzadeh, et al., 2018; Behnood & Mannering, 2019; Qin, Ivan, Ravishanker, Liu, & Tepas, 2006; Pahukula, Hernandez, & Unnikrishnan, 2015). Specifically, crash severity tends to increase during evening hours. Inconsistently, some studies are suggesting that the number of crashes is higher during rush hours than during the rest of the day (Adeyemi, Paul, Delmelle, DiMaggio, & Arif, 2023; Adeyemi, Arif, & Paul, 2021).

It appears that the day of the week plays a significant role in the frequency of crashes. Studies have indicated that the average number of crashes is highest during weekends (Mokhtarimousavi, Anderson, Azizinamini, & Hadi, 2020; Pape-Köhler, Simanski, Nienaber, & Lefering, 2014; Weast, 2018). Additionally, a high crash rate is observed from Monday to Thursday between 3 pm and 7 pm (Brorsson, 1983), potentially due to commuters returning home exhausted. Furthermore, holidays have been associated with an increase in fatal crashes (Weast, 2018), often linked to alcohol consumption. Findings addressing seasonal variations appear to be inconsistent. As suggested by most studies, it is concluded that an increased number of crashes occur in both the summer months (Weast, 2018; Pape-Köhler, Simanski, Nienaber, & Lefering, 2014; Farmer & Williams, 2005) and the winter months (Abdel-Aty & Yu, 2012). This phenomenon may be attributed to the different weather conditions in the study locations.

The number of intersections can potentially also impact traffic safety. Compared to road segments, it may be assumed that intersections are less safe due to the number of conflict points between traffic users. However, a direct comparison between the two situations seems limited in the literature. Nonetheless, numerous studies have focussed on the safety of intersections and have consistently found them to be unsafe locations (Dill, 2009; Wachtel & Lewiston, 1994; Briz-Redón, Martínez-Ruiz, & Montes, 2019; Alarifi, Abdel-Aty, Lee, & Park, 2017).

2.2.2 *Weather Factors*

Regarding weather factors, several studies show that reduced visibility conditions are associated with an increased risk of traffic crashes. It has been observed that reduced visibility significantly increases the risk of traffic collisions, especially rear-end collisions, with varying effects on different vehicle types and lanes (Peng, Abdel-Aty, Shi, & Yu, 2017). Additionally, crashes involving fog and smoke are more likely to involve multiple vehicles, cause more severe injuries, and are frequently caused by head-on and rear-end collisions, particularly on roads with high speeds and undivided rural roads (Abdel-Aty, Ekram, Huang, & Choi, 2011). The substantial impact of hazy weather on traffic safety is highlighted by how it increases the risk of collisions and hinders car-following performance (Gao, et al., 2020). Moreover, during reduced visibility, slow-moving traffic and lower speeds are common, increasing the likelihood of collisions (Das, Brimley, Lindheimer, & Zupancich, 2018). Studies also emphasise the significant interaction between vehicle speed and weather conditions to influence driving performance metrics. More variations in speed are observed in hazy weather than in clear conditions, especially at high or medium speeds (Gao, et al., 2020). Furthermore, beyond visibility, a slippery road surface can influence traffic safety, as several studies have demonstrated.

Due to poor road conditions, the risk of crashes increases. As temperatures drop and changes in current temperatures are relatively small, the severity of traffic crashes also increases (Lee, 2017). However, the risk of crashes is highest during sleet and icy road surfaces (Malin, Norros, & Innamaa, 2019). During snowfall, the collision probability may double due to the interaction of a sloping pavement and snow (Norrman, Eriksson, & Lindqvist, 2000; Ahmed, Abdel-Aty, & Yu, 2012). Additionally, the risk of crashes in a single vehicle is generally higher than in a multi-vehicle crash (Malin, Norros, & Innamaa, 2019). Studies indicate that different measures should be taken to reduce the probability of crashes based on the specific conditions of the ice and snow as well as the geometry of the road. During snowy and icy situations, measures such as salt sprinkling, setting speed limits, and obliging to install anti-slip chains or winter tyres can improve driving safety (Shan, Mingbao, & Boning, 2020). Other studies suggest that increasing public awareness by providing information to drivers is necessary to reduce the number of crashes during such situations (Norrman, Eriksson, & Lindqvist, 2000).

2.2.3 Built Environmental Factors

Several studies have shown that strongly urbanised areas negatively impact the number of crashes (Gonzalez, Cummings, Mulekar, & Rodning, 2006; Travis, Clark, Haskins, & Kilch, 2012; Azimian, Pyrialakou, Lavrenz, & Wen, 2021; Asadi, Ulak, Geurs, Weijermars, & Schepers, 2022). However, it is understandable that fatal crashes occur more often in rural areas (Gonzalez, Cummings, Mulekar, & Rodning, 2006; Travis, Clark, Haskins, & Kilch, 2012), which may be attributed to the time it takes for an ambulance to arrive at the scene. Furthermore, research has shown that the risk of vehicle-bicycle crashes is higher in strongly urbanised areas, possibly due to increased conflicts among multiple traffic users (Asadi, Ulak, Geurs, Weijermars, & Schepers, 2022). Land use has also been identified as a factor influencing the risk of crashes (Pulugurtha, Duddu, & Kotagiri, 2013). In the same study, a distinction was made between areas with mixed-use, urban housing, single-family homes, multi-family homes, business and office districts, and it was found that the number of crashes decreased with an increase in single-family home areas (Pulugurtha, Duddu, & Kotagiri, 2013). However, diverse land use appears to reduce the risk of crashes (Asadi, Ulak, Geurs, Weijermars, & Schepers, 2022; Chen & Shen, 2016).

2.2.4 *Traffic and Road Factors*

Traffic and road factors can be categorised into road design, traffic volume, bicycle, and parking facilities. Starting with road design, several studies have indicated an impact on the number of crashes. Multiple studies have shown that wider roadways are associated with increased crash rates (Abdel-Aty & Radwan, 2000; Othman, Thomson, & Lannér, 2009). However, other studies show contradictory results and indicate that wider roadways are associated with a decreased crash rate (FHWA, 1994) and reduced crashes (Hadi, Aruldhas, Chow, & Wattleworth, 1995). Additionally, the number of lanes and the width of these lanes have been found to impact the risk of crashes, with narrow lanes and a larger number of lanes increasing the risk (Othman, Thomson, & Lannér, 2009). Several studies have also shown that the number of lanes, as the only parameter, has a negative influence on the number of crashes (Milton & Mannering, 1998; Berhanu, 2004; Wang, Zhou, Quddus, Fan, & Fang, 2018). When no marked centreline is placed on roads with one lane, the number of crashes increases (Greibe, 2003), showing that lane marking is a crucial factor. Also, lane separations are a factor that can prevent crashes by 10% (Sawalha & Sayed, 2001; Bonneson & & Mccoy, 1997). However, there appears to be disagreement in the literature, as other studies show that more crashes occur on separate roads (Høye & Hesjevoll, 2020). Therefore, it would be interesting if this is also the case in the Netherlands.

Notably, a correlation has been found between pedestrian crossings on separated roads with high traffic volumes and a higher risk of fatal pedestrian crashes (Olszewski, Osińska, Szagała, & Włodarek, 2018). However, other factors, including traffic volume, pedestrian behaviour, and crossing design, also determine how well pedestrian crossings work (Noh, Ka, Lee, & Yeo, 2021; Ziolkowski, 2019; Al-Omari & Obaidat, 2013; Prakash & Karuppanagounder, 2023; Bak & Kiec, 2012). Therefore, road safety education is essential since it positively influences pedestrian behaviour and the risk of pedestrian injury (Modipa, Kockott, & Olutola, 2022).

Numerous studies have examined the impact of traffic volume on road crashes. Research indicates that general traffic volume significantly impacts the crash rate (Kashani & Zandi, 2020). Motor vehicle traffic volumes appear to be the most important model variable correlating with increased crash rates (Greibe, 2003). The phenomenon of safety-in-numbers may play a role here, with the number of crashes increasing less than proportionally to the traffic volume (Elvik & Bjørnskau, 2017). However, this complex relationship is linear at lower traffic volumes and quadratic at higher volumes (Retallack & Ostendorf, 2020). In urban areas such as London, research suggests that increasing the number of cyclists and reducing motorists or speed limits can reduce the risk of cycling injuries (Aldred, Goodman, Gulliver, & Woodcock, 2018). Once again, the 'safety-in-numbers' effect is evident, where an increase in cyclists leads to decreased bicycle crashes (Cai, Abdel-Aty, & Castro, 2021). However, accurately calculating the crash rate of cyclists and pedestrians on shared roads remains challenging due to the interaction between the volumes (Fournier, Christofa, & Knodler, 2019). These findings highlight the importance of comprehending the complex interactions between traffic volume and road safety.

Implementing bicycle lanes significantly increases road safety, particularly in suburban areas, where there is a significant speed difference between cyclists and drivers (Kaplan & Prato, 2015). However, studies indicate that intersections with more bike lanes have a higher risk of crashes, even after bicycle infrastructure modifications (Liu & Marker, 2020). Also, there is a noticeable increase of about 10% in both crashes and injuries following the introduction of bike lanes (Jensen, Bicycle Tracks and Lanes: a Before-After Study, 2008). Interestingly, a New York City study reveals that adding bike lanes does not necessarily increase the number of crashes, potentially due to reduced vehicle speeds and decreased conflicts between vehicles and cyclists (Chen, et al., 2012). However, this may be a specific to the study location conclusion, since the effect of bicycle lanes in the Netherlands significantly contributes to the number of crashes (Boele-Vos M. , et al., 2017). Meanwhile, studies indicate that separate bicycle lanes reduce the risk of bicycle-motor vehicle crashes. Physically separated cycle paths have led to a 50-60% reduction in bicycle crashes compared to cycle paths on distributor roads (Schepers, Twisk, Fishman, Fyhri, & Jensen, 2017; Petegem, Schepers, & Wijlhuizen, 2021; Pucher & Dijkstra, 2003).

Numerous studies have explored the correlation between traffic crashes and parked cars. Parked cars on the side of the road pose a considerable risk of crashes (Greibe, 2003). Drivers often reduce their speed and shift their position to the centre of the road to compensate for the increased mental load. Still, these adaptations often prove insufficient to reduce reaction time (Edquist, Rudin-Brown, & Lenné, 2012). A 24% increase in crashes is observed on road sections where parking is prohibited. In contrast, in areas where parking is permitted, a 14% decrease is observed (Jensen, Rosenkilde, & Jensen, 2008). Although the relation to the increased mental load is unclear, it may influence these findings. Furthermore, parking along the curb and the presence of trams are related to an increased risk of bicycle crashes by a factor of 2 and 1.7-2, respectively (Petegem, Schepers, & Wijlhuizen, 2021).

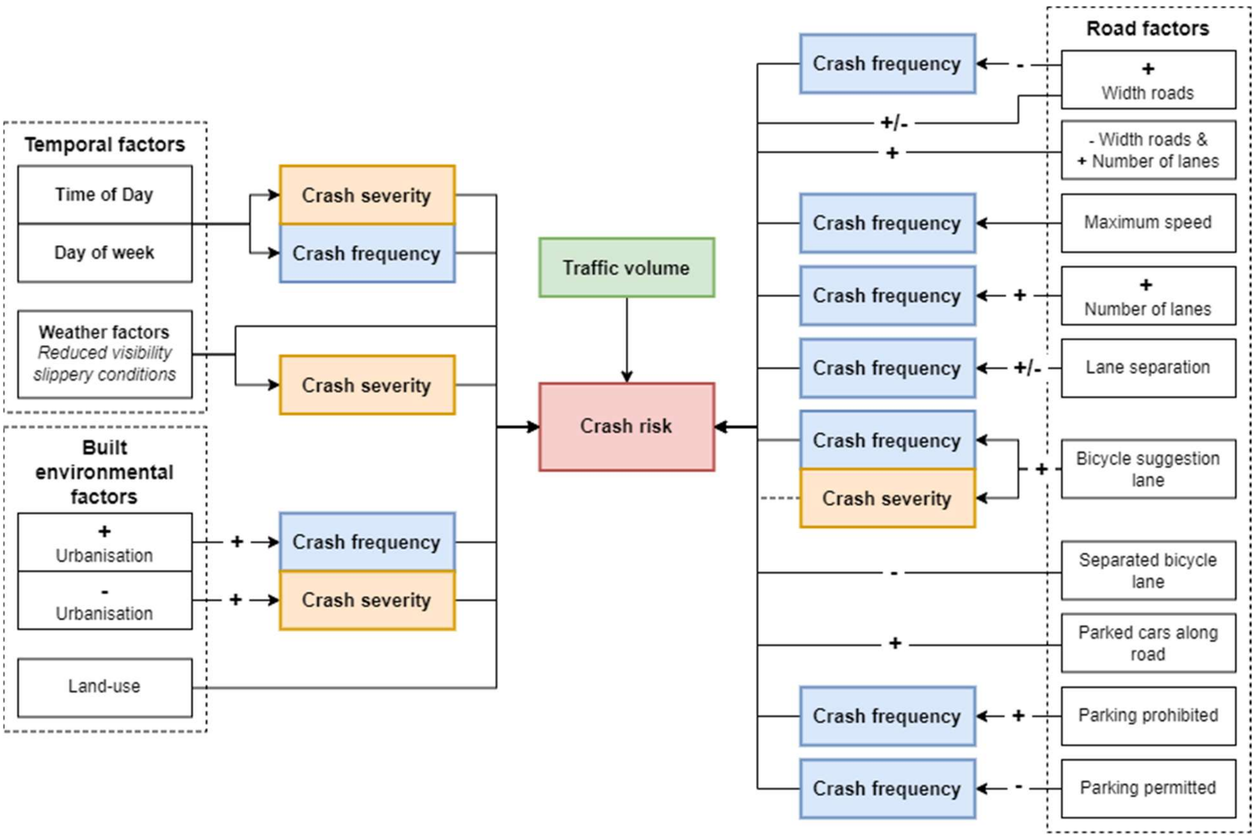

Figure 1: Conceptual Framework

2.2.5 Conceptual Framework

A conceptual framework has been developed to clarify the relationships between the examined factors, as outlined in the literature. This framework, shown in Figure 1, illustrates the expected relationships between these factors. The figure displays that the factors, as discussed in the literature, directly or indirectly influence the crash risk. Each factor is related to crash severity, crash frequency, or crash risk. The crash frequency and traffic volume are utilised to determine the crash risk. While crash severity does not directly influence the crash risk, a decision can be made as to whether to determine the crash rate per severity class, evaluate the cost of crash risk or not include the severity of a crash. For example, the figure shows that the literature indicates that increased urbanity leads to increased crash frequency, and decreased urbanity leads to increased crash severity. In the current research, the crash rate is the metric utilised to assess the crash risk.

3. Data

This section describes the available data. Table 2 provides an overview of the utilised sources. The remainder of this section describes each dataset.

Table 2: Overview of the Datasets

Dataset name	Type	Description	Source/Owner	Available Years
Bestand geRegistreerde Ongevallen in Nederland (BRON)	Crashes	BRON is a file with crash data which is mainly sourced by police reports, covering the whole of the Netherlands..	Rijkswaterstaat	2003-2022
Motor vehicle intensity model	Traffic-intensities	The car intensity model is a transport demand model developed by Goudappel and is part of the national mobility model OmniTRANS Spectrum.	Goudappel, OmniTRANS Spectrum	2018-2022
Freight intensity model	Traffic-intensities	The freight intensity model is a transport demand model developed by Goudappel and is part of the national mobility model OmniTRANS Spectrum.	Goudappel, OmniTRANS Spectrum	2018-2022
Bicycle intensity model	Traffic-intensities	The bicycle intensity model is a transport demand model carried out by Goudappel and is part of the national mobility model OmniTRANS Spectrum.	Goudappel, OmniTRANS Spectrum	2018-2022
Nationaal Wegenbestand (NWB)	Network	NWB is a dataset that contains all roads in the Netherlands, including the characteristics of these roads.	Rijkswaterstaat	2018-2022
Bicycle network	Network	The bicycle network is originating from Fietsersbond and contains the bicycle roads of the Netherlands, including the characteristics.	Fietsersbond	2018-2022
Districts and neighbourhoods data	Built environment	Displays, among other properties, the degree of urbanisation per district or neighbourhood in the Netherlands.	CBS	1995-2023

3.1 Crash Datasets

The "*Bestand geRegistreerde Ongevallen in Nederland*" (BRON) is a valuable source of crash data for road safety research in the Netherlands. Managed by Rijkswaterstaat, this dataset provides an extensive collection of structured data on traffic crashes throughout the Netherlands, recorded by the Dutch police and/or road inspectors. It includes variables such as the crash location and times, the crash severity (property damage only (PDO), injury and fatal), the type of vehicles involved, weather conditions and other relevant factors. Covering nearly two decades (2003-2022), BRON provides a valuable source for calculating crash rates of the non-primary road network. While the dataset is of high quality and registration by the police has increased, it may not be complete since the police cannot be present at every traffic crash to make a registration. The dataset presents under registration and indicates a discrepancy between recorded incidents and the actual occurrence of crashes. This discrepancy is particularly pronounced in the context of PDO crashes and incidents without of motor vehicle involvement. Nevertheless, BRON remains the most comprehensive crash dataset available in the Netherlands and, therefore, the primary crash dataset used in this study.

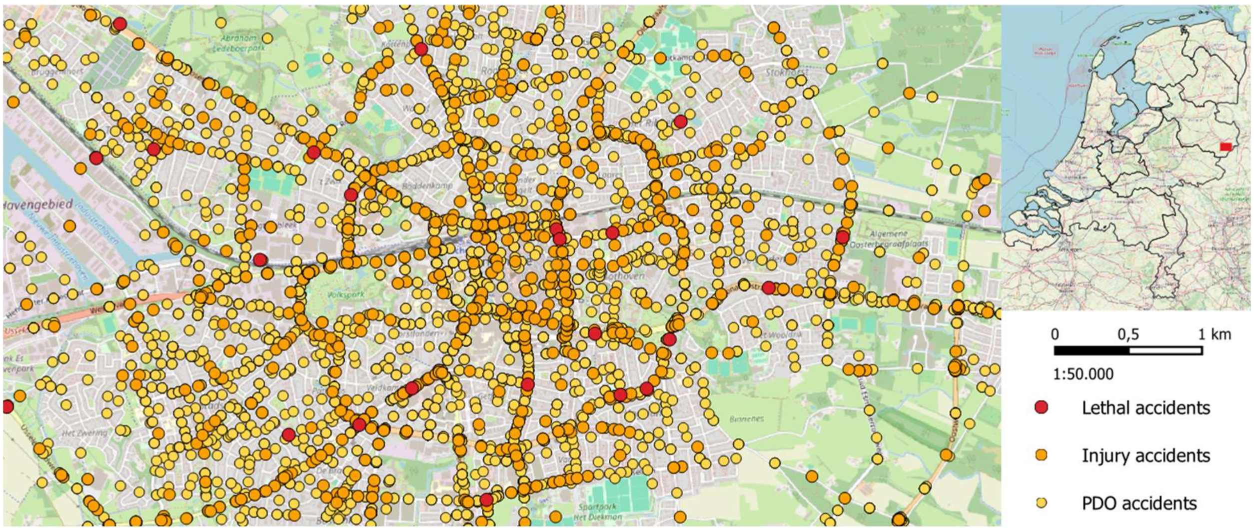

Figure 2: Sample of the Crash Dataset, Location: Enschede

Figure 2 shows a part of Enschede, highlighting the distribution of crashes categorised by severity. PDO crashes are the most common, followed by crashes resulting in injury, with fatal crashes being the least common. This representation is consistent with the overall statistics for the Netherlands, where 81.3% of all crashes on the non-primary road network are PDO crashes, 18.2% result in injuries, and 0.5% are fatal crashes, which can be seen in Table 3. Additionally, the table reveals that most crashes occurred on a road segment (60.7%), compared to intersections (34.9%). Furthermore, most crashes are exactly linked (61.7%), but several crashes are linked at the municipal level and therefore unusable. Considering the provinces, the most crashes were registered in Zuid-Holland (21.9), closely followed by North Holland (16.8), while the province with the fewest crashes is Flevoland (1.9%). Regarding other crash variables, it is worth noting that many crashes are incompletely registered, resulting in unavailable information, e.g. road surface, weather conditions and lighting conditions at the time of the crash.

Table 3: Descriptive Statistics of the Crash Dataset

Variable	Count	Perc. (%)
Severity		
Fatal	4.298	0,5
Injury	149.952	18,2
PDO	669.756	81,3
Crash location		
Intersection	287.747	34,9
Segment	536.259	60,7
Location Accuracy		
Exact	508.755	61,7
Segment level	212.212	25,8
Intersection level	63.246	7,7
Municipality level	39.793	4,8

Variable	Count	Perc. (%)
Province		
Zuid-Holland	180.566	21,9
Noord-Holland	138.618	16,8
Noord-Brabant	114.016	13,8
Gelderland	100.620	12,2
Overijssel	68.920	8,4
Limburg	56.933	6,9
Utrecht	56.452	6,9
Groningen	28.227	3,4
Friesland	24.981	3,0
Drenthe	19.660	2,4
Zeeland	19.651	2,4
Flevoland	15.362	1,9

3.2 Traffic Intensity Datasets

The transport demand model OmniTRANS Spectrum provides a unique mobility data source that offers detailed insights into various aspects of mobility in the Netherlands. This data source includes spatial data and mobility patterns, providing information on traffic intensities for cars and bicycles, among other modes, on all roads in the Netherlands. Developed by Dat.mobility and Goudappel the platform utilises data fusion techniques to combine different data sources to create a holistic view of mobility. Covering the years 2018 to 2022, including regular updates, OmniTRANS Spectrum is a valuable tool for analysing and understanding mobility at any scale. The traffic intensities for cars and cyclists are essential for this study, enabling the calculation of exposure on a road section. Notably, the models used for traffic intensity calculations are based on the road and bicycle networks and socioeconomic data in the Netherlands. They are afterwards calibrated on traffic counts, ensuring the dataset's high quality. The datasets utilized

