TO MIX OR NOT TO MIX: COMPARING THE SAFETY OF BICYCLE FACILITIES ON 30 KM/H DISTRIBUTOR ROADS IN AMSTERDAM

THESIS
submitted in fulfilment
for the degree of
Master of Science
in Metropolitan Analysis, Design and Engineering

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Amsterdam, 19 August 2026

PREFACE

Long before I knew that spatial planning existed as a field of study, I was already deeply fascinated by the streets, neighbourhoods, and cities that surround us. I would spend hours studying atlases and maps, and try to memorise every country and capital. My notebooks were filled with sketches of imaginary street plans of grandiose cities, and proposed expansions of my hometown. At the time, these were simply things I enjoyed doing. I did not think of them as clues about what I might one day become.

Of all those fond childhood memories, one in particular has always stuck with me. I was handed a copy of SimCity 3000, which I would play incessantly on the ancient, yellowed living room PC complete with a CRT monitor. Somewhere in that game was when I encountered the term "spatial planner" for the first time. At the age of nine, I had no clue what those words meant, let alone imagine that one day, I would make it my profession. And yet, many years later, those small steps have become a journey that has ultimately culminated in this thesis. I am deeply grateful that I was able to have discovered my passion. And being able to study it, build my career out of it, and contribute to society is an even greater privilege.

Having said that, none of this however could have been accomplished alone. To Marjan and Erick, thank you for your guidance throughout the entire process; your feedback and questions helped me elevate my work beyond what I could have achieved on my own. I would also like to thank the Municipality of Haarlemmermeer for giving me the opportunity to conduct this study during my internship with them. A special word of thanks also goes out to Teun Uijtdewilligen from SWOV, who provided me the bicycle volume data that was essential to this study. Lastly, I would like to express my gratitude to my family, friends, and those dearest to my heart, for I would not have made it this far without them. It has not always been easy to stay disciplined, and their encouragement and companionship inspired me to keep on going.

ABSTRACT

The introduction of 30 km/h distributor roads (GOW30) as a new road category in the Netherlands has raised the question for road authorities whether physical separation between cyclists and motor vehicles remains necessary at lower speeds. This study investigated the safety of bicycle tracks and bicycle lanes on GOW30 roads in Amsterdam across road segments and intersections. 572 police-registered bicycle-motor vehicle crashes from 2024 and 2025 were analysed using crash prediction modelling. On road segments, bicycle lanes had approximately three times the expected crash frequency of bicycle tracks, after accounting for segment length, bicycle volume, motor vehicle volume and V_{85} speed. At intersections however, no statistically significant difference was found between the two facility types. The results indicate that the lower speed limit on GOW30 roads do not make bicycle lanes comparable to bicycle tracks in terms of segment level safety.

Keywords: GOW30; bicycle safety; bicycle tracks; bicycle lanes; crash prediction modelling; Poisson regression; logistic regression; bicycle-motor vehicle crashes; BMV crashes

SUMMARY

Purpose

Recently in the Netherlands, a new type of distributor road has been introduced: GOW30, which aims to preserve the traffic flow and distribution function of a distributor road but with a lower speed limit of 30 km/h. The preliminary design guidelines recommend bicycle lanes as the standard bicycle facility on these roads, while noting that bicycle tracks may be retained if already present. This, however, raises the question of whether physical separation remains necessary when motor vehicles travel at lower speeds and if, hypothetically, conditions would be safe enough to allow cyclists and motor vehicles to mix.

Previous research generally finds bicycle tracks to be safer than bicycle lanes on road segments, while findings at intersections are less consistent. However, to the author's knowledge, no study to date has investigated the safety of these facilities specifically on GOW30 roads. This study therefore addresses the following research question: "What is the relationship between bicycle facility type and bicycle-motor vehicle (BMV) crash frequency on GOW30 distributor roads, when controlling for traffic volumes and speeds, and distinguishing between road segments and intersections?".

Method

To compare the safety of bicycle tracks and lanes, a crash prediction modelling approach was used. For this purpose, 572 police-registered bicycle-motor vehicle (BMV) crashes on GOW30 roads in Amsterdam from 2024 and 2025 were gathered, together with data on bicycle facility type, bicycle volume, motor vehicle volume, and motor vehicle V_{85} speed. These data were linked to a road network sourced from the Dutch National Road Database (NWB), with GOW30 segments identified using municipal data. Intersections were subsequently generated from GOW30, which yielded a master road dataset in which each GOW30 road segment and intersection

had the relevant crash, infrastructure, exposure, and speed data. The data were then exported into a separate segment- and intersection-level dataset.

Using these two datasets, regression modelling was then used to estimate the expected frequency of BMV crashes while accounting for differences in traffic volume and motor vehicle speed. Initially, quasi-Poisson regression models were estimated for road segments and intersections, but because the crash data as highly sparse, logistic regression was also performed as a sensitivity analysis to assess the quasi-Poisson regression results.

Results

The regression modelling show that on road segments, bicycle lanes were associated with a higher expected crash frequency of approximately 3.0 times that of bicycle tracks. At the intersection level however, no statistically significant difference in expected crash frequencies was found between bicycle tracks and bicycle lanes. Increased bicycle and motor-vehicle volumes were positively associated with higher expected crash frequencies, which is in line with existing literature. Finally, a higher V_{85} motor-vehicle speed showed a negative association with crashes on segments, which was interpreted as being a reflection of local road complexity or congestion, rather than a positive safety effect caused by higher speeds.

Conclusion

This study shows that the physical separation that bicycle tracks offer remains important, and the lower speeds associated with bicycle lanes is in itself insufficient reason to replace existing bicycle tracks. In situations where bicycle lanes are already present, additional measures should be considered to further improve cyclist safety, despite the lowered speed limit.

The findings for intersections remained inconclusive; instead, based on prior literature, intersection treatments such as setbacks from the carriageway should be taken in mind in the GOW30 road design process. Several limitations should be kept in mind when interpreting these conclusions, such as the highly sparse crash data and the limited number of variables included in the intersection models. Future research could address these limitations by incorporating ambulance-registered crash data and more detailed intersection characteristics.

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1 INTRODUCTION

1.1 INTRODUCTION

Cycling has been increasingly promoted as a sustainable alternative to motorised travel, as there is strong evidence that it yields substantial health benefits, contributes to more liveable environments, and improves accessibility for all road users (Scheepers et al., 2014; Winters et al., 2017; Xiao et al., 2022). However, cyclists are particularly vulnerable in crashes with motor vehicles; in 2023, they accounted for 39% of road fatalities and 70% of serious injuries in the Netherlands (Oude Mulders, 2024).

A disproportionate share of these crashes occurs on distributor roads, which typically carry higher traffic volumes at greater speeds than access roads (Schepers et al., 2017). In an attempt to mitigate these safety risks, road design guidelines in the Netherlands aim to categorise the road network into a hierarchy, with each road category having its own specific function and design recommendations (CROW, 2021a; Weijermars & Van Schagen, 2009). Its aim is to increase road safety by implementing network-level separation, with slower, local traffic on access roads segregated from through traffic on distributor roads.

In recent times, concerns about traffic safety and liveability have been growing regarding distributor roads within built-up areas, which usually have a speed limit of 50 km/h (CROW, 2021b), leading to the introduction of a new road standard: GOW30 (30 km/h distributor road). Because this category is relatively new, policy and design guidelines for GOW30 roads are still in development and rely largely on preliminary recommendations and ongoing research efforts (Odijk et al., 2025). Under these preliminary design guidelines, visually demarcated bicycle lanes are the default facility for GOW30 roads (CROW, 2023). However, it also specifies that existing bicycle tracks can be retained if already present. This creates a decision-making problem for road authorities: when redesigning a road as GOW30, should existing bicycle tracks be retained or should they get replaced by bicycle lanes?

Although a substantial body of research has compared the safety effects of different types of bicycle facilities, results specifically comparing bicycle tracks against lanes remain inconclusive. While literature generally seems to agree that bicycle tracks offer more safety for cyclists than bicycle lanes (Petegem et al., 2021; Welleman & Dijkstra, 1988), it also suggests that the safety differences between the two may vary across the road segment and intersection level. On road segments, bicycle tracks offer physical separation, which reduces direct conflicts that may occur when bicycle lanes are present, such as overtaking manoeuvres or rear-end collisions (DiGioia et al., 2017). At intersections, however, this separation may have adverse effects on safety, due to e.g. reduced driver awareness and visibility (Herslund & Jørgensen, 2003).

Therefore, it remains unclear how these two bicycle facilities perform in terms of safety on 30 km/h distributor roads, measured across segments and intersections. To gain further insights in this gap, the central research question of this study is as follows: What is the relationship between bicycle facility type and bicycle-motor vehicle (BMV) crash frequency on GOW30 distributor roads, when controlling for traffic volumes and speeds, and distinguishing between road segments and intersections?

1.2 RESEARCH AIMS, RELEVANCE & SCOPE

The main objective of this study is to evaluate the safety of two different bicycle facilities, bicycle tracks and bicycle lanes, on 30 km/h distributor roads (GOW30), and whether these differ between the road segment level and the intersection level. To investigate this, a crash prediction modelling approach is used and estimated with quasi-Poisson regression, which allowed for controlling for factors such as bicycle volume, motor vehicle volume, and motor vehicle speed.

Multiple studies have evaluated the safety of various bicycle facilities using a crash prediction modelling approach; however, existing Dutch and international literature remains limited in several aspects. First, earlier studies that modelled crash frequency across the road segment an intersection level may be outdated (Welleman & Dijkstra, 1988) as road design guidelines have changed considerably in the Netherlands since then. Second, previous crash modelling studies predominantly evaluated roads with higher speed limits (Kondo et al., 2018; Mahmoud et al., 2023; Ugan et al., 2022), while the GOW30 road standard is an unique case as it combines a lower speed limit of an access road while serving higher traffic volumes characteristic of distributor roads. Last, many previous studies model bicycle safety either at a macro-level, such as area or network wide (Abbasi & Ko, 2024; Yasmin & Eluru, 2016), or aggregate the segment and intersection levels into a single road corridor level (Petegem et al., 2021). By modelling both the two levels of measurement separately, this study aims to isolate how bicycle tracks and lanes perform safety-wise across both levels and whether the crash rate between segments and intersections balance out.

From a policy perspective, this research aims to provide road authorities with empirical evidence to better substantiate and motivate design choices when designing GOW30 roads. The current preliminary guideline (CROW, 2023) establishes bicycle lanes as the standard bicycle facility at these roads, but permits for retaining tracks if already present. This leaves uncertainty for road authorities during the design process, as they lack empirical evidence whether converting existing bicycle tracks with lanes is permissible from a safety standpoint.

As this study operationalises the safety performance of bicycle lanes and tracks as the expected frequency of bicycle-motor vehicle (BMV) crashes, other types of crashes such as single-bicycle crashes (falls or collisions with public street furniture), crashes with other traffic modes, injury severity, or perceived safety fall outside its scope and are therefore not considered.

Additionally, the analysis in this study is limited to the municipal road network of Amsterdam. This case was selected as it implemented a 30 km/h speed limit across its network in December 2023, which provided a large number of GOW30 roads to evaluate and allows for the evaluation of two years of crash data, namely 2024 and 2025 (Municipality of Amsterdam, 2025). Furthermore, this pick was motivated by data availability, as modelling crash frequency on a micro-level (segments and intersections) required segment-level bicycle volume data, which was made available for the Amsterdam road network by Teun Uijtdewilligen.

2 Literature review

2.1 Cyclist safety and infrastructure

As chapter 1.1 establishes, cyclists are at increased risk of severe injuries or fatality in traffic crashes, when compared to motor vehicle occupants (Kreißig et al., 2022); which can be attributed to the substantial differences in mass and speed between cyclists and motor vehicles. As impact energy in a crash increases with both mass and speed, cyclists face significantly more severe injury outcomes in collisions with motor vehicles due to their lack of physical protection and direct exposure to impact forces. This effect gets further exacerbated by higher vehicles speeds, as Mofolasayo (2020) shows that crash severity displays a non-linear correlation with speed, which means even relatively small increases in vehicle speed lead to significantly higher injury severity.