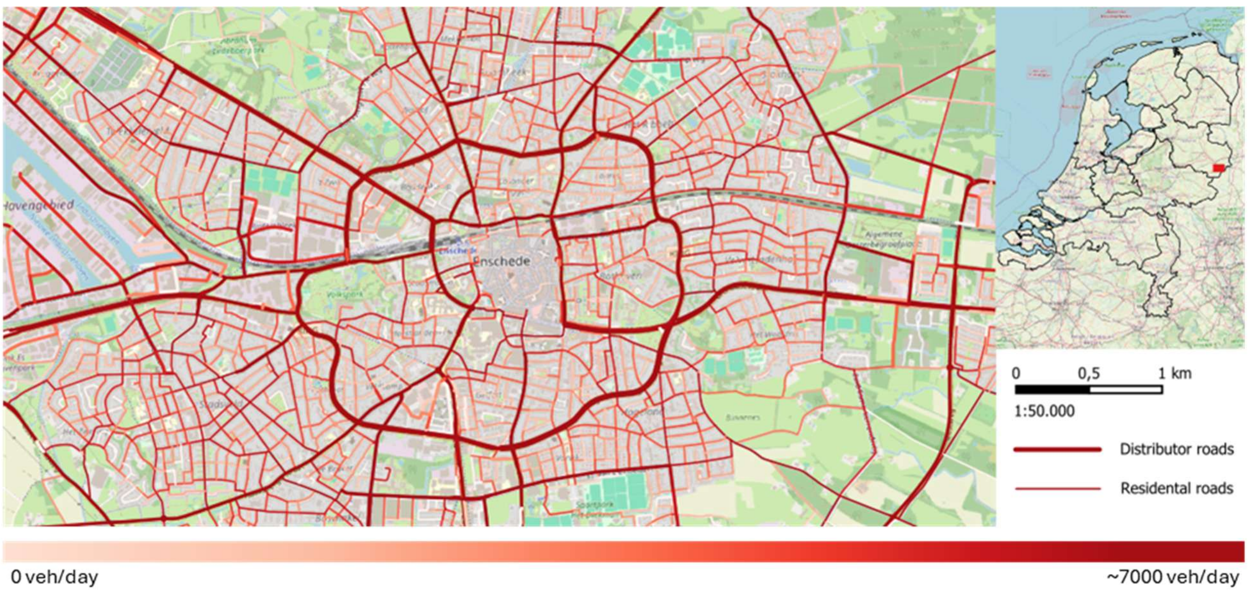

Figure 3: Sample of Motor Vehicle Intensities, Location: Enschede

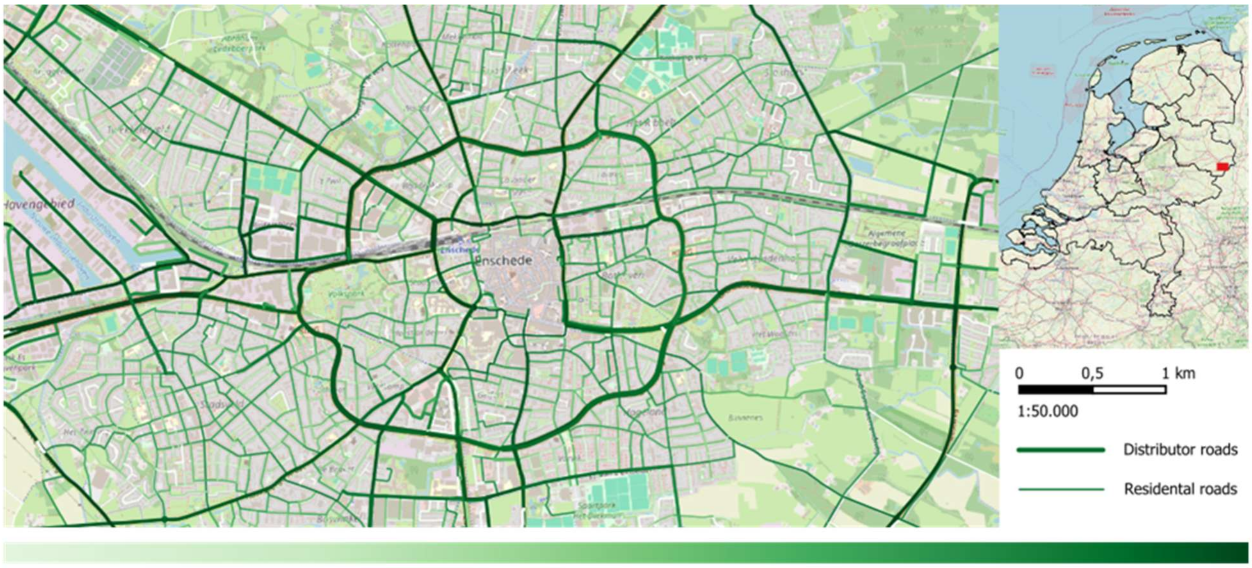

Figure 5: Sample of Freight Intensities, Location: Enschede

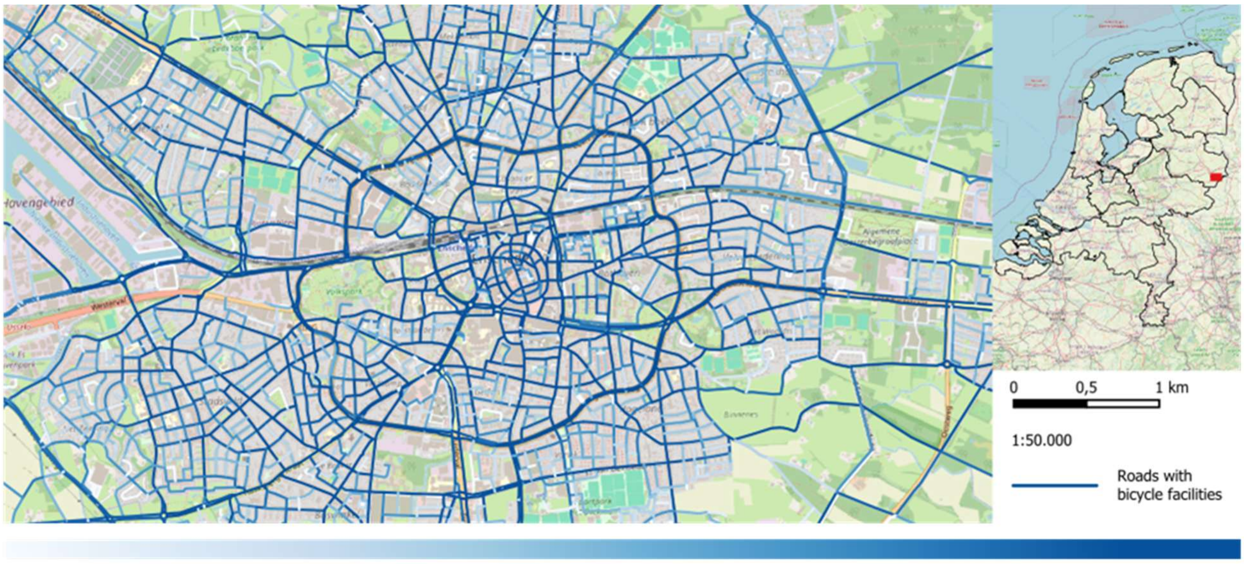

Figure 4: Sample of Bicycle Intensities, Location: Enschede

in this study exhibit a notable limitation characterized by the absence or low intensity of data representation on certain road segments. However, it is acknowledged that a higher level of intensity may, in fact, be present in these areas. Such occurrences are infrequent, and therefore, the datasets are applicable for this research.

Figure 3 illustrates the intensities of motor vehicles originating from the dataset. As illustrated, the number of vehicles per day varies on different types of roads, with a maximum intensity of approximately 7000 vehicles per day. The pattern shows that access roads relatively contain more motor vehicles than residential areas. This can also be observed in Figure 5, where freight intensities are illustrated. In this instance, the impact is more pronounced, as freight vehicles generally have fewer destinations in residential areas. Furthermore, as expected, freight vehicles predominantly utilise distributor roads and roads in industrial areas. The highest intensity recorded for freight traffic is approximately 1,200 vehicles per day. Figure 4 shows bicycle intensities. Compared to motor vehicle and freight patterns, cyclists tend to utilise residential areas more frequently, and clear destinations are highlighted with decreased cyclist activity. Additionally, bicycle traffic is more dispersed on the network and centred around the city centre, where the areas are strongly urbanised (described in 3.4 Built environment Dataset).

3.3 Network Datasets

3.3.1 Road Network

The "*Nationaal Wegenbestand*" (NWB) is a dataset that provides a thorough overview of the road infrastructure network managed by all road authorities in the Netherlands. The road characteristics database (WKD) is part of the NWB and contains various road characteristics. These open datasets from Rijkswaterstaat contain detailed information about various types of roads, including highways, provincial roads, and local roads. NWB, combined with WKD, contains data on the geographical locations of roads, such as road segments and junctions, and additional attributes, such as road categories, speed limits, road lengths and road authorities. The NWB covers the period from 2007 to 2023 and provides precise geographic coverage, so it is a valuable resource for crash rate research. Additionally, cycle paths have been incorporated into NWB since 2022, showing continued improvement in quality. One limitation of this dataset is that it occasionally lacks accurate information or contains discrepancies regarding road segments. For instance, a road segment may be classified as a distributor in the dataset while it is a motorway. However, these discrepancies are infrequent and are unlikely to substantially affect the outcomes of this study.

Table 4: Descriptive Statistics of Road Lengths in Kilometres of Various Road Network Variables

Variable	Sum	Perc. (%)
Speed limit		
12	190	0,3
30	13.000	23,4
50	12.000	21,6
60	20.000	35,9
70	840	1.5
80	9.600	17.3
100	34	0.1
Road type		
Access roads	33.000	59.2
Urban distributor road	12.000	21.5
Rural distributor road	10.000	18.9
Residential area	190	0.4

Variable	Sum	Perc. (%)
One way road		
False	48.000	86.2
True	7.700	13.8
Number of lanes		
1	54.000	97.5
> 1	1.400	2.5

Table 4 presents the descriptive statistics of different variables based on the length of the road segments. 60 kph roads show the highest share of 35.9% of the Dutch non-primary road network. Other lower speeds, such as 30 and 50 kph, also form a significant part of the road network. Conversely, speed limits of 12 kph, 70 kph, and 100 kph seem rarer in the road network. Regarding the road type, the majority are access roads with a share of 59.2%, which is the sum of 30 kph and 60 kph roads. This suggests a strong correlation between the speed limit and road type. Two-way roads make up the vast majority of the dataset at 86.2%. Finally, single-lane roads are highly prevalent, representing 97.5% of the total, compared to multi-lane roads comprising only 2.5%.

3.3.2 Bicycle Network

The Dutch Cyclists' Union's ("*Fietsersbond*" in Dutch) bicycle Network offers a collection of data about cycle paths and cycling infrastructure throughout the Netherlands. This dataset contains detailed information about the type of bicycle facilities, such as cycle paths along roads, moped paths, solitary cycle paths and moped paths. It also includes the nature of the road, whether it has a specific bicycle facility or contains a bicycle lane (suggestion). Additionally, data about the direction (one- or two-way traffic), the type of road surface, the quality of the road surface (experienced), and the presence of lighting are included for all cycle paths. This dataset is essential for determining the traffic exposure by calculating the cycling infrastructure's length.

Table 5: Descriptive Statistics of Road Lengths in Kilometres of Various Bicycle Network Variables

Variable	Sum	Perc (%)	Variable	Sum	Perc (%)
Bicycle facility			Road surface		
Suggestion lane	7.300	5,3	Asphalt	66.000	55,2
Bicycle path	15.000	11,1	Semi paved	2.300	1,9
No facility	17.000	12,1	Cobblestone	33.000	27,5
Mixed traffic	97.000	71,5	Unknown	12.000	9,8
			Unpaved	3.900	3,2
Road level			Other	140	0,1
Motorway	1.700	0,0	Shell road	160	0,1
Major main road	4.900	4,0	Road tiles	2.500	2,0
Along busy road	9.800	8,1			
Unknown	4.000	3,3			
Other road	100.000	84,5			

Table 5 indicates a limited number of road characteristics have been linked to the network of Fietsersbond. The most relevant variable is the type of bicycle facility. It is evident that most roads are classified as mixed traffic (67.4%) while the lowest percentage as roads with bicycle suggestion lanes (5.0%), possibly due to the limited number of suitable roads. Additionally, it is interesting to point out that for the data is sometimes less useful, given the high number of roads that are classified as other road. For road surface type, it is noteworthy that it is classified for the bicycle network, which is not the case for the road network. Finally, this figure shows that most roads are paved with asphalt (55,2%), cobblestone roads are also common (27,5%) and almost 10% of the roads have unknown pavement.

3.4 Built environment Dataset

The Built environment dataset from Statistics Netherlands (CBS) provides detailed insight into the degree of urbanisation of various municipalities, districts, and neighbourhoods in the Netherlands. The "CBS Wijk- en Buurtkaart" dataset includes information about the degree of urbanisation of the area in question, measured by the number of inhabitants per square kilometre. The “CBS Wijk- en Buurtkaart” dataset also has other specific national properties, although irrelevant to the current study. Covering the years 1995 to 2023, the dataset extends a wide range of urban and rural areas across the country. With this dataset, the degree of urbanisation can be included as a factor in the research as a characteristic of the crash rate. Figure 6 shows a sample of the illustrated dataset. It can be seen that more inhabitants live per square kilometre in dark areas than in rural areas of, in this case, Enschede. In rural and village locations, the areas are primarily classified as not urbanised.

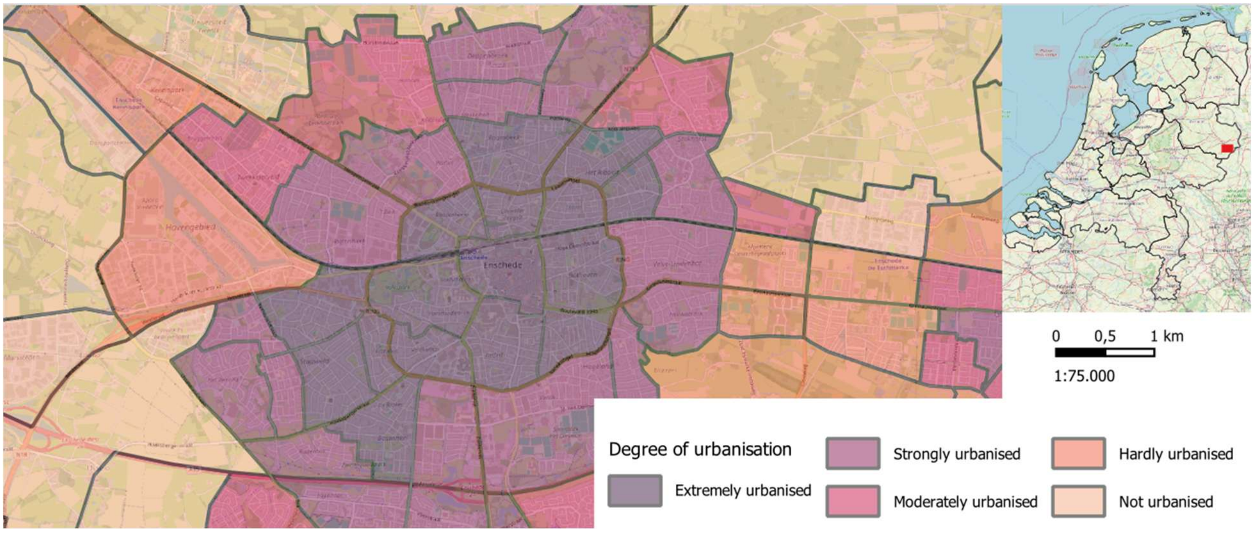

Figure 6: Sample of Degree of Urbanisation, Location: Enschede

4. Methodology

This section describes the methodology employed in this study. To give more structure to the methodology, Figure 7 shows the methodological framework. This reveals that the datasets described in the previous section are the origin of the research. After preparing, processing and

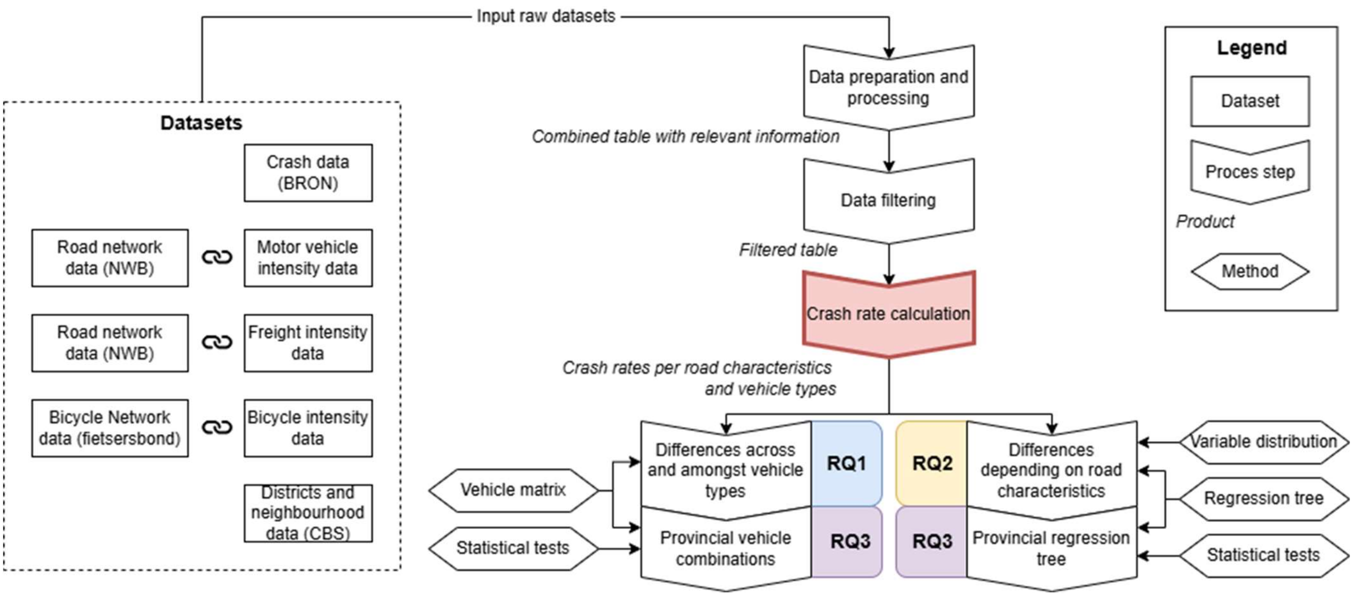

Figure 7: Methodological Framework

filtering, the crash rates were calculated per road characteristic and vehicle type, utilising the number of crashes and distance travelled from the filtered table. With these crash rates, various analyses were done to answer the research questions. This methodology follows the same structure as the sequence of the process steps shown in the figure.

4.1 Data Preparation and Processing

The software package QGIS was used to prepare and process the data. Firstly, the crash data was spatially joined with the road network (including road characteristics, motor vehicle and bicycle intensity) and demographic data. Subsequently, road segments without crashes were joined.

The intensities from the traffic model only distinguish between motor vehicles, freight vehicles and cyclists. BRON offers a more detailed categorisation of vehicles. To facilitate a match between intensities and crashes, the vehicles in BRON have been reclassified into a more general classification, as seen in Table 6. E.g., the number of crashes involving cars, vans, motorcycles, agricultural vehicles, etc., are classified as motor vehicles. Two classifications have been chosen: a classification with a higher level of detail that can be used to analyse overall crash rates for vehicle types and a classification that is used to analyse crash rates for road characteristics.

Table 6: Classification of Road Users

Road user	**Classification for vehicle types**	**Classification for road characteristics**
Passenger car	Motor vehicle	Motor vehicle
Van/minibus	Motor vehicle	Motor vehicle
Motorcycle	Motor vehicle	Motor vehicle
Microcar	Motor vehicle	Motor vehicle
Unknown vehicle	Other motor vehicle	Motor vehicle
Tractor	Other motor vehicle	Motor vehicle
Agricultural vehicle	Other motor vehicle	Motor vehicle
Freight with semi-trailer	Freight	Motor vehicle
Truck	Freight	Motor vehicle
Bus	Freight	Motor vehicle
Bicycle	Bicycle	Bicycle
Moped	Bicycle	Bicycle
e-bike	Bicycle	Bicycle
Other fixed object	Object	Object
Other road furniture	Object	Object
Light pole	Object	Object
Tree	Object	Object
Loose object	Object	Object
Pedestrian	Pedestrian	Pedestrian
Mobility scooter	Pedestrian	Pedestrian

Finally, all relevant information was combined in a table, including crash characteristics, parties involved in a crash, motor vehicle, freight and bicycle intensities, demographic data, network characteristics and the presence of bicycle facilities. This table serves as the basis for calculating crash rates.

4.2 Data Filtering

Subsequently, the prepared data is filtered to make the outcome more reliable. The following filters are applied:

- Level of crash severity: exclude PDO crashes
- Level of detail in registration: exclude crashes registered on the municipality level.
- Selection of study period: exclude not representative years (2013, 2014, 2020 and 2021)

In the following sections, the filters will be elaborated, starting with the level of crash severity, followed by the level of detail in registration and the selection of the study period.

Level of crash severity

Crash severity is categorised into three levels: property damage only (PDO) crashes, injury crashes, and fatal crashes. PDO crashes are often underreported. This underreporting primarily occurs since BRON only considers crashes officially recorded by law enforcement. In many instances, police are not present at the scene of PDO crashes, as these incidents are viewed as less severe. Consequently, due to the underreported PDO crashes, the overall perception of traffic safety is skewed.

Research efforts frequently exclude PDO crashes from analysis due to the unreliability of PDO data. A more accurate understanding of road safety can be achieved by concentrating solely on incidents involving injuries or fatalities. This approach ensures that resources and attention are directed toward preventing the most serious outcomes, ultimately contributing to a safer driving environment. Therefore this study will exclude PDO crashes and only utilises injury and fatal crashes.

Level of detail in the registration

Crashes registered at the municipality level have been excluded from the selection process due to the imprecise nature of their reported locations. This lack of accuracy makes it challenging to connect these crashes to the specific road characteristics on which they occurred. Without reliable data on the exact locations of these crashes, it becomes increasingly difficult to analyse the contributing factors and implement effective safety measures. With the exclusion of crashes registered at the municipal level, this study's level of detail in registration concerns crashes registered at the intersection level, segment level and spatially exactly registered crashes. Accidents at this level of detail are valuable enough to be able to link them to specific road characteristics.

Selection of study period

As described earlier, several years of data are available for the different datasets. However, some years have not been representative of a normal, stable traffic situation. Therefore, it is necessary to select the study period. The dataset concerning intensities is central to this choice, as it is available for a limited number of years. The year 2018 has been chosen since it is the first year the model intensities are available. It is assumed minimal changes have been made to the network during these years and that the vehicle kilometres of 2018 are representative. However, several years present an unrepresentative situation, derived from the number of registered crashes and vehicle kilometres from the figures of Rijkswaterstaat (Rijkswaterstaat, 2023). Figure 8 shows the trend of crashes and vehicle kilometres.

Figure 8 shows a low registered number of crashes in 2013 and 2014. This can be explained by the methodology used by BRON to register the crashes. After 2014, this methodology changed, and a manual correction or addition is no longer necessary. The years 2020 and 2021 also show a lower number of crashes and vehicle kilometres, which can be attributed to the pandemic's impact. Additionally, it is assumed that traffic participants had relatively other motives, and the share of cyclists may be higher during these years. Given these inconsistencies, it has been decided to exclude the data from 2013, 2014, 2020 and 2021 in this study, so only the years 2015 to 2019 and 2023 are utilised.

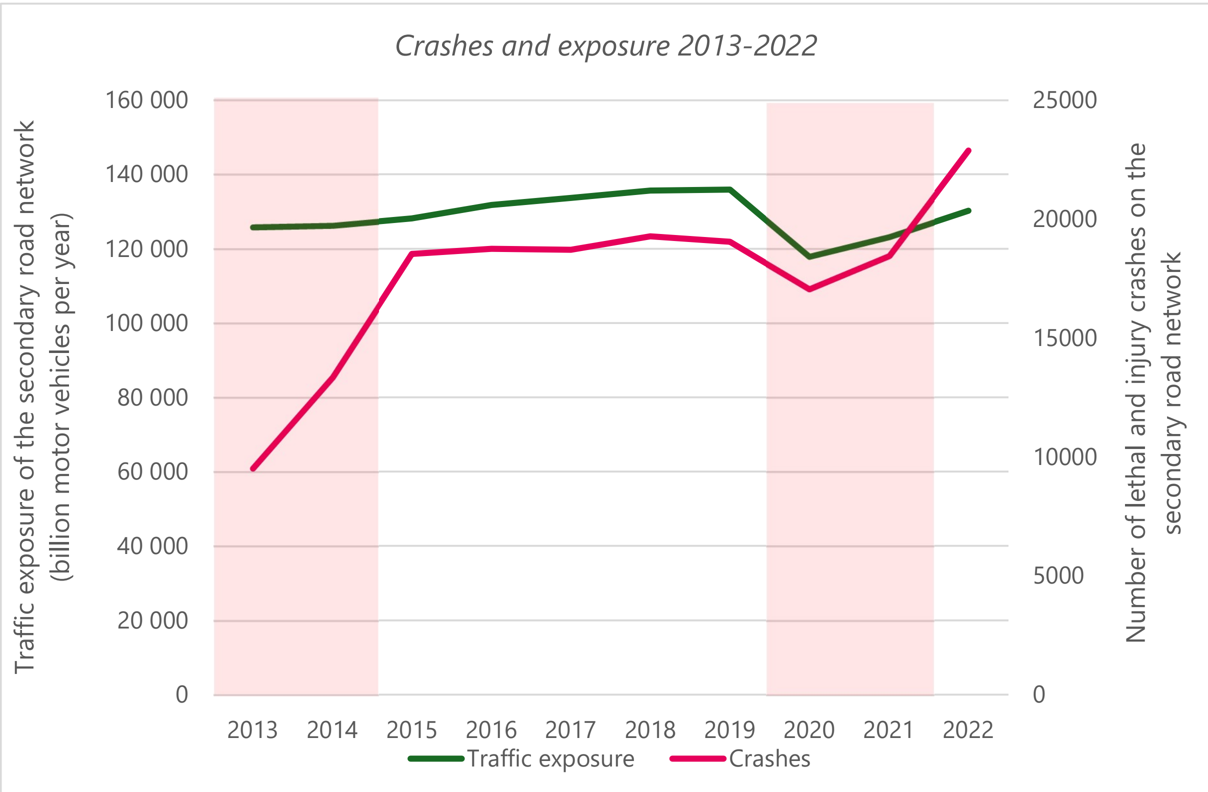

Figure 8: Crashes and Exposure 2013-2022

4.3 Crash Rate Calculation

After completing the filtering process, the crash rate is calculated. Calculating the crash rate requires determining the number of crashes and traffic volumes. The objective of this study was to use the intensities of the traffic model to determine the traffic volumes. However, the output from the traffic model contains average peak and off-peak hours for working days, which are converted into weekday intensities. These converted intensities are then utilised to calculate the traffic volumes. The associated number of crashes and distance travelled is summed to calculate the total number of crashes and total distance travelled for each desired road characteristic or vehicle type combination. These variables are utilised to calculate the corresponding crash rate by dividing the variables (Golembiewski & Chandler, 2011):

$$R = \frac{C \times 1.000.000.000}{V \times L \times N \times 365} \tag{1}$$

Where:
R is the calculated crash rate per billion vehicle kilometres; C is the subtotal of crashes; V is the number of vehicles per day for all segments; L is the total length (kilometres) for all segments; N is the number of years of the available data.