The increased vulnerability of cyclists within the transport system becomes especially relevant in urban environments, as motor traffic volumes tend to be higher in comparison with rural areas, leading to more interactions between road users and thereby raising cyclists' exposure to potential conflicts, and consequently, crashes (Dumbaugh & Li, 2010; Hamann & Peek-Asa, 2013). It should be noted that within urban areas, the possibility of a crash occuring is not evenly distributed across the road network. A disproportionate share of BMV crashes occur along distributor roads. In addition, multiple studies show that BMV crashes are heavily concentrated at intersections, which account for the majority of such incidents in urban networks (Cai et al., 2021; Schepers et al., 2017; Twisk et al., 2013). This can largely be attributed to the increased complexity in the manoeuvres of road users and possible conflicts, when compared to straight road segments (Schröter et al., 2023).

These findings suggest that cyclist safety is closely related to the environments and conditions under which interactions between cyclists and motor vehicles occur within the network. To mitigate crash risk, policymakers widely use bicycle infrastructure as an instrument to reduce or influence interactions between cyclists and motor vehicles (Meuleners et al., 2020), which can be done through e.g. network level separation (Schepers et al., 2017), or the provision of bicycle facilities, such as bicycle tracks and bicycle lanes.

2.2 SAFETY EFFECTS OF BICYCLE TRACKS AND BICYCLE LANES

Existing literature indicates that bicycle infrastructure influences cyclist safety: in a review that analysed 23 studies on transportation infrastructure and cyclist safety, Reynolds et al. (2009) find that purpose-built bicycle facilities reduce the risk of crashes compared with mixed-traffic conditions, in which cyclists share the same road space as other traffic users. However, the studies included in their review cover a wide variety of bicycle facility types with differing designs. These facilities can broadly by distinguished by the method and degree of separation it offers to cyclists from motor traffic. Morrison et al. (2019) categorises these facility types into bicycle lanes, which are designated spaces on the main carriageway intended for bicycle use indicated by painted markings, and bicycle tracks, which are adjacent to the carriageway and physically separated from motor vehicles.

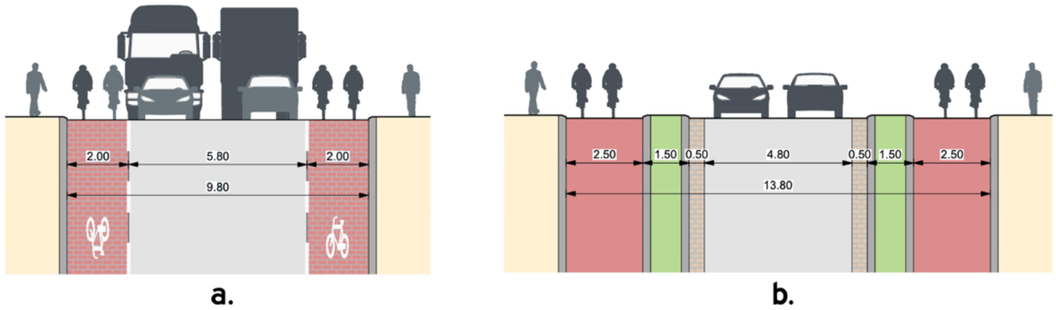

Figure 2.1. Common bicycle facilities on urban distributor roads in the Netherlands. Road layouts with bicycle lanes (a) and bicycle tracks (b). Source: Goudappel, (2025)

While both bicycle lanes and bicycle tracks are generally associated with lower BMV frequency than the absence of a dedicated bicycle facility (Deliali et al., 2023; Reynolds et al., 2009), findings from studies that directly compare the two remain mixed. Multiple comparative studies find that bicycle tracks are associated with lower crash frequencies than bicycle lanes (Deliali et al., 2023; Welleman & Dijkstra, 1988), but other studies suggest that this safety advantage does not seem to apply consistently across the entire network. Madsen and Lahrmann (2017) note that while bicycle tracks may be associated with fewer crashes on road segments, they display higher crash rates at intersections. Overall, the literature thus seems to suggest that differences in safety between bicycle tracks and bicycle lanes depends on the level at which safety is measured. For that reason, the literature is discussed separately below for road segments and intersections.

2.2.1 Road segment level

DiGioia et al. (2017) identify that in order for a bicycle facility to reduce either the number of BMV crashes, it needs to increase the separation of bicycles and motor vehicles in time and space, increase the visibility of non-motorised users, improve lines of sight between the modes, reduce the number of interactions between modes, and reduce motor-vehicle speeds.

Therefore, given these principles, bicycle tracks can be expected to offer safety advantages on road segments, as they provide a greater degree of separation from motor traffic than bicycle lanes. This separation may be implemented through physical barriers, such as raised kerbs, or through placing the cycle track at a distance from the main carriageway. Multiple empirical studies report findings consistent with this expectation. Thomas and DeRobertis (2013) conducted a literature review of bicycle tracks covering 23 papers in which they conclude that bicycle tracks can improve safety when compared to mixed-traffic conditions, especially if appropriate intersection treatments are applied. Additionally, they argue that bicycle tracks appear to eliminate the collision types that occur at the road segment level, such as cyclists riding into a car door or being hit by a motor vehicle from behind, with the latter having the highest fatality rate.

This is consistent with findings from studies that compare bicycle tracks against bicycle lanes more directly. A prominent Dutch study by Welleman and Dijkstra (1988) analysed 145 road segments, controlling for volumes of cyclists and motor vehicles, and found that at the level of road segments and unsignalised intersections, bicycle tracks experienced 59% fewer BMV crashes than those with bicycle lanes. A notable finding is that bicycle lanes performed worst at this level, with crash rates exceeding even those of roads without any bicycle facility. These similar patterns were also noted by Madsen and Lahrmann (2017), who observe that earlier studies associate bicycle tracks with fewer crashes on road segments, whereas bicycle lanes perform worse compared to both bicycle tracks and roads without bicycle facilities.

More recent studies, however, suggest that bicycle lanes can still offer safety benefits. Deliali et al. (2023), for example, find that bicycle lanes are associated with lower crash rates on road segments than roads lacking any bicycle facilities, although the reported safety effect is substantially stronger for bicycle tracks. A similar finding is reported by Morrison et al. (2019), who similarly note that bicycle tracks are associated with the most substantial safety benefits, but that bicycle lanes still offer improvements in cyclist safety, reducing crash rates with up to 25% compared to road segments without any facility.

In conclusion, while the literature consistently indicates a clear safety benefit of bicycle tracks at the segment level, compared to other facility types (or lack thereof), the consensus regarding bicycle lanes remains mixed, which was also concluded by a critical literature review by DiGioia et al. (2017). Across the studies they reviewed, they found the safety benefits of bicycle lanes to be mixed, and not statistically significant. Instead, their analysis suggests that other factors should be taken into consideration when considering their safety, such as design factors (bicycle lane width) or environmental factors (presence of on-street parking).

2.2.2 Intersection level

When shifting the unit of analysis from the road segment level to the intersection level, the comparative safety of bicycle tracks versus bicycle lanes becomes less clear, with multiple studies showing conflicting results. Several studies have found bicycle tracks to be associated with higher BMV crash rates at signalised intersections: Madsen and Lahrmann (2017) reviewed earlier literature regarding bicycle facilities at intersections and found the general consensus to be that although bicycle tracks reduce crashes on road segments, they are associated with more crashes at intersections, particularly at those with traffic signals (signalised intersections). In a direct comparison between bicycle lanes and tracks, Welleman and Dijkstra (1988) found that the latter were associated with 50% higher crash rates at signalised intersections. This result was similarly observed by Liu and Marker (2020), who proposed that it may be explained by reduced visual interaction between cyclists and motorists due to physical separation. Because bicycle tracks are located further from the main carriageway, cyclists may remain less visible to motorists while approaching an intersection, until their paths cross at the intersection. This may increase the potential of conflicts between cyclists travelling straight, and turning vehicles.

However, at the same time, Liu and Marker (2020) also note that the safety effects of bicycle facilities depend heavily on their context, and that studies should thus also consider such contextual factors, such as geometric design and other infrastructure characteristics. A method that aims to improve bicycle safety at intersections are intersection treatments such as advanced stop lines, raised or coloured bicycle crossings, or setbacks. Madsen and Lahrmann (2017) compared five different bicycle facility layouts at signalised intersections in Denmark, and found a recessed bicycle track, i.e. placed at a distance from the main carriageway, to be the safest layout. As an interpretation of this result, they propose that a sufficiently large setback allows a turning motorist to complete their initial part of the turn, before crossing the bicycle facility present at the intersection. At this position, the vehicle finds itself nearly perpendicular to the bicycle facility, which makes it easier to observe approaching cyclists, and at the same time provides space in which the motorist can wait before crossing.

This positive safety effect of setback is supported by Schepers et al. (2011), who evaluated BMV crash frequency at unsignalised priority intersections between distributor roads and access roads. When the bicycle track was positioned 0-2 metres away from the carriageway, no significant difference was found between tracks and lanes. However, when the setback distance was 2 to 5 metres, one-way bicycle tracks were found to be substantially safer than bicycle lanes, and resulted in 45% fewer BMV crashes.

The effects of setback distance in influencing crash rates at intersections is commonly explained through the visibility of cyclists and the scanning behaviour of motorists (Elvik et al., 2009; Liu & Marker, 2020). By introducing additional space between the carriageway and the bicycle facility at the intersection itself, motorists have the opportunity to reduce speed and perform additional visual scanning before completing their turn. This is consistent with findings by Asgarzadeh et al. (2017), who note that speed reduction interventions such as speed bumps near intersections can help improve the visual scanning behaviour of motorists and result in increased hazard detection.

To conclude, the literature regarding the safety effects at intersections suggest that facility type should not be viewed in isolation to determine bicyclist safety. While the reduced visibility due to physical separation has been hypothesised as a possible explanation for worse safety effects of tracks at intersections, several studies (Madsen & Lahrmann, 2017; Schepers et al., 2011) show that this can be overcome with appropriate intersection treatments, and even result in bicycle tracks being safer than lanes at intersections.

2.3 DUTCH CONTEXT: SUSTAINABLE SAFETY AND GOW30 ROADS

2.3.1 Road categorisation

For multiple decades, road and traffic safety has been an important policy goal in the Netherlands. In 1991, the term *Duurzaam Veilig* (Sustainable Safety) was introduced as a vision for systematically improving traffic safety (Weijermars & Van Schagen, 2009). The following year, this vision was further elaborated by SWOV (1992) in a publication which introduced three leading traffic safety principles: 1. Functionality, 2. Homogeneity, and 3. Recognisability. These principles have since served as the foundation for a wide range of policy measures and design standards (SWOV, 2018).

For example, its first principle, Functionality, has led to the categorisation of the Dutch road network into three types ranked in a hierarchical order, from highest to lowest:

Road category	Function
Stroomweg (SW) *Through road*	Designed for high-speed, motorised through traffic; separation of traffic streams and minimal conflict points.
Gebiedsontsluitingsweg (GOW) *Distributor road*	Connects through roads to access roads. Facilitates traffic flow on road segments and the exchange of traffic at intersections.
Erftoegangsweg (ETW) *Access road*	Provides direct access to destinations (e.g. residences, shops) and the exchange and mixing of traffic, typically at low speeds.

Table 2.1. Road network hierarchy. Overview of the functional classification of Dutch roads as governed by Sustainable Safety.