4.4 Differences Across and Amongst Vehicle Types

The first research question can be addressed after processing, preparing, filtering the data and clarifying how the crash rate is calculated. This question focuses on the challenges posed by the various types of vehicles in traffic, where the various intensities contribute to a complex exposure calculation. To illustrate the safety comparisons among different vehicle types, research commonly utilises vehicle matrices showing the number of crashes between these vehicles. However, such matrices can often create a misleading impression that a higher risk exists for many crashes involving a specific vehicle type and others. A more accurate representation of crash risk can be developed by applying an exposure metric, such as distance travelled, and correlating it with the number of crashes to determine a crash rate. Nonetheless, this still leaves the initial challenge open.

Published studies have sought to combine various vehicle kilometres to calculate crash rates. However, when this method is selectively applied only to crashes involving multiple vehicle types, the resulting crash rates cannot be compared with those involving a single vehicle type. Therefore, it has been decided to establish crash rates by counting the number of crashes involving multiple vehicle types and the distance travelled by a single vehicle type. This approach clarifies the risk of a crash involving both vehicles from a certain perspective. As a result, the crash rates will be comparable, utilising the previously described vehicle classification for different types (Table 6).

Due to the limited range of vehicle intensities considered in this study, the analysis focuses exclusively on three perspectives: motor vehicles, bicycles, and freight vehicles, with each perspective based on the distance travelled. For instance, the crash rate is determined from the perspective of motor vehicles for incidents involving both a motor vehicle and a cyclist. Specifically, this involves calculating the distance travelled by the motor vehicle per billion motor vehicle kilometres. These crash rates are derived using Equation 1, as the previous section outlines. The resulting crash rates for each vehicle type are organised into a matrix, providing a comprehensive overview of crash rates across different road users. This matrix serves as a tool for analysing which vehicle type is most susceptible to collisions with others.

4.5 Differences Depending on Road Characteristics

To answer the second question, a decision tree will be utilised to investigate road characteristics and how the combination of road characteristics impacts the crash rates most. Specifically, a regression tree will be used to investigate the influence of combination of road characteristics. Regression trees are nonparametric models that require no distributional assumptions and demonstrate resilience to outliers, multicollinearity, and heteroscedasticity (Breiman, Friedman, Olshen, & Stone, 1984). A regression tree repeatedly splits the data into subsets based on feature values to minimise the variance within each subset. To ensure the biggest reduction in variance, the algorithm utilises the feature results and threshold at each split. The algorithm will keep running until it meets a stopping criterion, such as reaching a maximum tree depth or having a minimum number of samples in a leaf node. Once the algorithm is stopped, the regression tree could be pruned to remove certain leaves to achieve the desired level of detail.

In this research, the regression tree will systematically split the road characteristics with the corresponding crash rates as feature values. This regression will be used to find impactful road characteristics on the crash risk and what combination of road characteristics leads to more/less risky situations. For this, the Friedman MSE splitting algorithm was chosen due to its utilisation of the mean squared error with Friedman's improvement score for potential splits, making it a more favourable choice than a standard MSE.

The characteristics that have been chosen for consideration are based on the literature and the conceptual framework described in the introduction. Some of these characteristics addressed in the introduction were not selected due to temporary situations, such as time of day, and due to the need for intensive modifications of the datasets that require too much time, such as determining road widths, parking facilities and land use. A sufficient amount of data was available for the selected road characteristics and are, therefore, included. The selected road characteristics are speed limit/road type, type of cycling facility (divided into mixed traffic, cycle path, cycle lane and cyclists prohibited), degree of urbanisation (divided into strongly urbanised: 1500 addresses or more per square kilometre; moderately urbanised: 500 to 1500 addresses per square kilometre; and not urbanised: fewer than 500 addresses per square kilometre), one-way road, number of lanes (divided into single lane and multi-lane) and proportion of freight traffic (divided into no freight traffic (0%), below average freight traffic (>0% and ≤4%), about average freight traffic (>4% and ≤15%) and above average freight traffic (>15%)).

The degree of urbanisation and freight share are ordinal categorised variables. However, bicycle facilities are not ordinal and cannot be categorised as variables due to limitations in the package used for creating the regression trees. Therefore, the presence of various bicycle facility types is the variable used. Additionally, the regression tree is pruned based on a minimum value of traffic exposure (<0.1% of the total vehicle kilometres), meaning that no leaves appear if the traffic exposure is too low and the crash rates are unreliable and sensitive to minimal chances. To minimise the number of regression trees, it was decided to combine freight transport with motor vehicles, as shown in Table 6. As a result, the regression trees were generated from different perspectives: motor vehicle, bicycle, combination of motor vehicle and bicycle crashes per billion motor vehicle kilometres and combination of bicycle and motor vehicle crashes per billion bicycle kilometres.

4.6 Regional differences in Crash Rates

To understand the regional differences in the crash rate and to assess the applicability of national figures at the regional level, the vehicle matrices and the regression trees are recreated per province in the Netherlands. Provinces have been chosen due to the balance between the level of detail of the region and the region's size, which ensures sufficient observations and enhances reliability. Furthermore, variations in regional policies make provinces a suitable scale.

For each province, vehicle type matrixes is made to compare differences and additionally tested for significance with a Z-test. This test is used to statistically determine significant differences between a provincial crash rate and the national crash rate. Since the crash rate is not a pure observation, the number of vehicle kilometres on a road segment and the number of crashes on a road segment are utilised. While the sample quantity is Poisson distributed ($R_{PROVi,j}$), the Z-test is normally distributed. Nonetheless, given the considerable number of measurements, the Poisson distribution can be approximated to a normal distribution, allowing us to use the Z-test in this specific case:

$$Z - crit > \frac{|R_{NAT,j} - R_{PROVi,j}|}{\sqrt{S(R_{PROVi,j})^2 + S(R_{NAT,j})^2}} \tag{2}$$

Where, $R_{NAT,j}$ is the national crash rate for vehicle type combination j (in a Z-test the population mean) , $R_{PROVi,j}$ is the provincial crash rate for province i for vehicle type combination j (in a Z-test the sample mean), in the denominator is the standard error calculated as in a Z-test. $S(R_{REGi,j})$ is the crash rate with a Poisson distributed crash:

$$S(R_{REGi,j}) = \frac{\sqrt{\mathrm{C_i}} \times 1.000.000.000}{\mathrm{V_i} \times \mathrm{L_i} \times \mathrm{N} \times 365} \tag{3}$$

For the provincial difference with the national crash rate in which road characteristics are examined, it was decided to use the first three layers of the national regression trees (given the number of observations) and to calculate them per province. In this way, the different provincial trees can be compared. In addition, the same significance test is performed for the vehicle type combinations. In this test, j is replaced by the road characteristics from the given perspective. The results of these regression trees can answer the third research question.

5. Results

As the methodology has described, in this research, the crash rates are divided into perspectives of motor vehicles, freight vehicles and bicycles. This approach will clarify that, e.g., certain roads are less safe for cyclists than for motor vehicles. Also, for example, cyclists' safety is dominated by crashes involving a particular vehicle. This chapter will reflect these perspectives by covering the results of crash rates across and among different vehicle types, followed by the results of the regression trees to identify significant patterns in road characteristics. Furthermore, the section will examine the provincial differences in crash rates where the most striking results of both the crash rates of the vehicle matrixes per province and the first splits based on the national regression tree per province are presented.

5.1 Involvement of Vehicle Types

Figure 9 shows the results of the vehicle matrix for the national crash rate, revealing that certain vehicles are more frequently involved in crashes with other specific vehicles in relation to the respective distance travelled. The perspective in this figure indicates that the corresponding distance travelled was used for the specific vehicle type. The figure shows that cyclists are the most engaged in crashes per distance travelled, with motor vehicles being the most common opposing party; the crash rate of cyclists is 332 crashes per billion bicycle kilometres. This high number is followed by one-sided crashes of cyclists, with a crash rate of 119 crashes per billion bicycle kilometres, which is significantly lower than the highest crash rate. The figure also shows that freight traffic is among the fewest crashes per distance travelled and, thus, the safest of the three perspectives. However, in freight crashes, the opposing party mainly includes motor vehicles and cyclists, with crash rates of 25 and 13 crashes per billion freight vehicle kilometres, respectively.

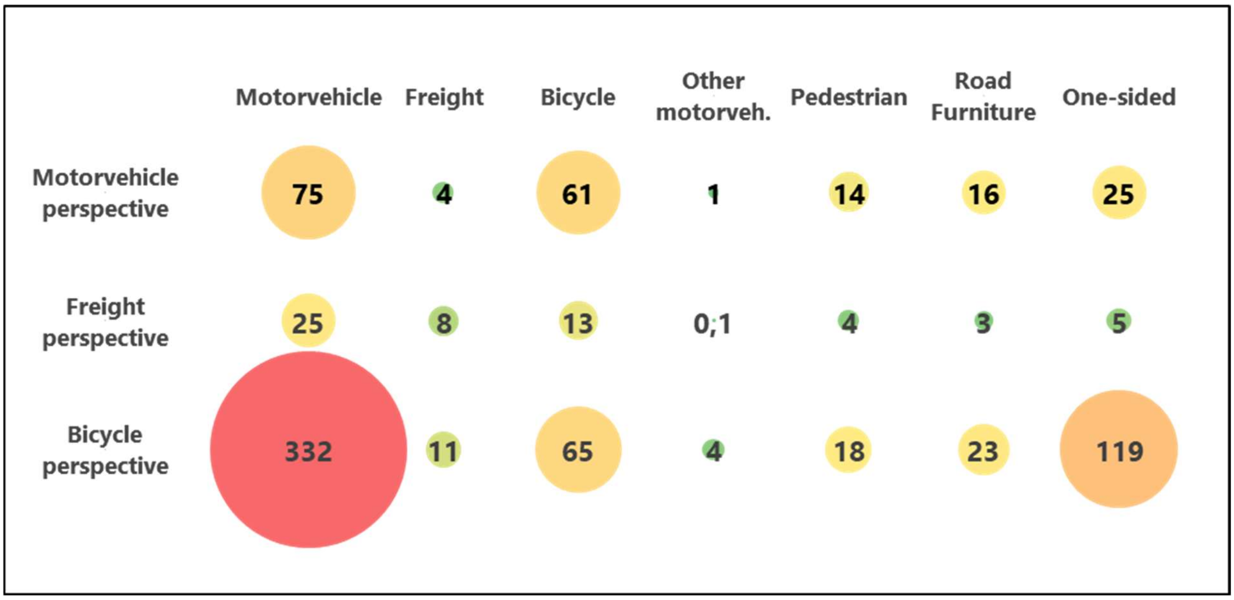

Figure 9: Vehicle Type Matrix
A perspective shows that for the crash rate, the exposure of the allocated vehicle type is used, i.e., the number of crashes between vehicle types per billion vehicle kilometres of that particular vehicle type.

This section presents the results in relevant detail. First, the motor vehicle perspective is given, followed by the freight vehicle perspective, and this section ends from the bicycle perspective.

5.1.1 Motor vehicle perspective

The crashes per billion motor vehicle kilometres (i.e. motor vehicle perspective) show the most considerable risk of crashes with other motor vehicles leading to injury or death, namely 75 crashes per billion motor vehicle kilometres. This is the third-highest crash rate in the table compared to other vehicle type combinations. As motor vehicles cover many vehicle kilometres (360 billion vehicle kilometres per year in the Netherlands), the high crash rate is probably related to this since the vehicle kilometres of the opposing party involved are not considered. From the perspective of the motor vehicle, cyclists are also often involved in accidents, with 61 crashes per billion motor vehicle kilometres.

The relatively small risk of a motor-freight vehicle crash appears to be 4 crashes per billion motor vehicle kilometres. This is remarkable, given that road users in motor vehicles and freight vehicles generally share the network in most places. The lowest crash rate is with other types of motor vehicles (agricultural or unknown vehicles due to a hit-and-run vehicle), with 1 crash per billion motor vehicle kilometres.

5.1.2 Freight perspective

The overall picture of the crashes per billion freight kilometres (i.e. freight perspective) shows relatively low figures compared to the other perspectives. This indicates that freight vehicles have fewer injuries and fatal crashes per billion vehicle kilometres. This is remarkable, given that a relatively low freight exposure on the non-primary road network is present.

According to a study by SWOV, while the total number of freight kilometres on the Dutch road network is lower than that of motor vehicles, the distance travelled per freight vehicle is 3.7 times greater than that of motor vehicles (SWOV, 2020). This finding is interesting since it could be expected that more severe crashes would occur due to the size and weight of freight vehicles. However, this does not seem to impact the crash rate significantly. From the freight perspective, the highest risk of injury and fatal crashes involves motor vehicles, with 25 crashes per billion freight vehicle kilometres. Figure 9 also shows that crashes involving freight and other motor vehicles are rare, with 0.1 crashes per billion freight kilometres. The crash rate between freight vehicles and vulnerable road users (pedestrians with 4 crashes per billion freight kilometres and cyclists with 13 crashes per billion freight kilometres) is expected to be higher, given the lower likelihood of no injuries or crashes between these vehicle types.

5.1.3 Bicycle perspective

The high crash rates per billion bicycle kilometres (i.e. bicycle perspective) stand out in this table. This shows bicycles are most vulnerable per distance travelled on the Dutch network. Moreover, motor vehicles are the most significant contributor, with a crash rate of 332 crashes per billion bicycle kilometres. Given the vulnerability of cyclists, it can be expected that they are more exposed to injuries and fatalities. The second highest crash rate is seen for one-sided bicycle crashes, with 119 crashes per billion bicycle kilometres. These crashes often involve vulnerable groups, such as older people, who may fall due to instability. This argument could also be used for the crash rate among cyclists, which shows a crash rate of 65 crashes per billion bicycle kilometres. In addition, the trend for freight and agricultural vehicles continues in crashes from cyclists' perspective since the crash rate involving freight or agricultural vehicles is low, 11 and 4 crashes per billion bicycle kilometres, respectively. This could also be seen from the perspective of freight drivers, where the crash rates were expected to be higher between freight and bicycles.

5.2 Influence of Road Characteristics

In addition to the involvement of different vehicles, road characteristics also influence road safety, as described in the literature review (chapter 2). This section presents the results of variable distributions of road characteristics, followed by the regression tree from the motor vehicle perspective, excluding bicycle crashes. Next, the regression tree results of a combination of crashes between motor vehicles and cyclists from the motor vehicle perspective are presented. This is followed by the results of the regression tree of crash combination between motor vehicles and bicycles per billion bicycle kilometres. In the end, this section concludes with the results of the bicycle perspective, excluding motor vehicle crashes.

5.2.1 Variable Distributions

Before the regression trees are presented, the national distributions of the different road characteristics are shown, and the different road characteristics are discussed.

Speed limit

From the perspective of motor vehicles without bicycle crashes, it can be seen that a lower speed limit is more unsafe than a higher speed limit, as shown in Figure 10. Roads with a speed limit of 12 kph (i.e. special residential roads) are the most unsafe, with a crash rate of 220 crashes per billion motor vehicle kilometres, and this unsafety decreases to a crash rate of 51 crashes per billion motor vehicle kilometres for 70 kph. It can also be seen that the risk of a motor vehicle crash between 70 kph and 80 kph remains about the same, where 80 kph shows a crash rate of 49 crashes per billion motor vehicle kilometres. For crashes between motor vehicles and bicycles, a different distribution of crash rates can be seen from the perspective of the motor vehicle. Here, 30 kph is higher than 12 kph, 216 and 167 crashes per billion motor vehicle kilometres, respectively. For speed limits 70 and 80 kph, crash rates seem to be heading towards zero crashes per billion motor vehicle kilometres due to the low activity of bicycles on these roads. Interestingly, this is not the case for 50 and 60 kph; the number of bicycle kilometres on these roads is high, at 37 billion kilometres per year. These speed limits show one of the lowest crash rates in the figure.

For the same type of crashes, but with bicycle kilometres, a high crash rate of 630 crashes per billion bicycle kilometres can be seen, which is the highest in this figure. This crash rate is associated with a speed limit of 50 kph. This high crash rate is explained by the high number of motor vehicle kilometres travelled on these roads in the Netherlands, namely 190 billion kilometres per year. From this perspective, the other crash rates show that the speed limit does not necessarily impact the crash rate.

From the cyclist's perspective, with no motor vehicle crashes, the highest crash rate is also 50 kph, at 276 crashes per billion bicycle kilometres. The other speed limits show a relatively equal crash rate; this suggests that motor vehicle speed does not impact cyclist-only crashes unless the speed limit is 50 kph.

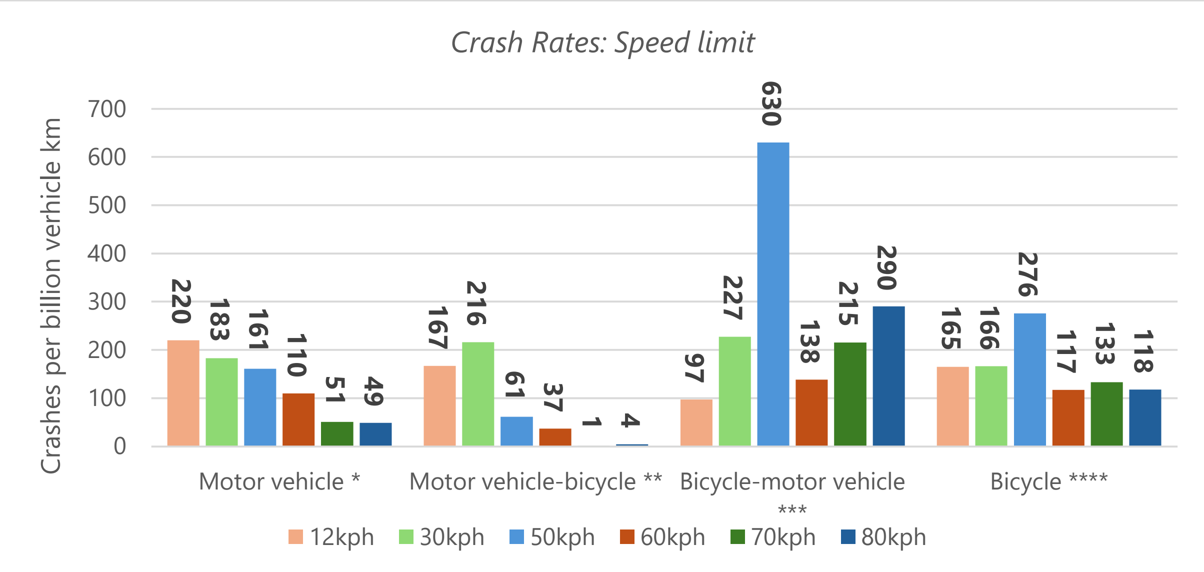

Figure 10: Estimation of Crash Rates by Speed Limit
** Motor vehicle crashes without bicycle involvement, per billion motor vehicle kilometres*
*** Crashes between motor vehicles and bicycles, per billion motor vehicle kilometres*
**** Crashes between motor vehicles and bicycles, per billion bicycle kilometres*
***** Bicycle crashes without motor vehicle involvement, per billion bicycle kilometres*

Bicycle Facility

From the perspective of motor vehicle crashes without cyclist involvement, it can be seen that the situation on roads with mixed traffic poses the most risks, with 137 crashes per billion motor vehicle kilometres (Figure 11). The crash rate is the lowest when cyclists are prohibited, i.e., motor vehicles and cyclists do not meet, with 78 crashes per billion of motor vehicle kilometres. Crash rates for motor vehicle-bicycle crashes show a similar picture. Mixed traffic shows the highest crash rates followed by bicycle suggestion lanes, with 162 and 139 crashes per billion motor vehicle kilometres, respectively. Interestingly, bicycle-motor vehicle crash rates are the highest for bicycle-suggested lanes (353 crashes per billion bicycle kilometres), followed by mixed traffic (277 crashes per billion bicycle kilometres). This ratio is the same for bicycle crashes without motor vehicle involvement, namely 168 crashes per billion bicycle kilometres for mixed traffic and 214 crashes per billion bicycle kilometres for bicycle-suggested lanes.

In some cases, bicycle facilities do not show crashes per kilometre driven. This discrepancy arises from the method employed in merging datasets. Crash rates have only been calculated for the road network concerning motor vehicles. Since no intensities are known for cyclists on motor vehicle roads with a bicycle path or no bicycle facilities, the crash rate on these types of roads is 0 crashes per billion kilometres. This fact can also be seen in the subsequent perspectives.

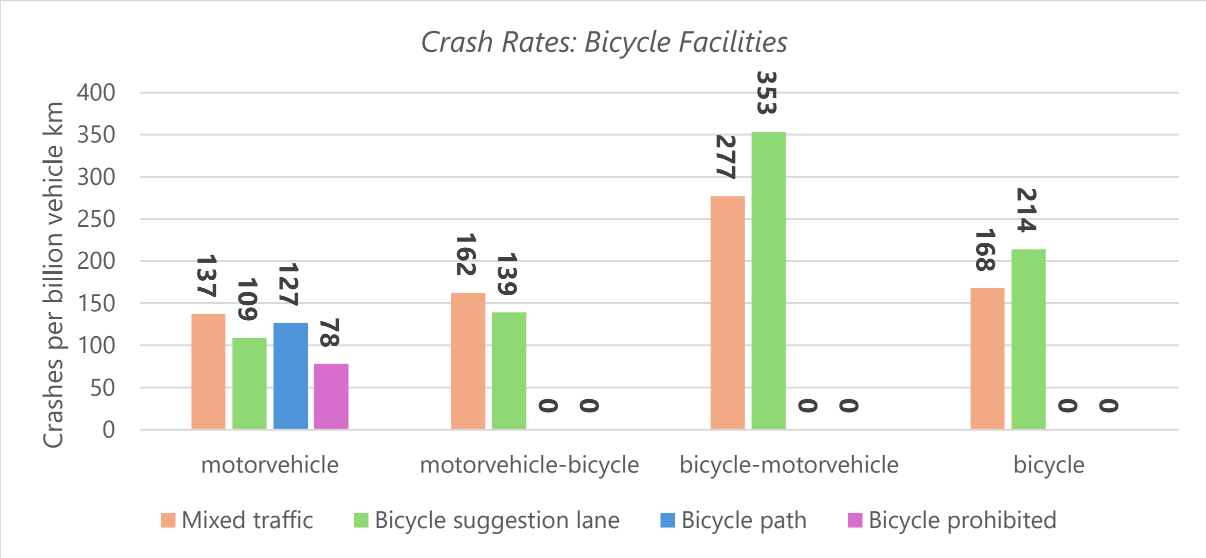

Figure 11: Estimation of Crash Rates by Bicycle Facilities

Number of Lanes

The crash rate from the perspective of motor vehicles not involving cyclists is significantly higher on single-lane roads (118 crashes per billion motor vehicle kilometres) than on roads with more than one lane (39 crashes per billion motor vehicle kilometres), as seen in Figure 12. On single-lane roads, 54 crashes between motor vehicles and cyclists per billion motor vehicle kilometres occur, while on roads with more than one lane, this number is almost negligible (0.48 crashes per billion motor vehicle kilometres). This substantial difference highlights that cyclists on single-lane roads are at a higher risk of colliding with motor vehicles.