The principle of Functionality prescribes that roads should ideally serve a single purpose: either the flow of traffic or the exchange of traffic. Roads with a traffic flow function are characterised by allowing for the smooth flow of traffic with little to no direct interaction between road users and its surrounding environment. In contrast, roads with a *verblijfsfunctie* (place function) facilitate the exchange of traffic and involve interaction between road users and its environment, where movements such as crossing, turning, and stopping takes place. As the former aims to reduce interactions and/or conflicts to a minimum, the place function facilitates movements and interactions, and thus combining both on the same road can lead to safety risks (SWOV, 2019).

In practice, however, many roads continue to serve both functions, especially in built-up areas. Some access roads have seen increases in traffic to the extent that they increasingly perform the function of a distributor road. At the same time, some distributor roads cannot be safely designed to allow for a maximum speed of 50 km/h, due to e.g. space constraints, which prevents the implementation of physically separated bicycle tracks. Another case where a lower speed limit of 30 km/h would be preferable from a traffic safety viewpoint would be due to contextual factors such as nearby schools, needs to facilitate safe crossings, or liveability concerns (CROW, 2023).

In light of this, a need emerged to differentiate within the distributor road category by distinguishing between the existing GOW50 (distributor roads with a maximum speed of 50 km/h) and a new sub-category, GOW30, with a maximum speed of 30 km/h (CROW, 2021c). Roads belonging to the latter category retain the traffic flow function of a GOW50 to a certain extent, but have a lower maximum speed to enhance safety and to better serve the place function. Although the maximum speed is like that of an access road, traffic circulation and travel times are generally more efficient on a GOW30 compared to an access road, since it is supposed to fulfil a more pronounced network function (CROW, 2023).

2.3.2 Bicycle facility classification

In the Netherlands, bicycle infrastructure can generally be found in several distinct types. Bicycle tracks are physically segregated from the carriageway, which provides cyclists with their own dedicated space that is separated from motorised traffic. On-road bicycle facilities can constitute types such an absence of a dedicated facility (commonly referred to as mixed traffic conditions), bicycle streets, or bicycle lanes (Uijtdewilligen et al., 2022). The latter are marked lanes on the carriageway itself, typically visually distinguished by red asphalt, white line marking, and a white bicycle symbol, signalling to traffic users that this space is exclusively intended for cyclists (Uijtdewilligen et al., 2024).

The provision of bicycle facilities is generally guided by recommendations published by CROW. CROW is a Dutch knowledge institute that develops and publishes advisory standards and guidelines for infrastructure and public space, and while their guidelines are not legally binding, they are widely used by road authorities and governments (CROW, 2025). In its publication Aanbevelingen voor Verkeersvoorzieningen binnen de Bebouwde Kom (Recommendations for Traffic

Facilities within Built-up Areas; ASVV), CROW (2021a) sets out the minimum and recommended design standards for GOW50 roads. Under both design standards, a dedicated bicycle facility should be present; mixed traffic conditions are not considered appropriate. The minimum standard prescribes bicycle lanes, whereas the recommended standard prescribes bicycle tracks.

These recommendations are consistent with the second leading Sustainable Safety principle, Homogeneity; which refers to the aim of reducing differences among traffic in mass, speed, and direction. The underlying rationale is that conflicts between traffic with large differences in mass or speed, or head-on conflicts are likely to result in more and severe injuries. Separating different types of traffic is therefore a primary method to achieve homogeneity and prevent these conflicts. This can be implemented at e.g. the network level (Schepers et al., 2017) or by applying physical separation at the road level. However, as mentioned in the previous chapter, implementing physical separation is often not possible due to space constraints. In these cases, based on the Homogeneity principle, vehicle speeds must be reduced to a level at which potential conflicts can occur without leading to serious injury (Weijermars & Van Schagen, 2009).

Given its relatively recent status as a distinct subcategory within distributor roads, the GOW30 road category and its design guidelines are still actively evolving. In 2025, an initial phase of a multi-year research was published by SWOV, which aims to provide insights for governments intended to better substantiate future GOW30 road design choices (Odijk et al., 2025). Pending the outcomes of these ongoing studies and updated guidelines, road authorities and governments currently rely on a document published by CROW (2023) that stipulates preliminary recommended design guidelines for GOW30 roads, such as paving type, road markings, and bicycle facilities. Similar to GOW50 roads, it prescribes the provision of a dedicated bicycle facility.

However, unlike GOW50 which ideally has bicycle tracks and at minimum bicycle lanes, the recommended default bicycle facility for GOW30 consists of bicycle lanes.

This choice is partly driven by practical considerations. In many cases, the GOW30 category is applied to former GOW50 roads that could not be safely designed to provide bicycle tracks due to space constraints (CROW, 2023). Aside from this practical reason, the recommendation to apply bicycle lanes is also grounded in the third leading Sustainable Safety principle, Recognisability. This principle stipulates that road design must be consistent and predictable to its users, so that they instinctively adopt the appropriate behaviour and speed.

In light of this principle, in its preliminary design manual for GOW30, CROW (2023) advises implementing bicycle lanes on GOW30 roads, and reserving bicycle tracks for GOW50. However, despite this guideline, it also mentions an exception that "if a bicycle track is already present on a GOW30 road, removing it in favour of a bicycle lane is illogical", as they state that bicycle tracks remain safer for cyclists. It can therefore be argued that this exception compromises the principle of Recognisability, and tolerates the risk of higher motor vehicle speeds (which the guideline mention tracks can induce) to maintain safety. This implies that while Recognisability enhances overall safety by guiding traffic user behaviour, the direct protection that bicycle tracks offer still outweighs consistency in design.

2.4 Relevant risk factors affecting BMV crashes

Chapter 2.2 focused on how the safety of bicycle tracks and bicycle lanes compare at road segments and intersections; however, bicycle crash risk is influenced not only by infrastructure, but also by a wider range of additional risk factors. In a systematic review of risk factors contributing to BMV crashes, Prati et al. (2018) evaluated 59 peer-reviewed studies and identified a total of 92 risk factors, which they grouped into 5 categories using a safe systems framework specifically adapted to cycling safety, developed by Schepers et al. (2014). Within this framework, crashes result from both exposure to risk and crash risk. Exposure to risk consists of traffic volumes, modal split, and the distribution of traffic over time and space), while crash risk is shaped by three safety pillars: infrastructure, road users, and the vehicles they use.