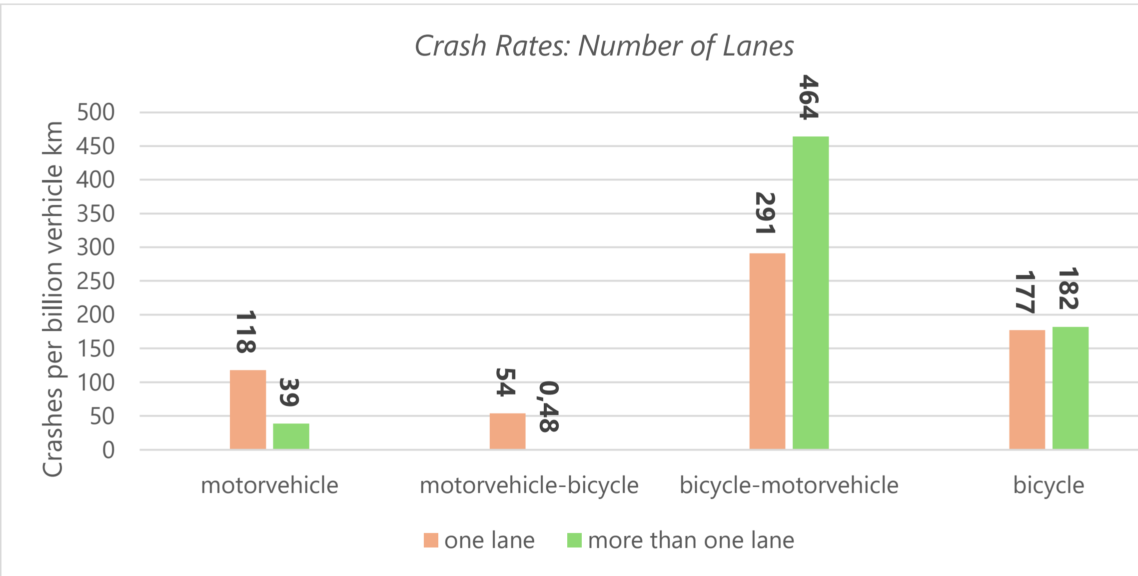

Figure 12: Estimation of Crash Rates by Number of Lanes

From the cyclist's perspective, the situation is strikingly different when comparing crashes between cyclists and motor vehicles. On roads with more than one lane, the number of crashes per distance travelled is notably higher (464 crashes per billion bicycle kilometres) than on roads with one lane (291 crashes per billion bicycle kilometres). This may be because the distance travelled by cyclists is very low (0.06 billion bicycle kilometres per year) on multi-lane roads. However, intersections between cyclists and multi-lane traffic may be the cause here. The difference between single-lane roads (177 crashes per billion bicycle kilometres) and roads with more than one lane (182 crashes per billion bicycle kilometres) is small for crashes involving only cyclists. This suggests that the number of lanes has minor impact on bicycle crashes without the involvement of motor vehicles.

Degree of Urbanisation

Figure 13 shows that the distribution of the degree of urbanisation per perspective is the same, i.e. strongly urbanised areas produce higher crash rates than when an area is moderately or not urbanised, with the latter being the safest. The highest crash rates are seen for crashes between motor vehicles and cyclists per billion bicycle kilometres, with 371 crashes per billion bicycle kilometres in strongly urbanised areas. In addition, it can be seen that the second highest crash rate is seen from the same perspective, this time for moderately urbanised areas, being 285 crashes per billion bicycle kilometres. This is remarkable considering that from other perspectives, the crash rate in strongly urbanised areas is thus lower. The lowest crash rates are seen for crashes between motor vehicles and cyclists per billion motor vehicle kilometres, with the lowest being 17 crashes per billion motor vehicle kilometres in not urbanised areas. In addition, the second lowest crash rate is also from this perspective, namely for moderately urbanised areas, with 45 crashes per billion motor vehicle kilometres.

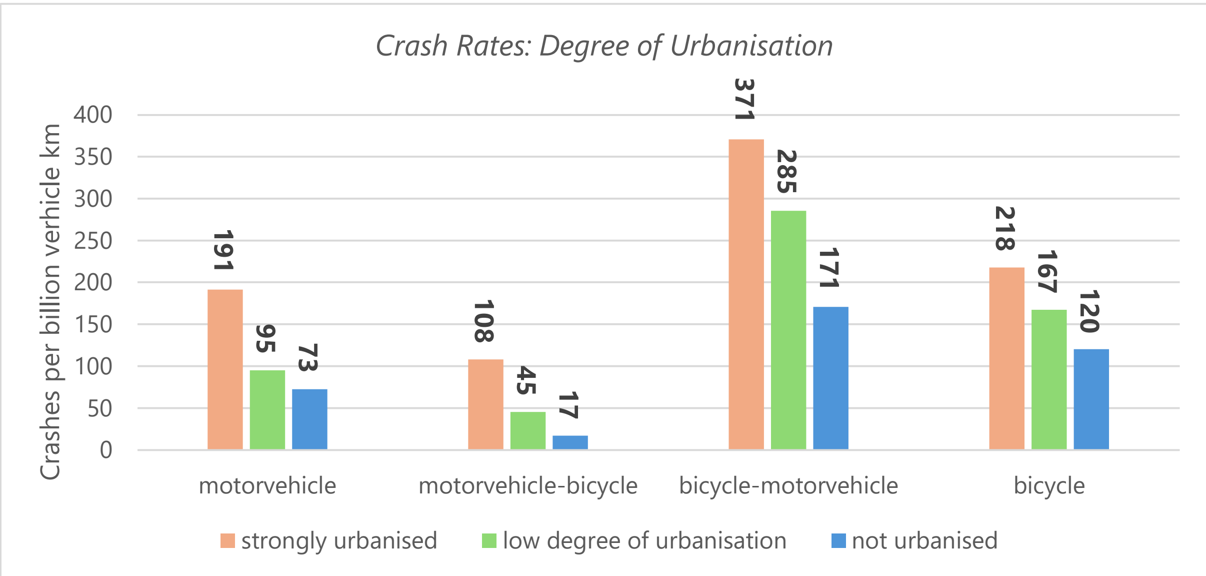

Figure 13: Estimation of Crash Rates by Degree of Urbanisation

One and two-way roads

Figure 14 shows that one-way roads are riskier from the cyclists' perspective, both in interactions with motor vehicles and crashes without motor vehicles. The highest crash rate can be observed in crashes with motor vehicles, with 381 crashes per billion bicycle kilometres. The ratio that one-way roads are riskier than two-way roads is also true for motor vehicles without cyclists; here, the risk for one-way roads is 121 crashes per billion motor vehicle kilometres and for two-way roads, 104 crashes per billion motor vehicle kilometres. From a motor vehicle perspective, the ratio is the opposite, where cyclists are involved in crashes. From this perspective, two-way roads are riskier than one-way roads, with 57 crashes per billion motor vehicle kilometres and 29 crashes per billion motor vehicle kilometres, respectively.

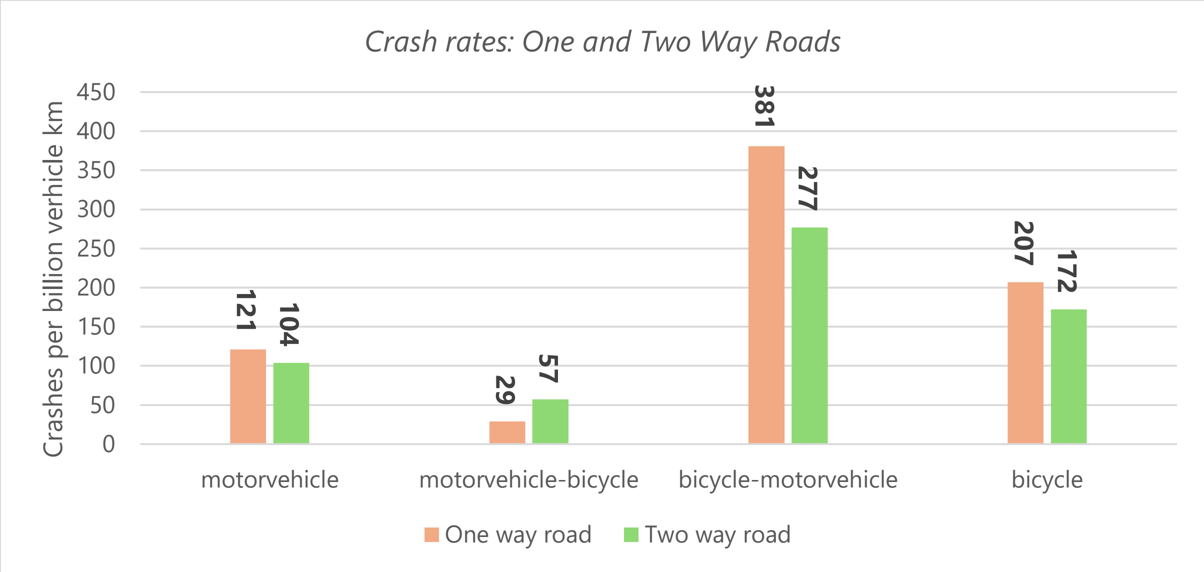

Figure 14: Estimation of Crash Rates by One and Two-Way Roads

Freight Share

From the perspective of motor vehicles without bicycle crashes, an extremely high crash rate of 9090 crashes per billion motor vehicle kilometres can be seen when no freight traffic is present, as shown in Figure 15. Possibly, this is due to the low and unrealistic exposure of 0.15 billion kilometres, which makes the crash rate very high. However, it can be seen that the crash risk decreases when there is a higher proportion of freight in traffic. For motor vehicle-bicycle crashes, an extremely high crash rate can also be seen where no freight traffic is present (4251 crashes per billion motor vehicle kilometres); this is due to the same reason as the perspective has not changed, and thus, the same exposure is used. Also, the trend compared to the crash rate without bicycle crashes has remained the same: increased freight creates a less risky traffic situation.

For motor vehicle-bicycle crashes the crash rate seems to increase with a higher share of freight traffic. Where the crash rate for no freight is the lowest, with 179 crashes per billion bicycle kilometres, for around average freight share; the highest, with 339 crashes per billion bicycle kilometres and the below and above average freight share in between, with 222 and 304 crashes per billion bicycle kilometres, respectively. For bicycle crashes without motor vehicle involvement, it can be seen that below-average traffic share causes the lowest risk with 151 crashes per billion bicycle kilometres). Notably, an around-average proportion of freight traffic causes the highest crash rate (186 crashes per billion bicycle kilometres). These other figures seem stable.

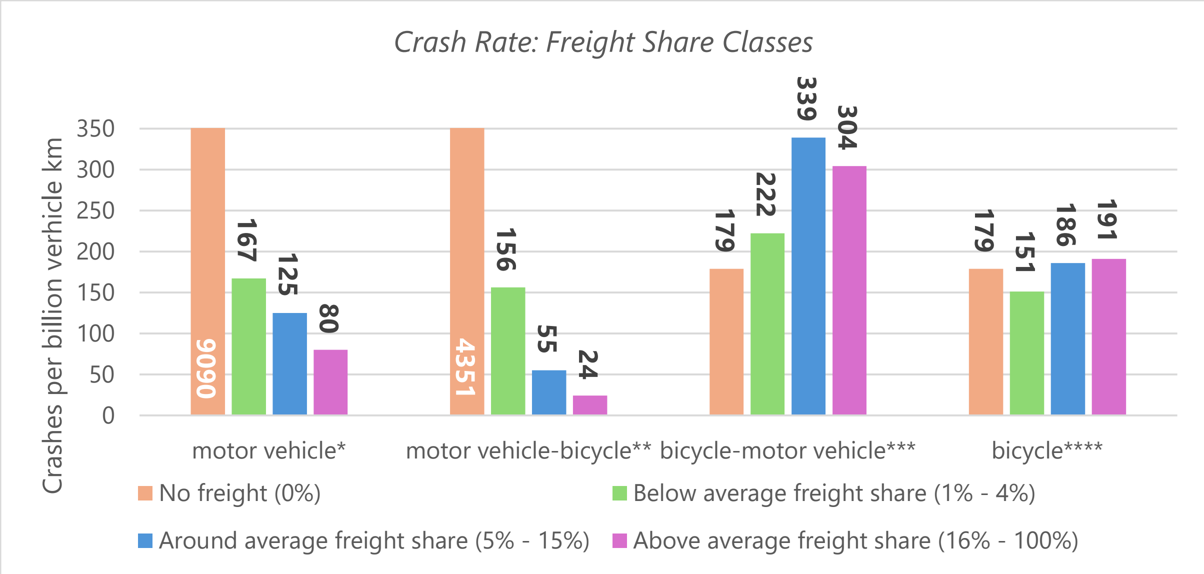

Figure 15: Estimation of Crash Rate by Freight Share Classes

5.2.2 Regression Trees

Regression trees were used to determine the most impactful road characteristics and the behaviour of the crash rate when road characteristics were combined. This method is used since regression trees have proven to be highly effective in solving problems and their ease of interpretation (Polzer, 2024). Regression trees are built up in different layers. The first levels of the regression tree are the variables that affect the crash rate most. On the other hand, there are fewer significant variations in the crash rate at deeper levels in the tree. The tree will end at a leaf when the proportion of vehicle kilometres is too low (0.1% of the total vehicle kilometres) that the calculated crash rate becomes unreliable.

Motor vehicle crashes without bicycle involvement per billion motor vehicle kilometres

Figure 16 shows the regression tree for the crash rate of motor vehicle crashes without bicycle crashes. A legend is shown in Table 7 to understand the meaning of the symbols in the regression trees. The first split from this perspective is for the speed limit. The regression tree shows that for a motor vehicle, the risk is higher on roads lower than or equal to 60 kph with a crash rate of 171.5 crashes per motor vehicle distance travelled than on roads higher than or equal to 70 kph with a crash rate of 54.5 crashes per motor vehicle distance travelled. The first three levels of both sides will be further explored.

60 kph roads or lower

From the roads with a speed limit below or equal to 60 kph, the degree of urbanisation seems to be the next most impactful split, with strongly urbanised areas containing more risk (crash rate of 247.7) than the not strongly urbanised areas in the Netherlands (crash rate of 125.6). When looking deeper into this branch, it can be seen that roads with below-average freight traffic where the speed limit is higher than 50 kph carry more risk than roads with a speed limit of 30 or lower.

Table 7: Legend of the Regression Trees Symbols

Symbol	Description	Symbol	Description
	Speed limit below or equal to e.g. 30 kilometres per hour. This figure can also be displayed at other speed limits.		Speed limit above or equal to e.g. 50 kilometres per hour. This figure can also be displayed at other speed limits.
	Degree of urbanisation class: not urbanised.		Degree of urbanisation class: moderately and strongly urban, i.e. urbanity is higher than non-urban.
	Degree of urbanisation: not urbanised and moderately urbanised, i.e. the degree of urbanisation is lower than strongly urbanised		Degree of urbanisation: strongly urbanised.
	Share of freight traffic is below 4%, classified as below average share of freight traffic and no freight traffic.		Share of freight traffic is higher than 4%, classified as an all-around average and above-average share of freight traffic.
	Share of freight traffic is below 15%, classified as around average and below average share of freight traffic and no freight traffic, i.e. not above average.		Share of freight traffic is higher than 15%, classified as above-average freight traffic.
	Two-way road.		One-way road.
	One lane road.		Two lanes available.
	Bicycle suggestion lane available.		No bicycle suggestion lane available, other bicycle facilities are possible if this has not occurred in the tree before.
	Bicycle facilities are available, all types of bicycle facilities are possible if this has not occurred in the tree before.		No bicycle facilities available, this means that there is no bicycle path, bicycle suggestion lane or mixed traffic.
	Mixed traffic, cyclists and motor vehicles travel on the same carriageway.		No mixed traffic, cyclists ride visually or physically separated from the motor vehicles. This means that both no bicycle facilities can be present, a bicycle path and a bicycle suggestion lane can be present.
	No bicycle path available, this means that mixed traffic, bicycle suggestion lane as well as no bicycle facilities can be available.		Cycle path available, which is located along the road for motor vehicles.

This is striking given that the national picture shows that roads with a speed limit of lower than 30 kph are the riskiest for crashes.

The next most impactful variable is the share of freight traffic, with <4% share of freight at a higher crash rate (189.9) and >4% share of freight at a lower crash rate (118.1). This is remarkable, given that, expectedly, more freight would make roads less safe. For the strongly urbanised areas, the

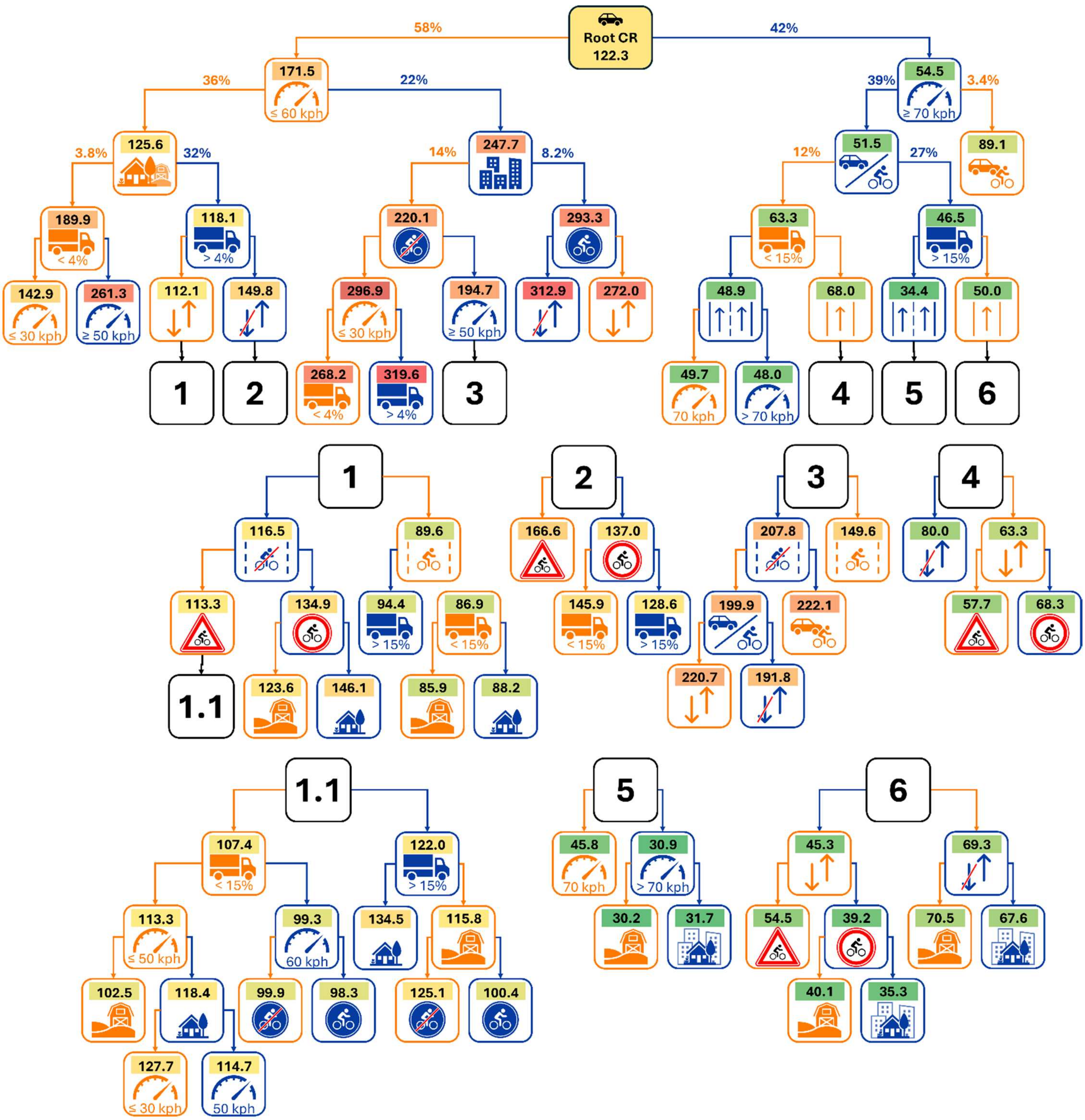

Figure 16: Regression Tree: Motor Vehicles' Perspective, Without Bicycle Crashes

presence of bicycle paths seems to be an impactful variable, with a crash rate of 220.1 when there is mixed traffic, a suggestion lane or no bicycle facilities and a crash rate of 293.3 when there is a bicycle path. Remarkably, given that the safety of cycle paths should be positive from a road safety point of view. However, this does not seem to be the case from the perspective of motor vehicles.

In addition, it is striking at a subsequent split of roads without cycle paths that roads with a speed limit lower than or equal to 30 kph show a higher crash rate (296.9) than 50 and 60 kph (192.7). Roads with 30 kph and below are expected to be safer for motor vehicles because the speed is lower. However, this trend is also shown in the national distributions. Since motor vehicle-bicycle crashes are excluded from the crash rate, it appears to be due to many single-vehicle crashes and crashes involving pedestrians. The higher proportion of pedestrians seems to be a plausible explanation, given that roads with a speed limit of 30 kph or lower often have more pedestrians than roads with a speed limit of 50 and 60 kph.

70 kph roads or higher

From the roads with a speed limit of 70 kph or higher, the split to the presence of mixed traffic seems to be the subsequent most impactful variable. Roads with mixed traffic are riskier (89.1 crashes per billion motor vehicle kilometres) than roads that do not facilitate mixed traffic (crash rate of 51.5 crashes per billion motor vehicle kilometres). After the roads with mixed traffic, no further division is made because these roads are uncommon and, therefore, have a too-low distance travelled for further splits. This shows that there are few roads with mixed traffic and higher than 70 kph (0.37 billion vehicle kilometres); from a road design point of view, this is logical since roads at this speed are often a separation between bicycle and motor vehicle. However, there are still plenty of rural roads with a speed limit of 80 kph and mixed traffic (13,10 billion vehicle kilometres), which explains why this split is being done in the first place. This crash rate is also the highest from the first split of the root. For roads with no mixed traffic, i.e., cycle paths, bicycle suggestion lanes or no bicycle facilities at all, the most impactful variable to make the split is the share of freight traffic. When the share of freight traffic is higher than 15%, the crash rate is lower (46.5 crashes per billion motor vehicle kilometres) than on roads with a share of freight traffic lower than 15% (63.3 crashes per billion motor vehicle kilometres).

Extreme crash rates

The highest value from the branch to 60 kph or lower is a road in a strongly urbanised area, without cycle path, a speed limit is less than or equal to 30 kph and more than 4 percent freight traffic is present. The highest risk is 319.6 crashes per billion motor vehicle kilometres. A low speed and a strongly urbanised area seem to create a high risk. On top of that, with an average share of freight, the risk becomes even more significant. The second highest value from the split to 60 kph or lower for motor vehicles is a strongly urbanised area road with a cycle path and a one-way rule. The crash rate of this is 312.9 crashes per billion motor vehicle kilometres. This figure is quite close to the highest crash rate.

The lowest value from the split to 60 kph or lower is a road in moderately urbanised areas, with an all-around average freight share with a bicycle suggestion lane and two traffic coming from two directions. Notably, the crash rate is almost the same as the highest value of the other branch of the regression tree. The lowest value from the split to 70 kph or higher is a road with a high share of freight traffic where two or more lanes are present and a not urbanised area. The crash rate here is 31 crashes per billion motor vehicle kilometres.

Crashes between motor vehicles and bicycles per billion motor vehicle kilometres

The first division for motor vehicle and bicycle crashes where the perspective of the motor vehicle is considered is between a road with mixed traffic and a road without mixed traffic, i.e., a bicycle suggestion lane, cycle path or no bicycle facilities (Figure 17). The crash rate of mixed traffic is higher (192.6 crashes per billion motor vehicle kilometres) than where there is no mixed traffic (16.5 crashes per billion motor vehicle kilometres). This vast difference in crash rate shows that this split is the most impactful.

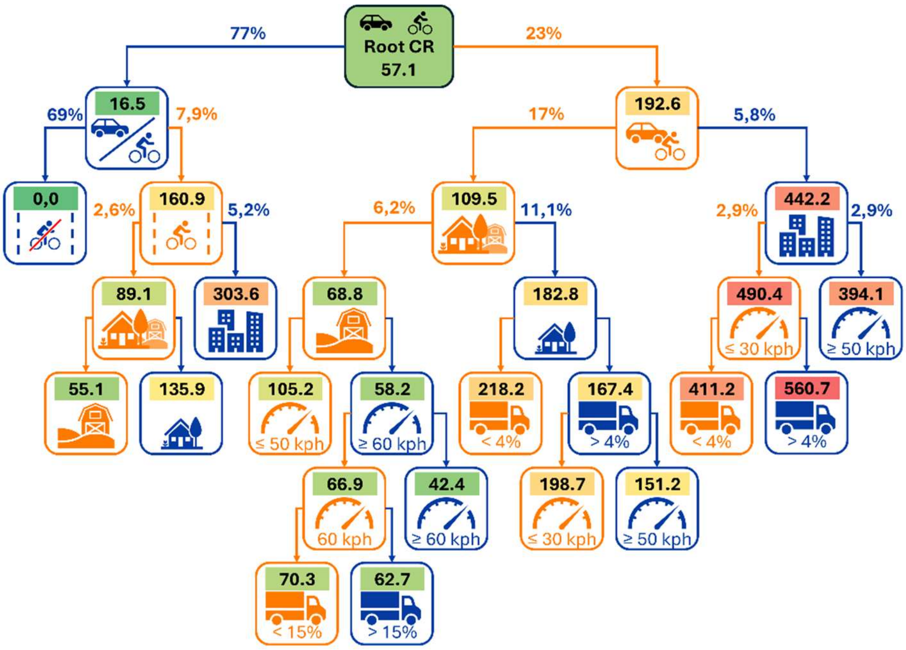

Figure 17: Regression Tree: Motor Vehicles' Perspective, Motor Vehicle-Bicycle Crashes

Not mixed traffic

The next split for roads with no mixed traffic is between a road with a bicycle suggestion lane and no bicycle suggestion lane. A road with no bicycle suggestion lane and mixed traffic does is not related to crashes involving motor vehicles and cyclists, so this crash rate is 0. This is because on roads without bicycle facilities, no bicycle kilometres are available and these vehicle types do not encounter each other. However, it appears that enough motor vehicle kilometres are driven on this type of road, which is why this breakdown is made. Where there is a crash rate, it is for roads with bicycle suggestion lanes; here, the crash rate is 160.9.

A further split is between strongly, moderately and not urbanised areas, with strongly urbanised areas showing a crash rate of 303.6, moderately urbanised areas a crash rate of 135.9, and not urbanised areas showing 55.1. This difference is huge, so in strongly urbanised areas, there is an extra risk of crashes between motor vehicles and bicycles. This can be explained logically because more cyclists participate in traffic in strongly urbanised areas.

Mixed traffic

The next split for mixed-traffic roads is between strongly urbanised areas and those not strongly urbanised (i.e. not and moderately urbanised). As the previous paragraph shows, the crash rate for strongly urbanised areas is higher (442.2) than for not strongly urbanised areas (109.5). This can be explained by more cyclists participating in the network in strongly urbanised areas. The same argument can be used for the next split between not urbanised and moderately urbanised areas. Not urbanised areas are less risky (68.8) than moderately urbanised areas (182.8).

The next split for roads with mixed traffic in a strongly urbanised area is between the 30 kph or lower speed limit and 50 kph or higher. Roads with 30 kph or lower put the road user at greater risk (490.4) than 50 kph or higher (394.1). This trend can also be seen in national figures, where a higher crash rate is shown at a lower speed limit. Looking even further at roads with a speed limit of 30 kph and lower, the next split is between below-average freight traffic and around average freight traffic or higher, with the former, however, still very high, being the safest (411.2) compared to the other (560.7). The crash rate of all-around average freight traffic or higher is also the highest for vehicle-cyclists' crashes per billion motor vehicle kilometres.

Crashes between motor vehicles and bicycles per billion bicycle kilometres

From the cyclist's perspective, where motor vehicles are also involved in crashes, the first split is between the speed limit for motor vehicles of 50 kph or lower and 60 kph or higher (Figure 19). Where 50 kph or lower gives a crash rate of 398.9 crashes per billion bicycle kilometres, and for 60 kph or higher, 178.4 crashes per billion bicycle kilometres, roads with a lower speed carry more risk for cyclists. This same observation has been made from the perspective of motor vehicles, where there is a higher risk of a crash at lower speeds. Since the vehicle kilometres of the motor vehicles are not used for this crash rate, the number of motor vehicle kilometres could significantly influence the risk for cyclists.

50 kph or lower

After the split of 50 kph or lower, the next is between the speed limit of 30 kph and below 50 kph. This, again, shows that the speed limits for motor vehicles greatly impact the risk that cyclists are exposed to. However, between 30 kph and 50 kph, the faster speed limits are less safe, with a crash rate of 741.9 crashes per billion bicycle kilometres, compared to the lower speed limits with a crash rate of 269.8 crashes per billion bicycle kilometres. Notably, the motor vehicle kilometres for 50 kph roads are also considerably higher, by a factor of 3.7, which may also affect cyclists' risk.

The degree of urbanisation is the following splits for a speed limit of 30 kph or lower and 50 kph. Where for 30kph or lower, a split had been made between not urbanised and urbanised (moderately and strongly urbanised) areas, the crash rate of the latter is higher (276.4 crashes per billion bicycle kilometres) than the former (200.3 crashes per billion bicycle kilometres). For 50 kph roads, the distinction between strongly urbanised and not strongly urbanised areas has

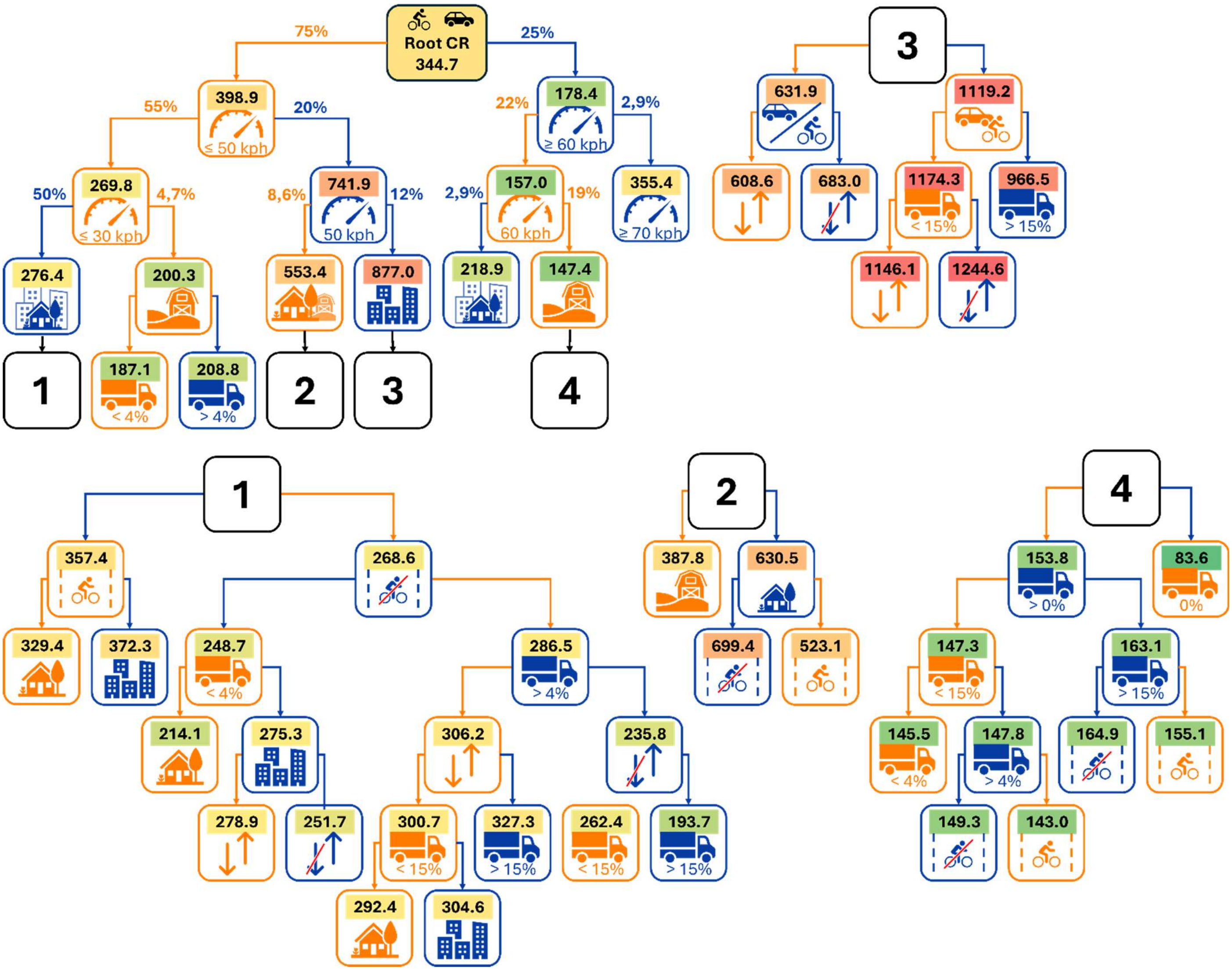

Figure 18: Regression Tree: Bicycles' Perspective, Motor Vehicle-Bicycle Crashes

been made. Crashes in strongly urbanised areas are more likely between cyclists and motor vehicles per billion bicycle vehicle kilometres (877.0 crashes per billion bicycle kilometres) than in not strongly urbanised areas (553.4 crashes per billion bicycle kilometres). Both differences may be related to the degree of urbanisation classes difference in motor vehicle kilometres, which possibly has a high correlation.

60 kph or higher

As for 50 kph or lower, the next most impactful split for 60 kph or higher is the speed limit, between 60 kph and 70 kph or higher. Again, it can be seen that the lower speed limit of 60 kph is a lower risk for cyclists (157.0 crashes per billion bicycle kilometres) than the higher speed limit of 70 kph or higher (355.4 crashes per billion bicycle kilometres); this is different from the trend from the perspective of motor vehicles. This shows that it is not evident whether a lower or higher speed limit of the motor vehicle is safer for the cyclist. However, in this way, the speeds are easy to compare, so it turns out that a road with 50 kph is the most unsafe for the cyclist, continued by 70 kph or higher, 30 kph or lower, where 60 kph is the safest. The reason could be the layout of the various roads. In addition, the number of motor vehicle kilometres may significantly contribute to the crash rates.

The branch to 70 kph or higher is also a leaf of the regression tree, which means that the number of bicycle vehicle kilometres becomes too small to create new child leaves. The branch to 60 kph is split based on the degree of urbanisation. Not urbanised areas are less risky for cyclists (147.4 crashes per billion bicycle kilometres) than urbanised areas (218.9 crashes per billion bicycle kilometres).

Extreme crash rates

The regression tree shows extremely high crash rates, the highest among all other regression trees. This means the cyclist is most at risk of a crash if a motor vehicle is involved. The combination of a road with a speed limit of 50 kph within strongly urbanised areas where there is mixed traffic, not above average share of freight traffic and where the motor vehicles travel in one direction is the most dangerous for cyclists with a staggering crash rate of 1244.6 crashes per billion bicycle vehicle kilometres. The previous split between mixed traffic and separated traffic seems to have the most influence on this. The splits after this, the share of freight traffic and one-way streets, increase the risk less significantly.

From the cyclist's perspective, the lowest crash rate between bicycles and motor vehicles is on roads where 60 kph is allowed for motor vehicles, in a not urbanised area, and where there is no freight traffic (with a crash rate of 83.6 crashes per billion bicycle kilometres). The combination of no freight traffic and not urbanised areas seems decisive here.

Bicycle crashes without motor vehicle involvement per billion bicycle kilometres.

The first split for the crash rate from the cyclist's perspective that does not involve a motor vehicle is between the degree of urbanisation (Figure 19). Strongly urbanised areas show a higher crash rate (267.2 crashes per billion bicycle kilometres) than not strongly urbanised areas (173.6 crashes per billion bicycle kilometres). This indicates that the most impactful difference in the crash rate is the degree of urbanisation. This fact seems intuitive, given that due to the busier areas, the cyclist has more mental load than in less crowded areas such as not urbanised areas due to multiple other road users, more intersections, possibly parked vehicles along the road or various objects.

Not strongly urbanised

The next split after not strongly urbanised areas is also for the degree of urbanisation, i.e. not and moderately urbanised areas. This immediately shows that the degree of urbanisation, in general, has a great impact on the risk that a cyclist is exposed to in situations in which no motor vehicle is involved. It shows that a not urbanised area is safer for cyclists (146.7 crashes per billion bicycle kilometres) than a moderately urbanised area (204.4 crashes per billion bicycle kilometres).

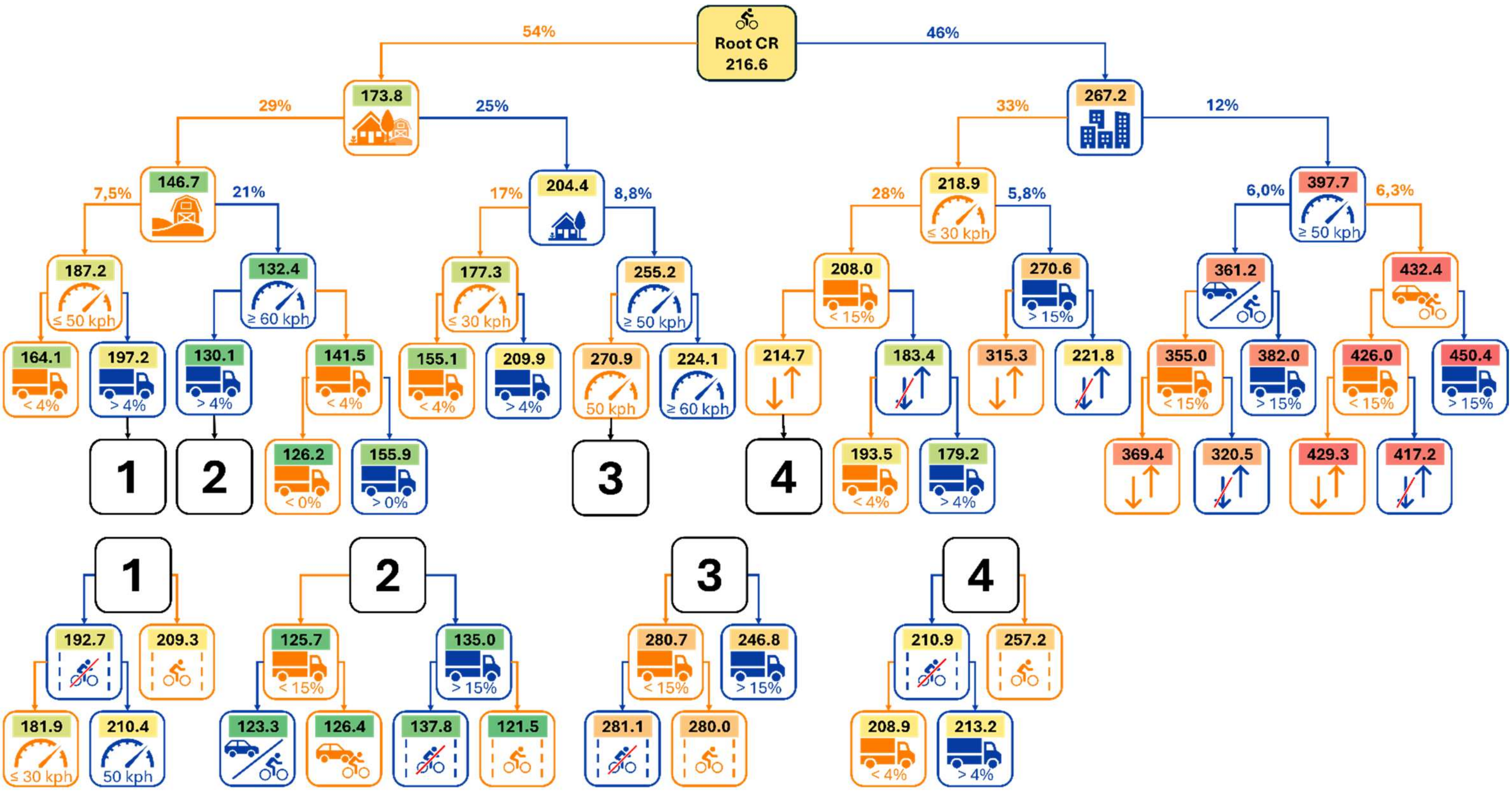

Figure 19: Regression Tree: Bicycles' Perspective, Without Motor Vehicle Crashes

The split is made based on speed limit after the split into a not urbanised area. Roads where the speed limit for motor vehicles is 50 kph or lower are riskier for cyclists (187.2 crashes per billion bicycle kilometres) than 60 kph or higher (132.4 crashes per billion bicycle kilometres). This shows that motor vehicles indirectly influence a crash in which only a cyclist is injured or killed since the speed limit for motor vehicles is impactful. When looking deeper into the regression tree, it seems that roads with a speed limit of 60 kph, a high share of freight traffic, and a bicycle suggestion lane are the safest for cyclists in this regression tree (121.5 crashes per billion bicycle kilometres). Although the split between the share of freight traffic shows that a high share entails more risk, the combination between a high share of freight traffic and a bicycle suggestion lane is less risky than around average freight traffic and separated traffic (123.3 crashes per billion bicycle kilometres). When a road is located in a moderately urbanised area, the most impactful split is also the speed limit of motor vehicles. However, for moderately urbanised areas, there is a split between 30 kph or lower and 50 kph or higher roads, with the former being less risky (177.3 crashes per billion bicycle kilometres) than the latter (255.2 crashes per billion bicycle kilometres).

Strongly urbanised

The next split after a strongly urbanised area is between the speed limits of 30 kph and below and 50 kph and above, with 30 kph showing a lower crash rate of 218.9 than that of 50 kph and above, which is 397.7 crashes per billion bicycle kilometres. This is similar to the trend shown on the other side of the tree, where slower speed limits provide more safety.

Furthermore, the regression tree shows that when the speed limit is 30 kph or lower, the following most impactful variable is the share of freight traffic, between below 15% and higher than 15%.

Here, a higher share of freight traffic (270.6 crashes per billion bicycle kilometres) is more dangerous for cyclists than a lower share of freight traffic (208.0 crashes per billion bicycle kilometres). This is in line with the national distribution, where a higher share of freight traffic causes a higher rate of crashes.

When a road has a speed limit for motor vehicles at 50 kph, the next split is between mixed traffic and no mixed traffic. Mixed traffic causes more unsafety (432.4 crashes per billion bicycle kilometres) than when there is separated traffic (361.2 crashes per billion bicycle kilometres). This, like the speed limit of motor vehicles, shows that the presence of motor vehicles impacts cyclists' safety, even if they are not involved in the crash. This may be because cyclists have to swerve or be surprised in situations that cause them to fall. The most unsafe situation for cyclists that this regression tree shows is when these mixed roads, within strongly urbanised areas and a speed higher than 50 kph, are combined with a high proportion of freight traffic of more than 15%, the crash rate is 450.4 crashes per billion bicycle kilometres. This number is not far from the number shown in the parent branch (432.4 crashes per billion bicycle kilometres), but what seems to make the most impact is whether the bike facility has mixed traffic and a higher speed limit.

5.3 Applicability of National Crash Rates at Regional Level

The general pattern of the crash rate between different vehicle combinations by province and the national picture seems to be the same (Table 8). However, it can be seen that the crash rate does not remain the same; for example, significant differences can be seen in the national crash rates. For example, for motor vehicle-bicycle crashes per billion bicycle kilometres, the lowest crash rate is shown in Limburg (214 crashes per billion cycle kilometres) and the highest crash rate in Zuid Holland (521 crashes per billion cycle kilometres). The findings in this figure are discussed further in this section. In Appendix A the provincial differences per road characteristic are shown.

5.3.1 Proportion Difference Between National and Provincial Vehicle Matrices

Table 8 shows that the distribution of crash types per distance driven between provinces nationwide differs little and appears homogeneous. This fact is remarkable, given that safety would be expected to differ between provinces due to demographic and infrastructural differences. For instance, it is common knowledge that provinces in the west of the Netherlands have more strongly urbanised areas than the rest of the Netherlands, and there may be age differences between provinces. In addition, infrastructural differences can also be imagined, given the non-primary road network of the different provinces follows regional policies and visions. However, CROW draws up national guidelines, and there are few significant differences; these minor deviations could be decisive for a difference in road safety. Given the general pattern between provinces, there seems to be minor difference.