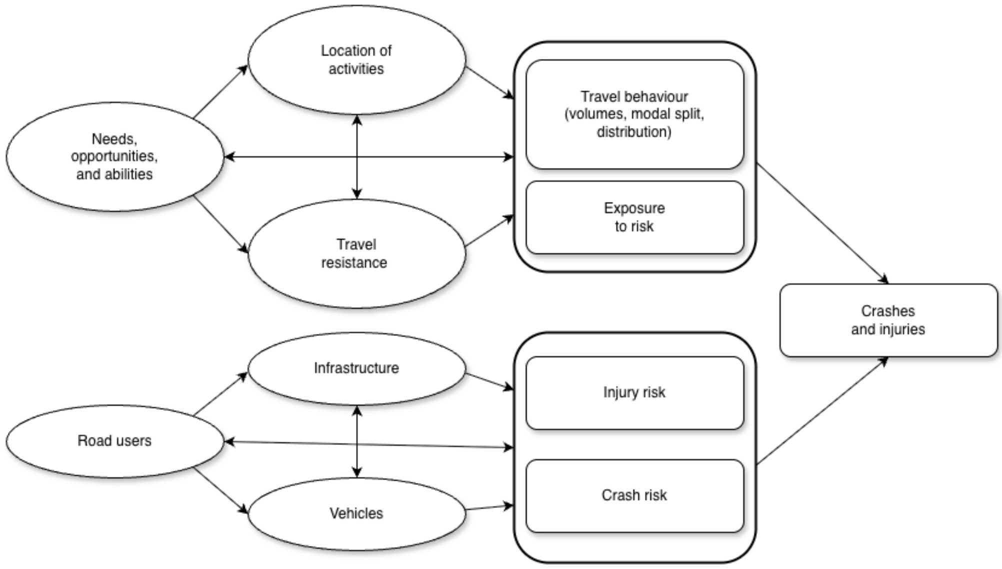

Figure 2.2. Conceptual framework for road safety. The framework includes exposure and risk. Source: Schepers et al. (2014).

2.4.1 Exposure

The relationship between exposure and crash rate is commonly described in crash literature as non-linear, which means that the number of crashes at a given road segment or intersection increases proportionally less with the increase in volume (Schepers et al., 2014). In bicycle safety literature, this non-linear relationship between bicycle volume and crashes is commonly referred to as the "safety in numbers" effect. Elvik (2017) explains that as bicycle volume increases, the number of crashes involving cyclists and motor vehicles increases less in proportion to the number of cyclists.

Several hypotheses have been proposed to explain the effect. Jacobsen et al. (2015) mention that places with higher bicycle volumes often also have more protective traffic laws and safer infrastructure, which attracts more people to cycle. The resulting improvements in safety may therefore partly stem from better conditions, rather than bicycle volume itself. However, safety in numbers has also been observed during seasonal changes in bicycle volume, while infrastructure remained unchanged. They also discuss changes in the behaviour and perception of drivers. In places where cycling is prevalent, drivers are more likely to cycle themselves, encounter cyclists regularly, and expect them more in traffic, which may make them more aware and considerate towards cyclists.

In the Dutch context where good quality bicycle infrastructure is prevalent and uptake of cycling is high, a safety in numbers effect may therefore be harder to identify (Uijtdewilligen et al., 2022). This is supported by Schepers et al. (2011), who note that Dutch drivers already know where to expect cyclists and have adapted their driving behaviour. The relationship between bicycle volume and crash frequency thus may show a lower degree of non-linearity.

Another contributing factor to exposure, in addition to bicycle volume, is motor-vehicle volume. In their review study, Prati et al. (2018) note that several studies found a positive association between motor-vehicle volume and BMV crash risk. Hamann and Peek-Asa (2013) provide empirical evidence to support this with a study of intersection crashes, where they found that for every five motor vehicles during a 30-min period, the odds of an intersection being a crash site increased by 1.04 times.

However, in a similar way as with bicycle volume, the relationship between motor-vehicle volume and crash frequency also takes on a non-linear shape. Elvik and Bjørnskau (2017) show this non-linearity in their meta-analysis and report a summary estimate of the regression coefficient for motor-vehicle volume of 0.50; which is below 1 and thus non-linear. The same coefficient value for bicycle volume was 0.43; which indicates that the relationship with crash frequency is more linear for motor-vehicle volume.

2.4.2 Road users

As shown in figure 2.2, Schepers et al. (2014) model crash risk by the three safety pillars: infrastructure, road users, and vehicles. Given the aim of this study, namely, to evaluate the comparative safety of bicycle facilities on GOW30 roads, the vehicle pillar is outside the scope of the analysis. Since infrastructure has already been discussed in Section 2.2 with the comparison of bicycle tracks and bicycle lanes, this section focuses on the road users pillar. Prati et al. (2018) define the road users pillar to include the behavioural factors of cyclists and drivers, one of which is motor-vehicle speed.

The speed of motor vehicles is highly relevant to cyclist safety because cyclists are vulnerable road users with little physical protection, which means that injuries are likely to be more severe than for car occupants in the event of a crash (Komol et al., 2021). In addition to crash severity, motor-vehicle speed is also relevant to crash occurrence itself. At lower speeds, drivers and cyclists have more time to detect each other and safely make manoeuvres if required, which explains the increased safety of 30 km/h roads (Arias et al., 2021; Prati et al., 2018). Safety literature exploring the relationship between motor-vehicle speed and crashes generally confirms this positive association (Chen, 2015; Yan et al., 2011).

However, more recent studies using observed motor-vehicle speed data show that this relationship can be more complex when it is included in crash prediction modelling. Arias et al. (2021) examined bicycle and pedestrian crashes with motor vehicles on distributor road using observed vehicle speed data. They found that in some models, a V_{85} speed, which is the speed that 85% of vehicles drive at or below, was negatively associated with crash frequency, which seems to contradict the positive association found in earlier safety literature. The authors argue that this result should not be interpreted as evidence suggesting that higher speeds lead to fewer crashes, but rather, a reflection of differences in exposure. In their dataset, higher-speed roads were often rural or suburban roads where fewer cyclists are present, and as a result, had fewer bicycle crashes. In contrast, lower-speed urban distributor roads tend to have higher bicycle volumes and thus a higher likelihood of recorded crashes.