Table 8: Vehicle Type Matrix per Province.
MV = Motor Vehicle, FR = Freight, BI = Bicycle, OM = Other Motor Vehicle, PE = Pedestrian, RF = Road furniture / object, OS = One-Sided, XX-P = from Perspective

Drenthe

	MV	FR	BI	OM	PE	RF	OS
MV-P	52	4	36	2	8	25	29
FR-P	24	6	5	0	2	2	5
BI-P	234	6	37	3	11	17	74

Flevoland

	MV	FR	BI	OM	PE	RF	OS
MV-P	38	3	29	1	6	7	18
FR-P	19	6	9	0	2	0	6
BI-P	276	15	42	3	19	22	91

Friesland

	MV	FR	BI	OM	PE	RF	OS
MV-P	42	2	39	1	8	16	23
FR-P	14	4	6	1	3	1	5
BI-P	257	7	43	6	13	16	72

Gelderland

	MV	FR	BI	OM	PE	RF	OS
MV-P	42	3	36	1	7	13	16
FR-P	16	6	8	0	2	3	4
BI-P	216	8	36	3	8	16	70

Groningen

	MV	FR	BI	OM	PE	RF	OS
MV-P	65	4	71	2	13	29	19
FR-P	24	8	17	0	3	4	3
BI-P	405	16	83	6	18	20	96

Limburg

	MV	FR	BI	OM	PE	RF	OS
MV-P	41	3	40	1	9	13	19
FR-P	18	6	12	0	3	2	6
BI-P	214	10	23	3	7	14	60

Noord-Brabant

	MV	FR	BI	OM	PE	RF	OS
MV-P	51	4	43	1	10	17	23
FR-P	22	6	10	0	3	2	4
BI-P	249	10	32	3	11	18	66

Noord-Holland

	MV	FR	BI	OM	PE	RF	OS
MV-P	101	6	81	1	20	15	28
FR-P	39	14	20	0	10	3	7
BI-P	374	14	92	5	24	32	156

Overijssel

	MV	FR	BI	OM	PE	RF	OS
MV-P	51	3	49	1	9	13	19
FR-P	18	5	9	0	0	1	3
BI-P	275	10	64	6	14	17	108

Utrecht

	MV	FR	BI	OM	PE	RF	OS
MV-P	89	4	67	1	11	17	34
FR-P	32	15	18	0	7	4	10
BI-P	326	12	67	4	16	24	97

Zeeland

	MV	FR	BI	OM	PE	RF	OS
MV-P	54	3	42	2	9	13	38
FR-P	15	2	7	0	1	1	2
BI-P	283	9	47	8	14	16	137

Zuid-Holland

	MV	FR	BI	OM	PE	RF	OS
MV-P	142	6	108	2	30	18	31
FR-P	37	13	19	0	7	5	8
BI-P	521	14	110	4	32	33	211

However, differences in the proportions can be found with respect to national proportions. These differences are shown in Table 9. The most significant difference in the ratio between the province and the national ratio is found in Zeeland. Where proportionally, there is a higher share of cyclists involved in a one-sided crash resulting in injury or death. In proportion, there is a 5% increase here compared to the national picture. This can be explained by the causes of a one-sided crash, which often involves falling after getting on or off a bicycle or crashes with objects such as kerbs and bollards (SWOV, 2023). These crashes are common among people who cannot stabilise themselves properly, such as the elderly. According to demographic data collected by CBS, the proportion of elderly people (people over 65) in Zeeland is higher than that in the Netherlands and also the highest of all provinces (CBS, Regionale kerncijfers Nederland, 2024). So, this could be a reason for this observation. Another province that also has a major difference in the ratio of

Table 9: Vehicle Type Matrix with Distributions per Province.
MV = Motor Vehicle, FR = Freight, BI = Bicycle, OM = Other Motor Vehicle, PE = Pedestrian, RF = Road furniture / object, OS = One-Sided, XX-P = from Perspective

Drenthe

	MV	FR	BI	OM	PE	RF	OS
MV-P			-1%			2%	2%
FR-P	1%		-1%				
BI-P			-2%				-2%

Flevoland

	MV	FR	BI	OM	PE	RF	OS
MV-P	-3%		-3%		-1%	-1%	
FR-P							
BI-P	5%	1%	-1%		1%	1%	

Friesland

	MV	FR	BI	OM	PE	RF	OS
MV-P	-2%		-1%			1%	1%
FR-P	-1%		-1%				
BI-P	4%			1%			-2%

Gelderland

	MV	FR	BI	OM	PE	RF	OS
MV-P	-1%					1%	
FR-P							
BI-P	2%		-1%		-1%		-1%

Groningen

	MV	FR	BI	OM	PE	RF	OS
MV-P	-2%					1%	-1%
FR-P							
BI-P	5%		1%			-1%	-4%

Limburg

	MV	FR	BI	OM	PE	RF	OS
MV-P	-1%		1%			1%	1%
FR-P	1%		1%				1%
BI-P	2%	1%	-3%		-1%		-3%

Noord-Brabant

	MV	FR	BI	OM	PE	RF	OS
MV-P						1%	1%
FR-P	1%						
BI-P	2%		-2%				-3%

Noord-Holland

	MV	FR	BI	OM	PE	RF	OS
MV-P	1%						
FR-P	1%						
BI-P	-4%		1%				1%

Overijssel

	MV	FR	BI	OM	PE	RF	OS
MV-P	-2%						
FR-P							
BI-P	1%		2%				2%

Utrecht

	MV	FR	BI	OM	PE	RF	OS
MV-P	1%						1%
FR-P	1%	1%	1%				1%
BI-P	-2%						-3%

Zeeland

	MV	FR	BI	OM	PE	RF	OS
MV-P	-1%		-1%				2%
FR-P	-1%	-1%	-1%				
BI-P			-1%	1%		-1%	5%

Zuid-Holland

	MV	FR	BI	OM	PE	RF	OS
MV-P	1%		1%		1%	-1%	-1%
FR-P							
BI-P	-2%						1%

unilateral bicycle crashes is Groningen. Here, the difference with the national ratio is a decrease of 4%. The opposite of Zeeland can be observed in this province; according to demographic data, more young people live in Groningen. This is, therefore, expected to be related.

This highest difference in proportion is followed by motor vehicle-bicycle crashes per billion bicycle kilometres in Flevoland. In proportion, there is a 5% reduction here compared to the national picture. There is also a similar reduction in Friesland of 4%. The infrastructure is likely arranged so bicycle and motor vehicle traffic are more often separated. For example, Flevoland's road network comprises 31% of roads without cyclists, compared to the national 16%. This fact does not seem to be the case for the province of Friesland; other possible factors related to the reduction is the degree of urbanisation in Friesland.

The opposite can be noted in the provinces of Groningen and Noord Holland where, on the contrary, there seems to be an increase in proportion, both 4%. For Groningen, this seems to approximate the increased number of mixed-traffic roads, 67% in Groningen and 58% for the whole of the Netherlands.

5.3.2 *Significance Tests on Regional Vehicle Type Matrix*

While it can be seen that relationships between provincial and national crash rates for vehicle matrices combinations exist, it is also interesting to test the significance of the differences between provincial and national crash rates. This was done through z-tests. The results of these tests can be read in this section.

Overall, provincial crash rates are significantly different from the national average in many cases. From the motor vehicle perspective, provincial crash rates and the national average are, in the most cases, significant different compared to the other perspectives (seen in Table 10). Only 21 out of 84 cases (25%) are not significantly different. It should also be noted here that crash rates with crashes between motor vehicles and other motor vehicles (agricultural vehicles and unknown vehicles due to hit and runs) for most of all provinces show a significantly non-different crash rate from the national average. Crash rates with crashes between motor vehicles and other motor vehicles and between motor vehicles and cyclists are significantly different from the national average in all provinces.

Table 10: Z-Score of the Z-Test From the Motor Vehicle Perspective.

Province	motorv.	freight	bicycle	other mv	pedestr.	objects	one-sided
Groningen	**4,22***	0,20	**4,49***	1,94	1,76	**8,80***	**4,24***
Flevoland	**17,74***	1,15	**17,63***	0,24	**10,52***	**9,56***	**4,49***
Friesland	**19,37***	**4,07***	**14,24***	0,28	**8,41***	0,45	1,51
Drenthe	**10,74***	0,04	**14,07***	**2,44***	**7,01***	**5,95***	**2,62***
Overijssel	**16,54***	1,65	**8,53***	1,02	**9,77***	**3,99***	**7,02***
Gelderland	**32,09***	**6,04***	**26,84***	**2,08***	**17,28***	**6,21***	**14,04***
Utrecht	**7,29***	0,18	**3,31***	1,42	**4,86***	0,84	**7,66***
Noord-Holland	**17,68***	**4,71***	**15,27***	0,56	**8,89***	1,46	**3,96***
Zuid-Holland	**42,80***	**4,75***	**34,09***	1,84	**22,06***	**3,65***	**8,74***
Zeeland	**8,56***	**2,63***	**8,90***	1,44	**5,01***	**2,94***	**6,58***
Noord-Brabant	**22,45***	0,71	**18,97***	**2,16***	**9,57***	1,64	1,84
Limburg	**24,60***	**3,40***	**15,35***	**2,46***	**7,56***	**3,98***	**6,44***

* *When a cell is green, the corresponding crash rate is significantly different ($p < 0.05$) to the national average.*

From the freight vehicle perspective, there seem to be many significant differences (seen in Table 12). However, this perspective does have the highest percentage (42%) compared to the different perspectives that a crash rate is not significantly different. In Flevoland, the highest significant difference is seen for a crash rate with crashes between freight vehicles and traffic objects; this is remarkable considering crash rates with crashes between freight vehicles and traffic objects for most provinces from this perspective does not show a significant different crash rate with the national average. It can also be seen that, from this perspective, Groningen does not differ significantly from the national figures in all cases, not including crashes involving other types of motor vehicles.

Table 12: Z-Score of the Z-Test From the Freight Perspective.

Province	motorv.	freight	bicycle	other mv	pedestr.	objects	one-sided
Groningen	0,36	0,09	1,37	**2,45***	0,63	1,15	1,53
Flevoland	1,74	1,16	1,48	**2,45***	1,44	**12,61***	0,37
Friesland	**4,5***	**4,15***	**4,09***	1,20	1,39	1,81	0,62
Drenthe	0,34	1,40	**4,76***	**2,45***	**2,21***	0,23	0,27
Overijssel	**3,54***	**3,08***	**2,37***	0,43	**10,32***	**4,66***	**3,37***
Gelderland	**6,02***	**2,01***	**4,33***	0,17	**3,59***	0,35	**2,32***
Utrecht	**2,19***	**3,1***	**2,31***	0,66	1,57	1,37	**2,56***
Noord-Holland	**5,76***	**3,67***	**4,22***	**2,45***	**4,98***	0,99	1,95
Zuid-Holland	**5,67***	**3,41***	**4,05***	0,02	**3,00***	**2,47***	**2,51***
Zeeland	**3,46***	**5,13***	**2,57***	**2,45***	**5,87***	1,93	**2,66***
Noord-Brabant	**2,22***	**2,50***	**2,82***	**2,45***	**2,94***	0,69	1,91
Limburg	**3,08***	**2,25***	0,17	**2,45***	0,82	1,21	0,13

** When a cell is green, the corresponding crash rate is significantly different (p < 0.05) to the national average.*

From a cyclist's perspective, 31% of cases are not significantly different, again a small number of all provinces (seen in Table 11). Combination bicycles and other motor vehicles are significantly not different from the national average in most provinces. This means that, apart from Noord Brabant, the difference with the national average is not large enough to rule out the possibility that it is a coincidence. It can also be seen that, from this perspective, Utrecht does not differ significantly from the national figures in all cases except in the case of a one-sided crash.

Table 11: Z-Score of the Z-Test From the Bicycle Perspective.

Province	motorv.	freight	bicycle	other mv	pedestr.	objects	one-sided
Groningen	**5,55***	1,65	**2,95***	0,94	0,04	1,11	**3,56***
Flevoland	**3,33***	1,04	**3,46***	0,64	0,17	0,32	**2,89***
Friesland	**7,27***	**2,37***	**5,40***	1,10	**2,01***	**3,01***	**8,62***
Drenthe	**8,41***	**3,15***	**6,17***	0,65	**2,92***	1,87	**6,83***
Overijssel	**7,42***	0,83	0,51	1,34	**2,20***	**3,01***	**2,23***
Gelderland	**20,68***	**3,23***	**12,76***	1,50	**8,48***	**4,50***	**15,04***
Utrecht	0,73	0,21	0,31	0,13	1,14	0,19	**4,94***
Noord-Holland	**6,67***	1,92	**8,59***	1,46	**3,81***	**4,66***	**9,31***
Zuid-Holland	**28,04***	**2,18***	**14,46***	0,55	**8,6***	**5,92***	**21,55***
Zeeland	**3,49***	0,94	**3,26***	1,44	1,07	**1,97***	1,80
Noord-Brabant	**14,97***	1,01	**15,82***	**2,03***	**5,86***	**3,38***	**18,11***
Limburg	**16,32***	0,53	**17,08***	1,03	**7,62***	**5,10***	**15,33***

** When a cell is green, the corresponding crash rate is significantly different (p < 0.05) to the national average.*

5.3.3 Significance Tests on Regional Regression Trees

In addition to conducting significance tests for the national and provincial crash rates in the vehicle matrix, it is also essential to examine the differences between the regression trees. To assist in this process, provincial crash rates have been calculated for the first three splits of the national regression tree.

Motor vehicle crashes without bicycle involvement per billion motor vehicle kilometres

Overall, it can be seen that for most provinces, the crash rates are significantly different from the national average in the first partition (Figure 20 and Figure 21). Only two cases from the root leaf for both sides are not significantly different from the national average crash rate. Both cases are in the province of Zeeland. The ratio between lower than 65 kph and higher than 65 kph, with higher than 65 kph being more unsafe for motor vehicles, is the case for all provinces. For roads below 65 kph, it can be seen that in Gelderland, a lower crash rate can be observed than the national average. Zuid Holland's crash rate is the highest for this tree branch. The proportion of 30 kph and 50 kph roads in this province is higher than in the other provinces, and given that lower speed limits cause a higher crash rate, this higher crash rate in Zuid Holland can be logically explained.

The crash rate is in Gelderland the lowest for all provinces, and in Zuid Holland highest for all provinces. For the third split for roads with the speed limit below 65 kph and not strongly urbanised areas, the highest crash rate is also found in Zuid Holland, with a share of freight traffic greater than 4%. Here, the crash rate is above the national average. For the third split for roads below 65 kph and in strongly urbanised areas, the lowest crash rate is found in Gelderland, where no cycle lane is present. Here, the crash rate is below the national average. Nationally, the split to have a cycle lane causes a higher crash rate. However, this is not the case in Drenthe; in this province, a road with bicycle land shows a lower crash rate than a road without a bicycle lane. So, with a bicycle suggestion lane, there is mixed traffic or no bicycle facilities.

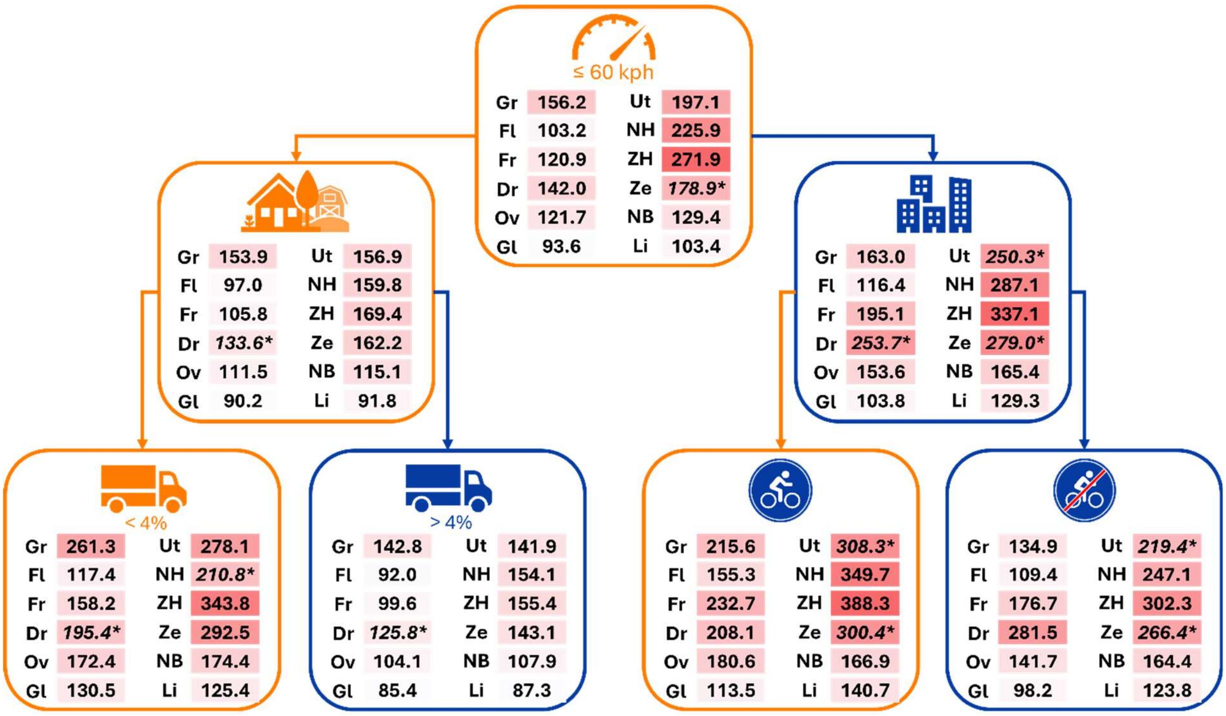

Figure 20: ≤60KPH Side of the Regression Tree With Provincial Crash Rates Motor Vehicles' Perspective Without Bicycle Crashes

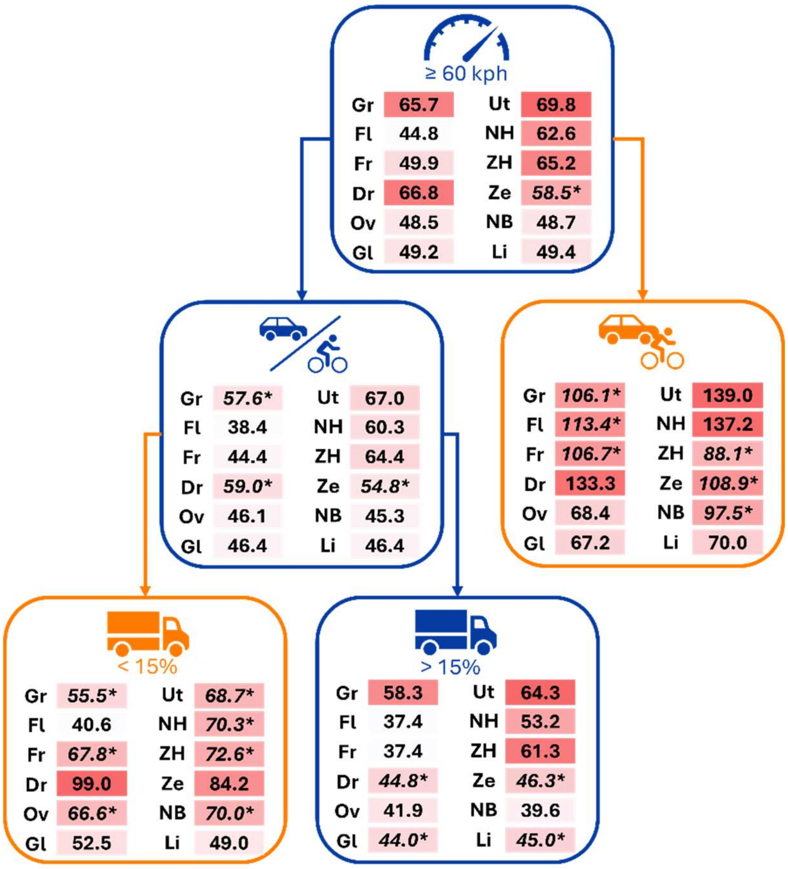

Figure 21: ≥60KPH Side of the Regression Tree With Provincial Crash Rates

The differences in crash rates for the roads with speed limits higher than 65 kph are comparatively less than for roads with speed limits lower than 65 kph. This shows that, while significantly different for the major part, they do not differ much from the national average. This is true for both after the second and third splits. Nationally, splitting to a road with a freight traffic share of <15% causes a higher crash rate. However, this is not the case in Groningen, where a freight traffic share of >15% causes a higher crash rate.

Motor vehicle crashes without bicycle involvement per billion motor vehicle kilometres.

For motor vehicle-bicycle crashes per billion motor vehicle kilometres, it is generally seen that most provinces differ significantly from the national average (Figure 23 and Figure 23). This is not the case for a few provinces. The crash rate for a road with mixed traffic in Zuid Holland is higher than the national average. Another road with mixed traffic follows this, but in Gelderland, the crash rate is lower than the national average. The crash rates for no mixed traffic, i.e. bicycle lane, bicycle suggestion lanes or no bicycle facilities at all, are lower than the other side of the tree. This shows that the degree of deviation from the national average is less.

After the first split, the highest crash rates were found in Noord Holland, and Zuid Holland for roads with mixed traffic in not strongly urbanised areas. All these provinces show higher crash rates than the national average. For all these provinces, these crash rates are higher than in strongly urbanised areas, which goes against the national average ratio, where not strongly urbanised areas provide less risk. In addition, compared with the national average, these are 2 to

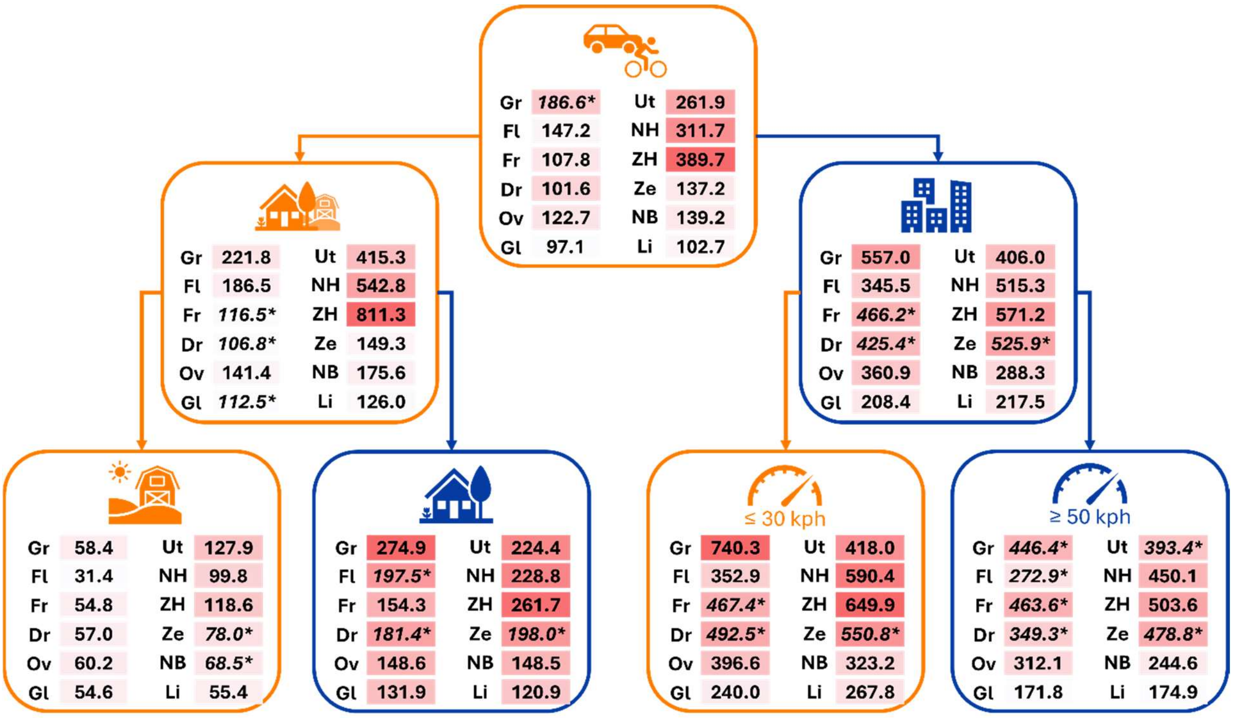

Figure 23: Mixed Traffic Side of the Regression Tree With Provincial Crash Rates Motor Vehicles' Perspective With Only Motor Vehicle-Bicycle Crashes

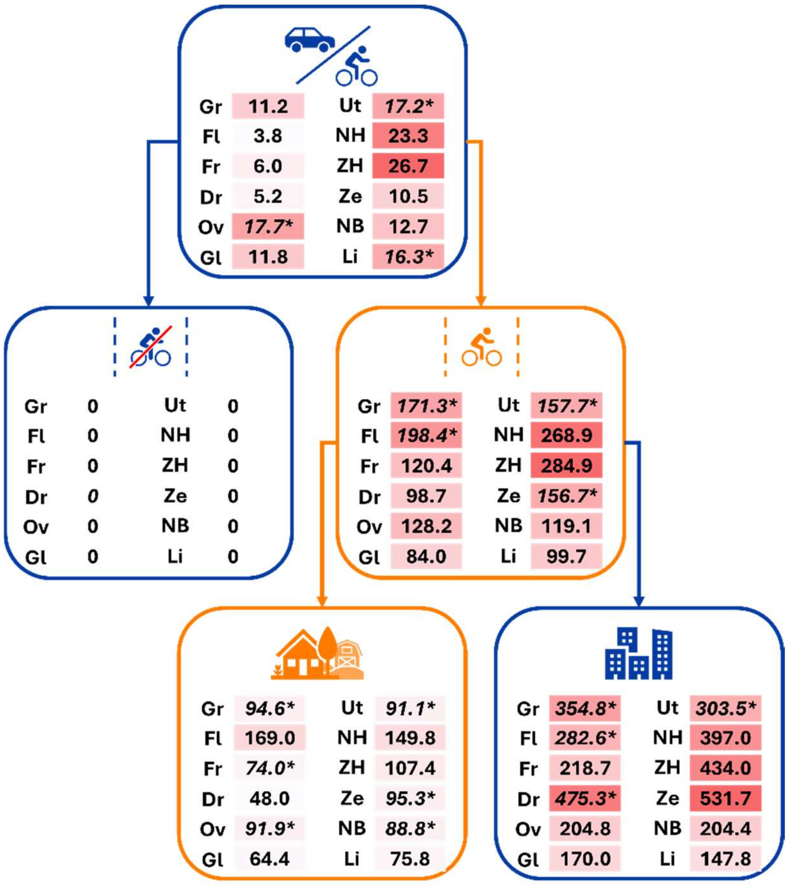

Figure 23: Not Mixed Traffic Side of the Regression Tree With Provincial Crash Rates Motor Vehicles' Perspective with Only Motor Vehicle-Bicycle Crashes

6 times higher for mixed-traffic roads and not strongly urbanised areas. After the second split, there are fewer notable cases. The only one is the crash rate of roads with mixed traffic where a speed limit of 40kph or lower may be driven within strongly urbanised areas. Here, it can be seen that Groningen has a very high crash rate.

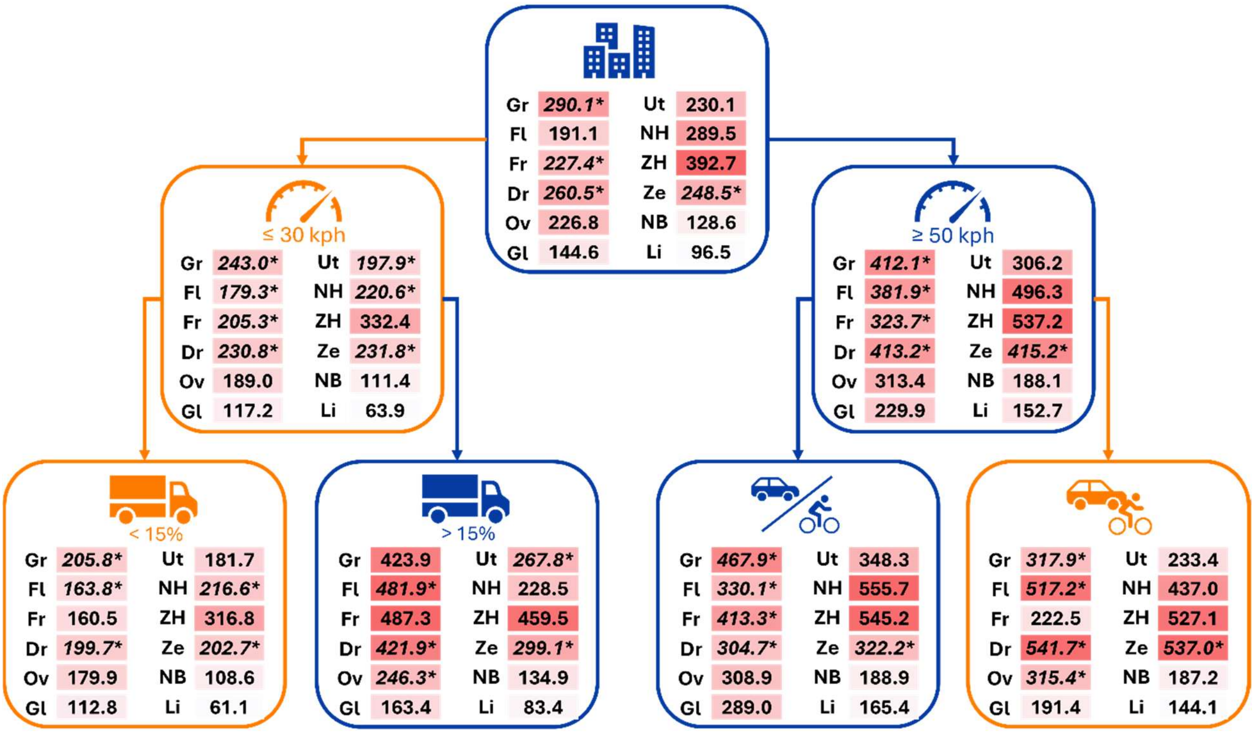

Figure 24: Strongly Urbanised Side of the Regression Tree With Provincial Crash Rates Bicycles' Perspective With Only Motor Vehicle-Bicycle Crashes

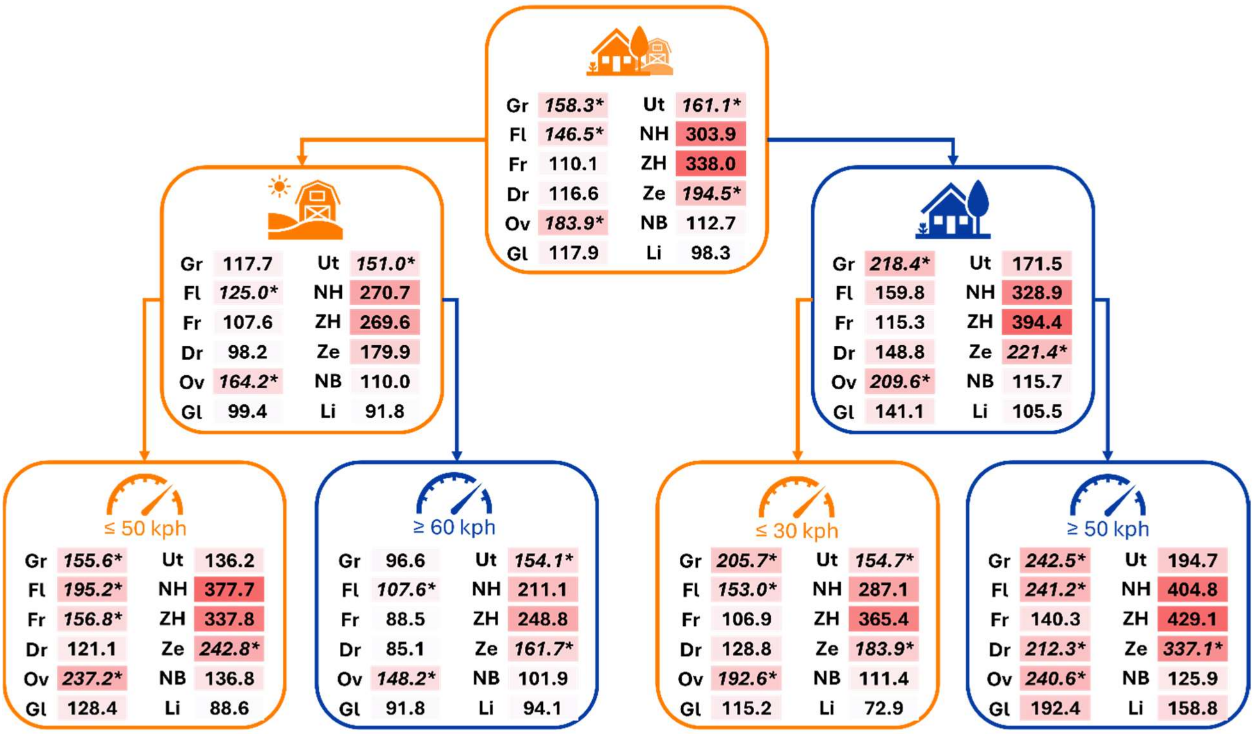

Figure 25: Not Strongly Urbanised Side of the Regression Tree With Provincial Crash Rates Bicycles' Perspective With Only Motor Vehicle-Bicycle Crashes

Crashes between motor vehicle and bicycle per billion bicycle kilometres

As with previous perspectives, crash rates in most provinces significantly differ from the national average (Figure 24 and Figure 25). However, the number of crash rates that are not significantly different is higher than previous perspectives. For both sides of the tree, it can be seen that Zuid Holland is an outlier with a higher crash rate. For roads below 55 kph, Limburg is the safest; for roads above 55 kph, Flevoland is the safest.

Roads with a speed limit higher than 65 show a very low crash rate in Groningen; it is 71% lower than the national average. Although this is only the third layer of the regression tree, it's important to note that the distance travelled is very low. In addition, there are a few notable points in this tree. However, it does show extremely high crash rates for roads with 50 kph in strongly urbanised areas, namely in Zuid Holland and Drenthe, where the crash rate exceeds 1100 crashes per distance travelled.

Bicycle crashes without motor vehicle involvement per billion bicycle kilometres

From the first split, several provinces generally show that they are not significantly different from the national average (Figure 26 and Figure 27). These are the provinces of Groningen, Flevoland, Overijssel, Utrecht and Zeeland for not strongly urbanised areas. For strongly urbanised areas, the provinces are Groningen, Friesland, Drenthe, and Zeeland. The rest of the cases are significantly different from the national average. Furthermore, the highest crash rates are observed in Zuid Holland and Noord Holland for both not strongly urbanised and strongly urbanised, with Zuid Holland being the highest in both cases. The lowest crash rates are observed in Limburg for both branches.

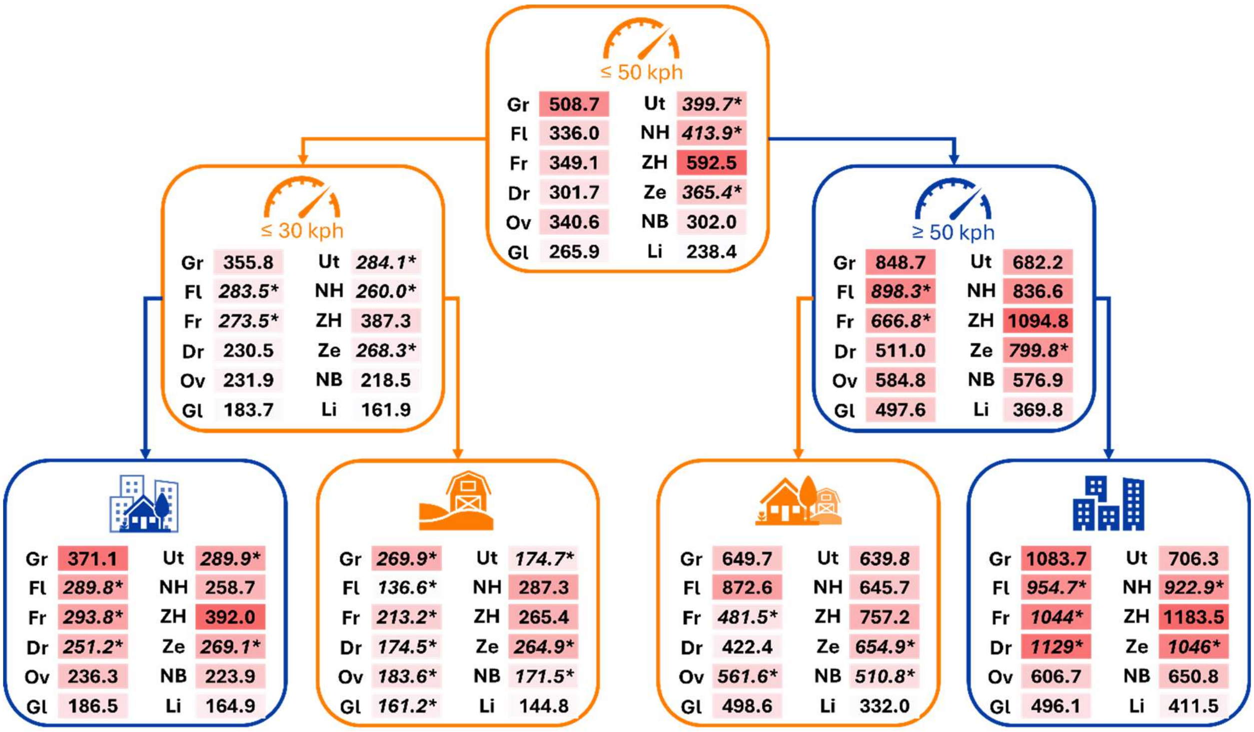

Figure 26: ≤50KPH Side of the Regression Tree With Provincial Crash Rates Bicycles' Perspective Without Motor Vehicle Crashes

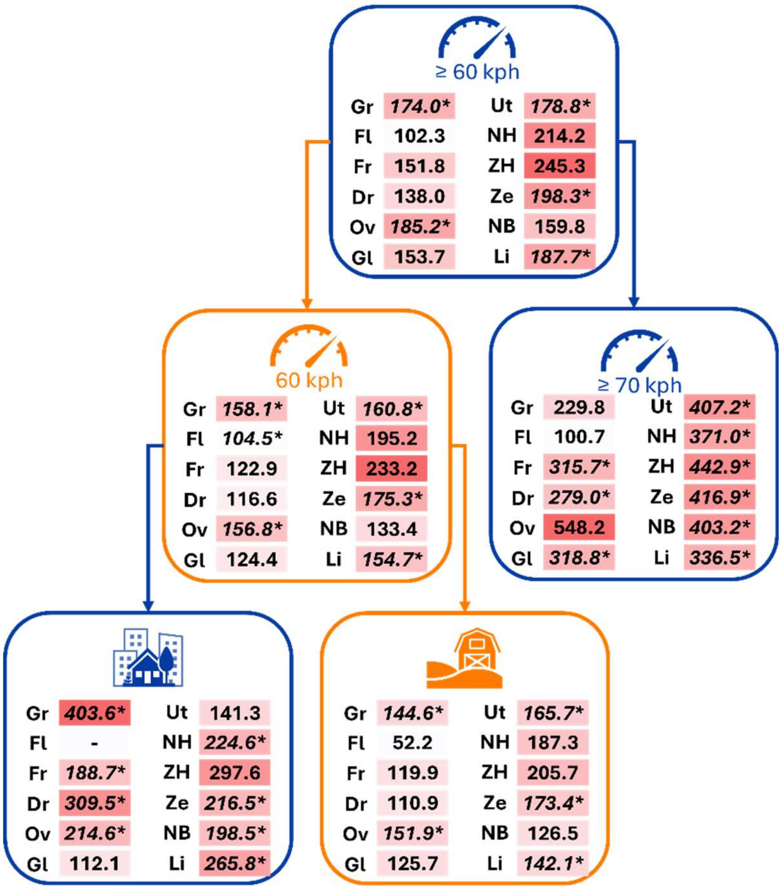

Figure 27: ≥50KPH Side of the Regression Tree With Provincial Crash Rates Bicycles' Perspective Without Motor Vehicle Crashes.

From the second split, Zuid Holland remains the province with the highest crash rate in each tree branch. In addition, the crash rate in Zuid Holland with moderately urbanised areas is even 92% higher than the national average. It is also high in Zuid Holland, at 83% higher for not urbanised areas. From the third split, this ratio increases with the national average. For example, the crash rate of not urbanised areas with a speed limit lower than 55 kph is 100% higher in Zuid Holland. For moderately urbanised areas in Zuid Holland with a speed limit lower than 40 kph, the crash rate is 105% higher than the national average. This shows that Zuid Holland has exceptionally high crash rates.

6. Discussion

In this section, the research is discussed. To begin, the research and data reliability and limitations are first described. This ensures credibility and an accurate picture of what can and cannot be concluded from the results. This is followed by recommendations to offer suggestions and concrete ideas for future research. Subsequently, the results of the current study are compared with those of the previously described SWOV study to highlight differences and the importance of employing a suitable methodology to assess crash risk accurately. This comparison is followed by a discussion of the results of this study, delving into the causes that led to these results.

6.1 Research and Data Reliability and Limitations

Although this research aims to provide reliable and usable crash rates for the non-primary road network of the Netherlands, it also contains several limitations.

Starting with the crash data, BRON contains several limitations, e.g., BRON collects crash data utilising police reports, meaning that the police must have been present to make a registration (Decae, Bos, N.M., & Aarts, 2023). In the case of a crash with cyclists, it often happens that they are not registered because there has been no police presence. Ambulance registrations are often more reliable for bicycle crashes, as can be read in Appendix B. The same is true for PDO crashes and, therefore, has been excluded in this study. In addition, there is often no exact spatial match between the crash and the network. This match is necessary to determine the number of crashes on a road segment. It is possible that, in some cases, crashes are linked to the wrong road segments. Still, it is assumed that the number of incorrectly attached crashes has little influence on the entire population since most of the crashes are, in fact, correctly attached to the network.

Additionally, it is good to note that only the network and the corresponding intensities from 2018 have been used. Consequently, there is an inconsistency between intensity data and crash data. An assumption has been made that the network has changed little in the years of crash data (2015 to 2019 and 2022). In cases where the network has changed over the years, it may be that a crash is linked to a road segment with incorrect road characteristics. Furthermore, it is important to acknowledge that the intensity data is derived from a model, which inevitably introduces a degree of uncertainty originating from the inherent limitations associated with model-based estimations. The reliability of these models depends on various underlying assumptions and the quality of input data utilized. Consequently, inaccuracies may arise that can significantly impact the validity of the results obtained.

6.2 Recommendations

Several recommendations could be made to steer future research in the right direction. Starting with the method used to determine crash rates for different vehicle volumes. This study used different perspectives of motor vehicles, freight, and cyclists to compare crash rates. However, another method that can measure the safety of a road is to calculate the number of crashes per conflict point between road users (Tarko, 2021). Using this metric, the vehicle kilometres of different road users can be used simultaneously, eliminating the perspective and measuring overall road safety per road. For example, there are points of conflict between the same type of vehicle (e.g. motor vehicles in conflict with another motor vehicle) and between different vehicles (e.g. motor vehicles in conflict with a cyclist). An example is the study of Fournier, Christofa, & Knodler (2019), where the multiplication of vehicle kilometres is proposed to calculate a crash rate between different vehicle types.

If the decision is made to use the same method as this study, which involves different perspectives of vehicle types. Including the share of any opposite vehicle is recommended, as done with freight share. This approach provides another method to address the recurring challenge of the distance travelled by the opposite vehicle. Another relevant road characteristic is the number of intersections or entrances connected to a road segment. This number reflects a different type of conflict point that this study did not include. However, it is labour-intensive to obtain these figures, which is why this road characteristic has not been included in this study.

Finally, it is recommended that road segments and intersections be separated. In addition to road characteristics, knowing which intersection characteristics (number of connecting roads or roundabout, priority arrangement, presence of pedestrians or cyclists etc.) contribute to a safe road network is valuable. To achieve this, data on these intersection characteristics must be available, currently this is under development and is possible in the near future.

6.3 Comparison with SWOV study

SWOV recently conducted a similar study (Schermers & Gebhard, 2023). The study aimed to find the crash rates on the non-primary road network in the Netherlands for different speed limits. Since the current study seeks to achieve the same objective, except with multiple road characteristics and a different methodology, it would be interesting to compare both studies and discuss the results. Table 13 shows the results of both studies and the differences between them.

Since the SWOV study has made other considerations, such as determining the crash rate for different speed limits only, it is necessary to adjust the figures used in the current study. The adjustments that had to be made were removing the intersection crashes and determining the crash rates based on the speed limit. In addition, the SWOV study determined the average number of vehicle kilometres and crashes per year; for this comparison, the same was performed by taking the average of the six years, which is the number of years used in this study.

The results show entirely different figures. The crash rates of the current study are significantly higher than the crash rates of the SWOV study. In the most extreme case, the crash rate of this study is almost ten times higher, namely for the crash rate with injuries on roads with a speed limit of 60 kph. Only in one case, the figures of the two studies seem to be the same, namely for the crash rate with fatal outcomes on roads with a speed limit of 50 kph.

In addition to the fact that the crash rates are significantly higher, the ratio between speed limits is also very different. For example, it can be seen that the crash rate for fatal outcomes is highest, with a speed limit of 50 kph in the SWOV study and 60 kph in this study. The crash rate for fatal outcomes is lowest for a speed limit of 30 kph in the SWOV study, and 50 kph is the lowest in this study. Therefore, 50 kph roads carry the highest risk of fatal crashes in the SWOV study and the lowest risk in this study. A different ratio can also be seen for injury crashes between the crash

Table 13: Comparison of the Results Between the Studies (Schermers & Gebhard, 2023)

	Study	30 kph	50 kph	60 kph	80 kph
Road length	SWOV	54.000	18.000	50.000	12.000
	Current (100%)	51.656	19.058	49.337	13.589
	Difference	105%	94%	101%	88%
Vehicle kilometres per year	SWOV	28,7	38,0	55,1	49,0
	Current (100%)	8,3	31,2	11,7	32,0
	Difference	346%	122%	471%	153%
Fatal crashes per year	SWOV	24,7	72,0	59,0	89,3
	Current (100%)	37,3	60,2	74,0	80,5
	Difference	66%	120%	80%	111%
Injury* crashes per year	SWOV	898,5	2.068,5	540,4	558,8
	Current (100%)	2.185,8	2.590,3	1.138,5	819,0
	Difference	41%	80%	47%	68%
Fatal crash rate	SWOV	0,9	1,9	1,1	1,8
	Current (100%)	4,5	1,9	6,3	2,5
	Difference	20%	100%	17%	72%
Injury* crash rate	SWOV	31,3	54,5	9,8	11,4
	Current (100%)	263,2	83,1	97,2	25,6
	Difference	12%	66%	10%	45%

* Crashes with outcomes: fatal, to hospital, and minor injury combined

rates of the studies. For example, the highest crash rates can be seen at 50 kph in the SWOV study and 30 kph in this study; the lowest crash rates can be seen at 60 kph in the SWOV study and 80 kph in this study. Lastly, it can be seen that the length of roads also differs per speed limit, but this difference is not very large, and the proportions are relatively equal.

The vehicle kilometres used for the current study could raise some questions, as the distance travelled for 30 and 60-kph roads is low compared to the other speed limits. However, this can be explained from the viewpoint of the trip distance road users make. Logically, of the total trip distance, only a small part is travelled in a 30 or 60-kph area, namely at the departure and arrival of a trip. The larger part between the origin and destination is expected to be used on roads with a speed limit of 50 and 80 kph.

Although some considerations are the same, there are differences in the methodology used. The main difference will be the calculation of vehicle kilometres. For example, SWOV used a sample of traffic counts done on different roads in the Netherlands to measure the intensity. Then, because there is a skewed distribution, the median was used to get a representative value of the intensity of all roads with the same speed limit. The median is then multiplied by the total road length at a given speed limit and the number of days a year to determine the vehicle kilometres. This road length originates from an earlier study by SWOV. In the current study, the transport demand model OmniTRANS-Spectrum estimated the intensity, calculated according to various variables and calibrated on counts. The exposure per road segment was calculated and summed per speed limit using the intensity and length of all road segments.

In addition, there are also differences in the determination of the number of crashes. For example, SWOV used years (2011 to 2020) different to this study (2015 to 2019 and 2022). The study lacks substantiation as to why SWOV chose these years. In this study, these years were chosen based on method change in the crash collection by BRON (from 2015 onwards) and the years in which fewer vehicle kilometres were made due to unusual circumstances in 2020 and 2021 due to COVID-19. SWOV also selected crashes that are precisely linked to the location of the crash, whereby only crashes linked at the municipal level were filtered in this study.

6.4 Discussion on the Results

6.4.1 Points of Conflict

One of the most recurring reasons crash rates from a specific perspective are high or low is that the number of vehicle kilometres travelled by the other vehicle is not included in the vehicle matrices. The figures are presented from a particular perspective to measure the risk of a crash from the perspective of a vehicle and compare it with the different parties involved. However, only the exposure of the respective vehicles is used; this means that the crash rate is also higher if the opposite vehicle has a relatively high number of vehicle kilometres. This is because the number of conflict points may be increased. This can be seen in the results mainly for motor vehicle-bicycle crashes per billion bicycle kilometres, where the crash rate is exceptionally high, and motor vehicles are the vehicle type with the highest exposure. This statement also applies to lower crash rates where the opposite vehicle shows fewer vehicle kilometres and fewer conflict points are present. This can be seen in the crash rate for crashes between motor vehicles and agricultural vehicles and crashes between cyclists and agricultural vehicles, where the crash rate is very low. Here, the number of conflict points is expected to be low.

In the results of the national distribution, conflict points may also be a factor in a higher crash rate. For example, the results show that a lower speed limit matches a higher crash rate for motor vehicle crashes. This seems counterintuitive, but it may be due to the number of intersections on roads where a lower speed limit applies; more intersections equals more points of conflict and, therefore, a higher crash risk. The opposite is true for the crash rate of bicycle crashes without motor vehicle involvement for speed limits. Here, it can be seen that the speed of motor vehicles does not influence bicycle crashes; this is possible because, in this type of crash, the two vehicles do not conflict.

6.4.2 Vehicle Characteristics

The characteristics of vehicles can also affect the risk of crashes, resulting in injury or death. The results show that, counterintuitively, the share of freight traffic relatively reduces crash rates, both in the crash rates for specific vehicle combinations and national distribution. Literature partly supports this, as heavier vehicles appear less likely to be involved in crashes, but the weight does influence the severity of crashes (De Winkel, Bos, Decae, & Aarts, 2024).