Mahmoud et al. (2023) found a similar negative association between V_{85} speed and crash frequency, but suggest that this may be because lower V_{85} speeds can indicate the presence of road congestion. Under these conditions, there are more interactions between road users and therefore also more opportunities for bicycle crashes to occur. Additionally, similar to Arias et al. (2021), they note that roads with high speeds tend to have lower bicycle volumes, which may explain the lower crash frequency. Since their models did not include bicycle volume data, the V_{85} result may therefore reflect congestion and differences in exposure, rather than a safety benefit from higher motor-vehicle speeds.

2.4.3 Adapted conceptual framework

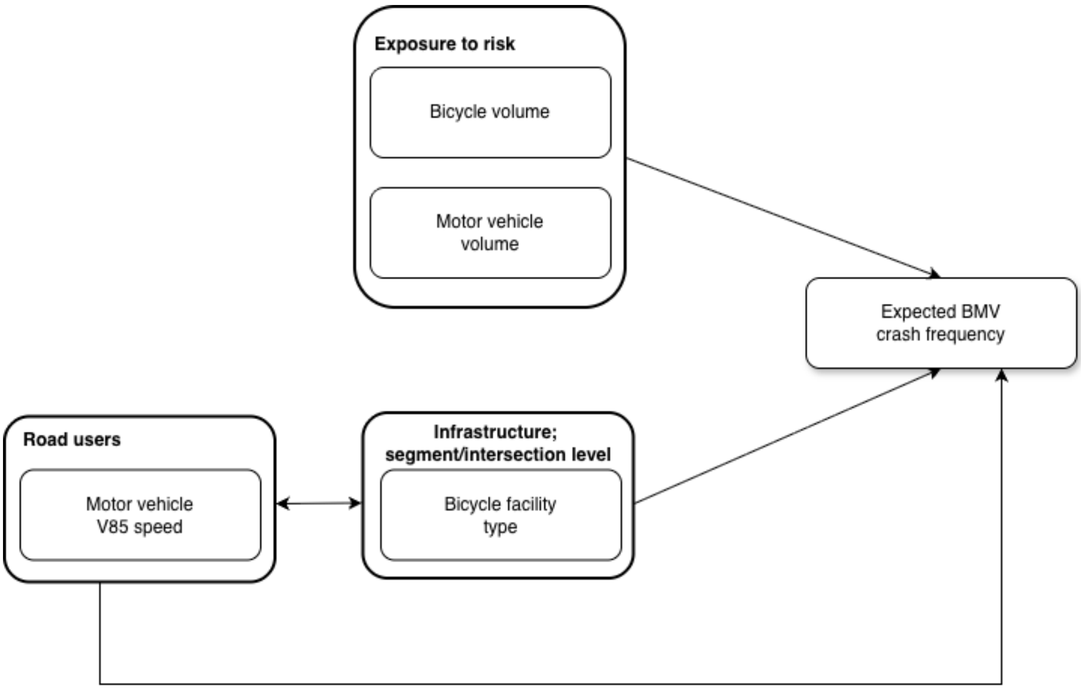

Figure 2.3. Conceptual framework for BMV crash prediction. Framework adapted from Schepers et al. (2014), which operationalises exposure and crash risk factors as traffic volumes, bicycle facilities and motor vehicle speed respectively, to estimate expected BMV crash frequencies.

The conceptual framework proposed by Schepers et al. (2014) was adapted to the this study, by omitting determinants that fall outside its scope, such as locations of activities and travel resistance. Since this study focuses on the occurrence of BMV crashes rather than severity, factors such as vehicle characteristics and injury risk were not included as well. The remaining determinants were operationalised as follows: exposure to risk was accounted for through bicycle and motor vehicle volumes. Crash risk is represented by infrastructure (bicycle facility type) and road users (motor vehicle V_{85} speed).

3 Method

To examine how BMV crash frequency differs between the two bicycle facility types, this study uses crash prediction modelling. As established in the literature review, bicycle facility type may have different cyclist safety effects, when measured on straight road segments or at intersections. Therefore, to reflect this difference, two separate modelling datasets were created.

3.1 Data collection

3.1.1 Road network and infrastructure characteristics

The spatial basis of the analysis required a road network dataset containing road segment geometries, which was sourced from the Dutch National Road Database (Nationaal Wegenbestand, NWB). The NWB is a publicly accessible and free to use national road network dataset that contains all public roads in the Netherlands (Ministerie van Infrastructuur en Waterstaat, 2024). The dataset contains road sections represented as line geometries and basic attributes such as a unique segment identifier (*WVK_ID*, road segment ID) and street name. Since this study focuses on GOW30 roads within Amsterdam specifically, these roads first had to be identified within the main NWB dataset. For this purpose, an open geographical dataset from the Municipality of Amsterdam was used (Municipality of Amsterdam, n.d.-a). This line dataset contains existing roads classified as GOW30.

Bicycle infrastructure characteristics were derived from multiple sources. NWB offers additional, separate datasets containing specific road characteristics: Road Characteristics Database (Wegkenmerkendatabase, WKD), which can be joined to the NWB road network dataset using each segment's unique identifier. In this study, the WKD road categorisation dataset was used as it classifies each segment into distinct categories, including segments with bicycle tracks. This was supplemented with a WKD specifically containing bicycle lanes (Nationaal Wegenbestand, 2025a, 2025b). However, upon manual inspection using street level imagery, these WKD sources appeared to have inconsistent segment geometries or the classification did not match the existing situation.

Therefore, these two sources were supplemented and checked against a municipal dataset, containing bicycle network information for Amsterdam, including the type of bicycle facility (Municipality of Amsterdam, n.d.-b). By combining the NWB/WKD sources with municipal data allowed each GOW30 segment to be classified into three distinct categories: bicycle track, bicycle lane or mixed conditions. The latter category refers to road segments with no bicycle facility present, which means cyclists have to share the carriageway with motor vehicles.