The fact that freight impacts traffic safety positively may be because freight vehicles are rigid due to the size and noise they make, so these vehicles are noticeably present, which may ensure a safer situation. The size of freight vehicles can also lead to different behaviours of other road users because they recognise the risk of a severe crash (H. Singh, 2021). A higher share of freight may result in more cautious driving behaviour near freight vehicles, and it could be that more distance is kept or that people drive defensively. In addition, drivers of freight vehicles are relatively more experienced than other road users since they use the network for many hours due to their profession (Chantal Timmermans, 2019). Also, freight vehicles often drive below the speed limit and have lower acceleration, which allows freight drivers to react quickly or other vehicles to swerve more quickly. The reasons given can also be combined to ensure greater safety in the presence of freight traffic.

However, the crash rates involving cyclists show different figures than freight vehicles. For cyclists, the crash rates are considerably higher. A primary reason could be that cyclists are vulnerable in the event of a crash. Cyclists have little protection and stay in place through balance (N. Kovácsová, 2016; Boele-Vos M. , et al., 2017). There is a high probability that the cyclist will fall, resulting in injury or even death. One of the reasons for this high figure may also be the vulnerable groups, such as the elderly, who participate in traffic as cyclists (Boele-Vos M. , et al., 2017). Single-vehicle bicycle crashes can happen when road users from vulnerable groups, such as the elderly, fall due to instability. This group appears to have a significant share in bicycle crashes. Other reasons for single-vehicle crashes by cyclists include slipping due to harsh weather conditions such as sleet or snow and cycling under the influence of alcohol or drugs (Anne Vingaard Olesen, 2021; Zoi Christoforou, 2023). It is also possible that the speed difference between cyclists is a significant factor in crash risk. This speed difference would be due to the rise of the electric bicycle, which usually rides 10 kilometres per hour faster than a bicycle without assistance (Westerhuis, Nuñez Velasco, Schepers, & de Waard, 2024).

6.4.3 Correlation of Road Characteristics

Road characteristics collectively define a road, complicating the assessment of its relevance to crash risk. For example, roads with bicycle suggestion lanes are often roads where a speed limit of 50 kph is also present and are located in strongly urbanised areas. In addition, the results show that for each perspective, a higher degree of urbanisation leads to a higher crash rate. This finding can also be argued from the combination of road characteristics. In strongly urbanised areas, there are often roads where a lower speed is allowed, as the speed distribution shows that a lower speed limit results in a higher crash rate. A higher crash rate can also be caused by a large number of intersections in strongly urbanised areas due to a higher distribution of conflict points. These claims show that road characteristics may be correlated to each other.

Another example is given if a road has multiple or separate lanes (which falls within the case of one lane). These roads often do not have bicycle facilities directly on the road itself. Bicycle paths often facilitate the bicycle, and a maximum of 50 kph may be driven within strongly urbanised areas. These combinations show that multiple road characteristics contribute to a specific crash rate. Therefore, it is challenging to attribute a crash rate to a road feature.

6.4.4 *Cognitive Load*

Differences in crash rates may also be due to the cognitive load experienced by road users. It has been known in several studies that participants in traffic face psychological challenges when a road design consists of complex situations (Engström, 2017; Du, 2020). This could be why a higher share of freight creates a higher risk of bicycle crashes in which motor vehicles are not involved (including freight traffic). This may be because freight vehicles put a higher cognitive load on cyclists, causing them to perform unpredictable manoeuvres because they are startled and, therefore, cause them to fall. In addition, it may be that the number of lanes reduces the risk of a crash, as multiple lanes ensure that road users have more space to drive at their speed and pass without causing immediate conflicts with the oncoming traffic.

6.4.5 *Impactful Road Characteristics*

In the results, the regression trees were used to show how different road characteristics impact crash risk from different perspectives. Additionally, the regression trees can derive impactful road characteristics, where higher positions in all trees generally indicate impactful characteristics. First, as expected, the speed limit seems to be an important road characteristic. This has also been investigated in previous studies and is often the leading feature used to calculate the crash rate (Schermers & Gebhard, 2023). Speed limits are often related to road safety, as shown in the regression trees. The degree of urbanisation also often occurs within higher divisions of the different trees. Literature supports this and suggests that the degree of urbanisation impacts traffic safety (Asadi, Ulak, Geurs, Weijermars, & Schepers, 2022). In addition, the bicycle facility type and the freight share also seem to impact the crash rate. Road characteristics related to the type of bicycle facility occur most often from the cyclist's perspective, which was expected since these road users are the main characters for these facilities. The proportion of freight is also a road property that significantly impacts the risk of a severe crash. This was to be expected as freight is often seen as a significant player in determining the safety of a road (H. Singh, 2021).

By following the trends in the regression trees, it can be seen that the number of driving directions and number of lanes are less impactful on the crash rate. If they occur at all, these splits are located in the lower splits of the regression trees. Therefore, it might be important not to include these road characteristics in a follow-up study to measure safety.

6.4.6 *Provincial Crash Rates*

The results of the provincial differences and significance tests between provincial and national crash rates show that, in most cases, provincial crash rates differ significantly from the national rates. This shows that national crash rates will not be valuable if quantities of road safety at a provincial level are desired, as the deviation is too big. There are several possible explanations for this. Firstly, the roads may differ greatly from province to province because different policies are pursued. E.g. one province has different goals in optimising accessibility, safety, or congestion than another province. Additionally, the proportion of unsafe roads may be more present in a generally unsafe province. An example of this is Zuid-Holland. This province usually scores a higher crash rate than the national average, the proportion of roads within strongly urbanised areas may be the reason. Another explanation for the significant difference between provinces is the general driving culture. It may be that in certain provinces, the road user takes more risks than in other provinces. The national crash rates assume this is nationally homogeneous, but this difference may be present between provinces.

Given these significant differences between provincial and national crash rates, it is recommended not to use the national crash rates for provincial figures. New calculations should be made to measure road safety at the provincial level. As a result, less crash and intensity data may be available for specific road characteristics, making the crash rate more sensitive to changes and less reliable.

7. Conclusion

This research project aimed to determine crash rates for non-primary roads with various characteristics in the Netherlands by utilising crash and exposure data and to investigate the applicability of national crash rate risks on a regional level. Following this objective, several research questions were drawn up. In this section, these questions will be answered.

1. How do crash rates differ across and amongst vehicle types on non-primary roads in the Netherlands?

The results have shown that cyclists face the biggest risk of being involved in a crash compared to motor vehicles and freight vehicles. For cyclists, motor vehicles are the highest risk factor, this risk is three times higher than the next highest crash rate. The reason for this may be the number of points of conflict since the distance driven by motor vehicles is high, which makes conflicts more likely. In addition, cyclists cover shorter distances, and many crashes occur in this short distance. Single-vehicle bicycle crashes also contribute to a high crash rate. This may be because cyclists must remain in place by balance, increasing the risk of falls and potential injuries. The results also show that freight traffic is the least involved in crashes per distance travelled compared to cyclists and motor vehicles. This is possibly due to experienced truck drivers, a lower average speed, and other road users being more aware of the hazards of freight vehicles.

2. How do crash rates differ depending on road characteristics on non-primary roads in the Netherlands?

The results have shown that a higher speed limit does not necessarily result in higher crash rates. From the perspective of the motor vehicle, a lower speed limit results in a higher crash rate because lower speed limits can be found in strongly urbanised areas, and more conflict points are present due to the high number of intersections compared to not strongly urbanised areas. This fact shows that it is difficult to explain the safety of an individual road characteristic, a road's characteristics collectively influence the crash risk. However, from the variable distributions, it can be seen that, from all perspectives, a higher degree of urbanisation leads to a higher crash rate. The results of the regression trees truly show which characteristic combinations cause a high or low crash rate. For motor vehicle crashes, it can be seen that the lowest crash rate is caused by a higher speed limit (≥70kph), a situation without mixed traffic and a share of freight traffic of more than 15%. The combination of a low speed limit (≤60 kph) and strongly urbanised area results in the highest crash rate. The same is true for motor vehicle-bicycle crashes per billion motor vehicle kilometres. However, the combining a low degree of urbanisation and a speed limit of ≥ 60kph provides the lowest crash rate. From the perspective of the cyclist with and without motor vehicle crashes, it can be seen that the same combination of road characteristics seems to cause the lowest and highest crash rate. At last, the regression trees also show impactful road characteristics on the crash rate, as they are higher up the tree for perspectives. These are the speed limit, the degree of urbanisation, bicycle facility type and the freight traffic share. These characteristics seem to influence the risk of a road crash, although these characteristics may still be correlated.

3. How do crash rates for different vehicle types and road characteristics on non-primary roads in the Netherlands vary at the regional scale?

The results of the provincial vehicle matrices have shown that the patterns remain the same as the national picture. The distributions appear to differ slightly, with a maximum difference of 5%. However, The results of the significance tests indicate that, in most cases, the national and provincial crash rates are significantly different. In all perspectives, variations in crash rates can be observed. The results of the provincial regression trees showed similar findings. Zeeland and Drenthe show the least significant differences compared to the national crash rate; this suggests these provinces are close to the national average. In most cases, other provinces significantly differ from the national crash rate. These significant differences in this analysis indicate that, supported by statistical evidence, the national crash rate is not applicable for provincial traffic safety issues.

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Appendix A. Provincial Differences per Road Characteristic

Table 14: Share Billion Motor Vehicle Kilometres in Percent per Provinces per Road Characteristics

Variable	***NL***	**Dr**	**Fl**	**Fr**	**Gl**	**Gr**	**Li**	**NB**	**NH**	**Ov**	**Ut**	**Ze**	**ZH**
Speed limit													
12	***0,2***	0,1	0	0,1	0	0	0,1	0	0,1	0,1	0	0,1	0,1
30	***20,2***	11,6	17,5	17,5	9,8	10,8	10,4	11,7	10,7	11,2	11,3	15,2	10,6
50	***51,7***	45,4	45,4	39,9	51,4	55,5	54,9	51,9	63,7	48,1	58	29	69,8
60	***6,8***	11,1	2,8	9,8	7,7	8,6	4,4	7,7	3,9	6,5	5,2	9,2	5
70	***3,5***	4,4	4,4	3,9	1,3	9,7	2,8	6,8	6,6	5,1	4,9	5,5	2,6
80	***17,4***	27,5	29,9	28,8	29,8	15,4	27,4	21,9	15	30	20,6	41	11,9
Bicycle Facilities													
Suggestion lane	***10,2***	5,4	3,9	7,2	12,8	6,8	18,6	11,6	10,1	16,1	9,5	7,6	10,3
Bicycle Path	***32,8***	32,4	16,3	25,2	33,6	29	35,2	34,7	32,4	26,2	32,2	28	34,9
Bicycle Prohibited	***27,4***	35,3	60,5	36,6	30,8	32,7	21,9	32,7	35,2	33	37,6	40,8	31,7
Mixed traffic	***29,6***	26,8	19,3	31	22,8	31,6	24,3	21	22,3	24,8	20,7	23,6	23,1
Number of lanes													
One	***93,7***	97,9	86,9	91,3	91,9	89,9	92,6	89	91,2	92,3	94,7	96,4	91,5
More than two	***6,3***	2,1	13,1	8,7	8,1	10,1	7,4	11	8,8	7,7	5,3	3,6	8,5
Urbanisation													
Strongly urbanised	***40,9***	10,7	32,6	27,7	29,4	40,4	34,4	36,3	57,3	29,2	47,6	18,4	66,1
Moderately urbanised	***31,1***	33	33,6	26,4	34,7	27,5	29,1	32,8	24,7	30,3	30,2	23,9	20,5
Not urbanised	***28***	56,3	33,7	45,9	35,9	32,1	36,5	30,9	17,9	40,5	22,2	57,6	13,4
Number of ways													
One	***37,4***	20,6	51,5	26,1	29,9	32,5	30,7	40,3	43,3	30,1	40,6	27,4	50,3
Two	***62,6***	79,4	48,5	73,9	70,1	67,5	69,3	59,7	56,7	69,9	59,4	72,6	49,7
Freight share													
No freight	***0***	0	0	0	0	0	0	0	0	0	0	0	0
Below avg freight	***8,8***	4,3	8	3,1	3,6	4,1	3,4	4,2	4,2	3,8	4,2	3,2	4,2
Around avg freight	***40***	31,4	35,1	36,1	36,7	32,3	43,7	38,9	39,4	28,1	43,6	33,3	44,3
Above avg freight	***51,1***	64,2	56,8	60,8	59,7	63,5	52,8	56,9	56,3	68,1	52,1	63,5	51,5

NL: Nederland, Dr: Drenthe, Fl: Flevoland, Fr: Friesland, Gl: Gelderland, Gr: Groningen, Li: Limburg, NB: Noord-Brabant, NH: Noord-Holland, Ov: Overijssel, Ut: Utrecht, Ze: Zeeland & ZH: Zuid-Holland.

Table 15: Share Billion Bicycle Vehicle Kilometres in Percent per Provinces per Road Characteristics

Variable	***NL***	**Dr**	**Fl**	**Fr**	**Gl**	**Gr**	**Li**	**NB**	**NH**	**Ov**	**Ut**	**Ze**	**ZH**
Speed limit													
12	***1,1***	2,5	0	0,6	0,6	0,6	0,5	0,4	0,5	0,8	0,3	1	0,6
30	***56,5***	45,3	72,9	53	44,3	46,6	40,9	48,1	47,2	46,8	42,4	55,4	41,2
50	***34***	35,2	21,3	29	39,5	45	48,6	39,3	48,1	40,7	46,3	25,6	52,8
60	***5,7***	11,1	1,9	11,1	9,8	5	4,6	8,1	2,4	7,7	6,7	11,1	3,9
70	***0,3***	0,6	0,4	0,3	0,1	0,3	0,6	1	0,5	0,8	0,5	0,3	0,2
80	***2,4***	5,3	3,5	5,9	5,7	2,4	4,8	3,1	1,3	3,2	3,7	6,6	1,3
Bicycle Facilities													
Suggestion lane	***13***	13,3	7,3	9,2	22,2	10,6	26,3	21,3	15,5	24,2	18,2	17,8	15,6
Bicycle Path	***26,1***	28,6	29,5	24,4	26,2	24,2	22,6	29,4	35,3	19,8	32,7	24	34,4
Bicycle Prohibited	***0***	0	0	0	0	0	0	0	0	0	0	0	0
Mixed traffic	***60,9***	58,1	63,2	66,4	51,6	65,2	51,1	49,2	49,2	56	49,1	58,2	50
Number of lanes													
One	***99,5***	99,9	99,8	99,1	99,3	99,7	98,7	98,9	99,5	99,2	99,6	99,9	99,1
More than two	***0,5***	0,1	0,2	0,9	0,7	0,3	1,3	1,1	0,5	0,8	0,4	0,1	0,9
Urbanisation													
Strongly urbanised	***25,1***	42,4	37	27,8	32,1	20,6	26,7	25,8	11,6	26,2	19,4	30,8	10,4
Moderately urbanised	***12,1***	31,4	7,2	25,8	19	13,2	16,3	14,7	5,1	13,9	10,3	24,4	4,4
Not urbanised	***62,8***	26,2	55,8	46,4	48,9	66,2	57,1	59,5	83,4	59,9	70,3	44,7	85,2
Number of ways													
One	***74,5***	88,2	84,4	85,2	80,7	75,1	76,9	74,6	62,6	79,2	73,4	80,8	60,2
Two	***25,5***	11,8	15,6	14,8	19,3	24,9	23,1	25,4	37,4	20,8	26,6	19,2	39,8
Freight share													
No freight	***33,6***	38,8	25,9	37,6	34,4	39,3	30,7	32	58	39,6	46,5	35,8	42,3
Below avg freight	***2,2***	2,7	6,2	2,6	2,1	1,8	1,4	1,7	1,7	2,2	2,4	1,7	1,4
Around avg freight	***21,1***	15,7	31,8	13,3	15,8	13,3	13,8	15,7	7,8	14,3	11,4	12,5	9,7
Above avg freight	***43,1***	42,9	36,1	46,5	47,7	45,6	54,2	50,6	32,6	43,9	39,7	50,1	46,6

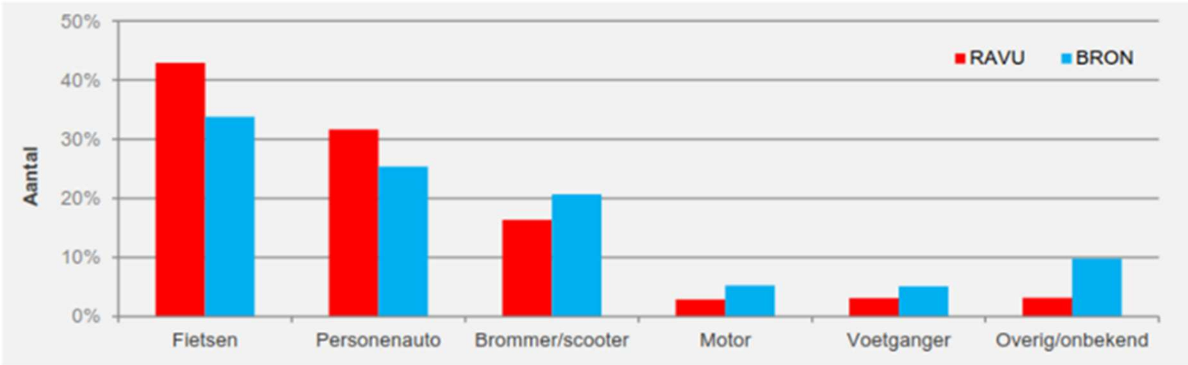
NL: Nederland, Dr: Drenthe, Fl: Flevoland, Fr: Friesland, Gl: Gelderland, Gr: Groningen, Li: Limburg, NB: Noord-Brabant, NH: Noord-Holland, Ov: Overijssel, Ut: Utrecht, Ze: Zeeland & ZH: Zuid-Holland.

Appendix B. Ambulance Versus BRON Data

Three separate analyses have been identified in the literature in which data from BRON and ambulance are compared. VeiligheidNL and SWOV carried out these studies. Veiligheid NL has access to ambulance data from various regions in the Netherlands. In two specific areas, namely the Province of Utrecht (Olij & Nijman, 2020) and the Municipality of Amsterdam (Stam, Versteeg, & Nijman, 2024), discrepancies have been identified between the BRON data and the ambulance incident registrations. SWOV has also conducted a similar study (Aarts, Wijlhuizen, Hermens, & Bos, 2020) but investigated the possibilities of integrating different data sets to obtain a more coherent picture of the crash data.

Veiligheid NL's research in the province of Utrecht established that the available data on ambulance incidents from 2018 is considerably more numerous (4762) than the data from police and BRON sources (1805) (Olij & Nijman, 2020). A similar pattern was observed in the municipality of Amsterdam, which showed that the number of registered traffic victims in BRON data was 1196, while in ambulance data 4845 traffic victims were registered, which is approximately a factor of four higher (Stam, Versteeg, & Nijman, 2024). SWOV's research, which mainly focuses on the linking possibilities of different data sets relating to crashes, also established that BRON data are clearly incomplete, especially regarding a significant number of cycling victims who were injured (Aarts, Wijlhuizen, Hermens, & Bos, 2020). This under-registration is estimated to be significant that BRON data is estimated to include only 10% of actual bicycle crashes without a motor vehicle and only 50% of bicycle victims with a motor vehicle (Aarts, Wijlhuizen, Hermens, & Bos, 2020) . SWOV suggests that the missing data could be supplemented with ambulance data. According to the study, 70,000 ambulance transports take place annually in connection with traffic-related incidents, in contrast to the 19,000 registered crash victims in BRON (Aarts, Wijlhuizen, Hermens, & Bos, 2020).

In the context of road traffic crash research, it is essential to note that ambulance data only includes casualty data, which is typically the reason for the presence of an ambulance at the scene of the crash. These data provide more detailed information about the development of traffic crashes, an aspect that appears to be significantly limited in police data (Olij & Nijman, 2020). This observation illustrates the benefits of ambulance data, but also highlights its limitations, as data regarding non-casualty related crashes are lacking. While such data is available in the BRON system, the completeness of this data is in question, especially when considering the significant discrepancies between the victim-related crash data sets.

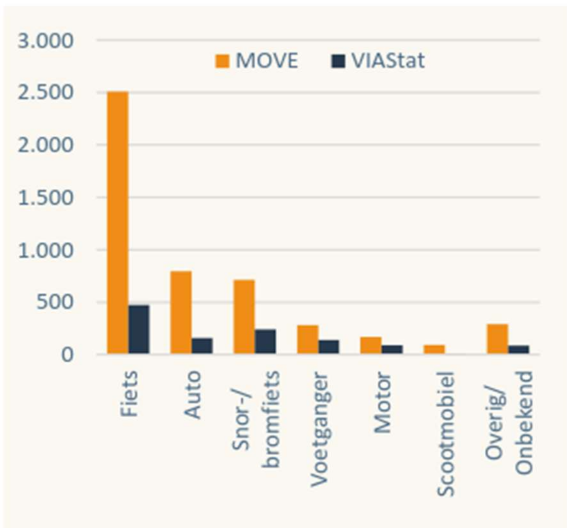


Bron: Verkeersongevallenregistratie Regionale AmbulanceVoorziening Utrecht, 2018, VeiligheidNL, Bestand GeRegistreerde Ongevallen in Nederland, 2018

Figure 29: Traffic Crash Victims RAVU (n=4,762) and BRON (n=1,805) 2018;
by mode of transport (Olij & Nijman, 2020)

In both the research in the province of Utrecht and in the municipality of Amsterdam, an analysis was carried out of the ratio of victims in different types of crashes within both datasets. A close inspection of these proportions' sheds light on interesting findings. In the context of the province of Utrecht, this ratio generally shows a certain degree of a consistent trend between the datasets. Nevertheless, it is essential to note that, as previously noted, bicycle crashes are recorded in more detail in ambulance data, as shown in Figure 29 (Olij & Nijman, 2020). This trend also applies to crashes involving passenger cars. It is striking that in the BRON dataset proportionally more victims are registered in moped and scooter crashes, motorcycle crashes, pedestrian crashes, and other traffic crashes (Olij & Nijman, 2020). This phenomenon can be attributed to the presence of significant gaps in the BRON data regarding bicycle crashes. The findings thus suggest that the observed number of casualties in specific crash categories may be influenced by the degree of data completeness within the data sets used.

	MOVE		BRON/VIA	
	Aantal	%	Aantal	%
Fiets	2.507	52	474	40
E-bike	245	5	75	6
Overige fiets	2.262	47	399	33
Auto	794	16	159	13
Snor-/bromfiets[1]	713	15	239	20
Voetganger	282	6	140	12
Motor	167	3	88	7
Scootmobiel	91	2	9	<1
Bus	15	<1	3	<1
Tram[2]	5	<1	1	<1
Overig/Onbekend	271	6	83	7
Totaal	4.845	100	1.196	100



Bron: VIAStat Amsterdam 2022; Monitor Verkeersongevallen (Ambulancedata) Amsterdam 2022, VeiligheidNL
[1] BRON/VIA: Brommer/snorfiets; MOVE Snor-/bromfiets/scooter. Idem in figuur
[2] BRON/VIA: Tram/trein. In figuur bus en tram i.v.m. kleine aantallen toegevoegd aan Overig/onbekend

Figure 28: Traffic Casualties in Amsterdam in 2022
based on BRON/VIA and MOVE ambulance data; by mode of transport (Stam, Versteeg, & Nijman, 2024)

The ratio of casualties between vehicle types for the municipality of Amsterdam is shown in Figure 28 (Stam, Versteeg, & Nijman, 2024), which also includes the total number of casualty crashes. These proportions appear to be reasonably comparable to those from the research conducted by the province of Utrecht (Stam, Versteeg, & Nijman, 2024). However, it is not possible to conclude from this that this also applies to national figures. Furthermore, this study includes an analysis of the spatial aspect of crashes, which shows that the locations with the most crashes for the datasets largely coincide (Stam, Versteeg, & Nijman, 2024). It is important to note that the traffic situation differs per city district, resulting in different numbers of registered crashes per district. Nevertheless, the data shows that the collection location of ambulance data does not always correspond to the location of the crash itself. This can occur, for example, when a victim travels home after the crash before he or she is picked up by the ambulance.