3.1.2 Traffic volumes and speeds

Network-wide motor-vehicle volume and speed data were obtained from VIA, which provides various traffic data products, such as road-level volume and speed data based on Floating Car Data (FCD) supplied by HERE (VIA, 2026). FCD are based on GPS data sourced from drivers using navigation systems, mobile applications, and connected vehicles. Compared with other methods, such as inductive loops in the road surface, traffic cameras, or models, FCD offer network-wide observations of actual vehicle movements at the road level (de Fabritiis et al., 2008). Vehicle volume and speed data were obtained from the April 2026 VIA dataset, which contained the number and speeds of observed motor vehicles for each road segment. The monthly vehicle count was converted to a daily motor vehicle count by dividing its value by 30. Speed data were provided in the form of average speed and the V_{85} speed.

Unlike motor-vehicle volume, bicycle volume data was more difficult to obtain. Previous Dutch cyclist safety studies often relied on data from the Dutch Bicycle Counting Week, which is a bicycle counting campaign conducted in the years between 2015 and 2017 (Jochemsen, 2018; Petegem et al., 2021; Uijtdewilligen et al., 2024) and provides crowdsourced data consisting of GPS tracks of participants. However, this data source seemed no longer publicly accessible at the time of this study. Therefore, bicycle volume counts per segment were obtained from a network-wide bicycle volume dataset developed by Uijtdewilligen et al. (2022). This dataset models hourly bicycle volumes on a segment level using 2016 Dutch Bicycle Counting Week data as a predictor, and subsequently validating this against data from local count stations across the city. For the purpose of this study, the resulting hourly estimates were aggregated to average daily cyclist volumes.

3.1.3 Crash data

In the Netherlands, traffic crashes are recorded through several channels, including police records, ambulance records and insurance data. Two principal sources for Dutch traffic crash data are BRON and MOVE RAV. Both datasets contain crash location and relevant characteristics such as crash type, injury severity and the transport modes of the parties involved.

The Database of Registered Crashes in the Netherlands (BRON) contains traffic crashes recorded by the police and is publicly available (Ministerie van Infrastructuur en Waterstaat, n.d.) However, police records tend to underreport cyclist crashes, especially single-bicycle crashes and crashes that did not involve a motor vehicle. These crashes are less likely to result in police attendance, and are therefore less consistently recorded in BRON when compared to ambulance-registered datasets (Petegem et al., 2021; Van der Does et al., 2025). Regional ambulance services (RAV) record ambulance responses to traffic injuries, including cases that may not be registered by the police. These records are combined in the MOVE RAV dataset.

For this study, both BRON and MOVE RAV were considered as potential data sources. Records were selected for 2024 and 2025 given the implementation of the Municipality of Amsterdam's GOW30 policy in December 2023. Additionally, since the study is limited to BMV crashes, single-bicycle crashes or crashes with vehicles other than motor-vehicles were excluded. This query resulted in 1153 BRON records and 600 MOVE RAV records. Although MOVE RAV was considered as an additional data source to supplement the police-registered records, permission was not granted to export the dataset for further analysis, and therefore solely the BRON dataset was used.

3.2 DATA PREPARATION

Data	Source	Citation
Road network geometry	National Road Database (NWB)	Ministerie van Infrastructuur en Waterstaat, (2024)
GOW30 road classification	‘30 km/u in de stad’ dataset	Municipality of Amsterdam, (n.d.-a)
Bicycle infrastructure	WKD Wegencategorisering, WKD Fietsstroken, ‘Fietsnetten’ dataset	Municipality of Amsterdam, (n.d.-b); Nationaal Wegenbestand (2022, 2025b)
Motor vehicle volume and speed	HERE Floating Car Data	VIA, (2026)
Bicycle volume	Modelled bicycle volumes based on GPS tracks and count stations	Uijtdewilligen et al., (2022)
Bicycle-motor vehicle crashes	Database of Registered Crashes in the Netherlands (BRON)	VIA, (n.d.)

Table 3.2. List of data and sources. Overview of the input datasets used to create the segment- and intersection-level analysis datasets.

3.2.1 Segment-level dataset

3.2.1.1 GOW30 road identification

The segment-level dataset was constructed using the Dutch National Road Database (NWB) as the master road network, to which all other variables were linked using QGIS, an open source geographic information system software (QGIS Development Team, 2009). First, all GOW30 road segments were identified by comparing the master road network with the municipal GOW30 dataset. Although the municipal dataset contained the same road segment identifier used by the NWB dataset (WVK_ID field), a substantial number of segments could not be matched through a direct attribute join. Therefore, a fallback approach was used by buffering the municipal GOW30 layer and flagging the intersecting NWB road segments as GOW30 roads.

3.2.1.2 Bicycle facility classification

Bicycle facility type was assigned to each GOW30 road segment in the NWB master road network using two Road Characteristics Databases (WKD) and a municipal dataset. Before combining the datasets, the original bicycle facility labels had to be recoded using a common classification scheme, as the datasets were sourced from different authorities and thus comprised multiple varying labels. These labels were simplified into three types: track, lane, and mixed; the latter covering roads without a dedicated bicycle facility.

The two Road Characteristics Databases (WKD) could be joined using an attribute join to the NWB using the common WVK_ID identifier field. To expand on this initial classification, a municipal bicycle-network dataset was subsequently added as a third source. This dataset was used to fill in remaining segments with an unknown facility type. However, since this dataset did not contain a WVK_ID field and did not correspond one-to-one with the NWB in terms of geometry and segmentation, it was joined using the 'Join attributes by nearest' geoprocessing tool, with a maximum search distance of 10 m. After linking the three datasets, 583 GOW30 road segments remained unmatched. To resolve this, unmatched segments that were part of a greater road corridor were assigned the facility type of its two adjoining segments when both had the same classification. Lastly, any remaining ambiguous cases were classified manually through visual inspection of street-level imagery.

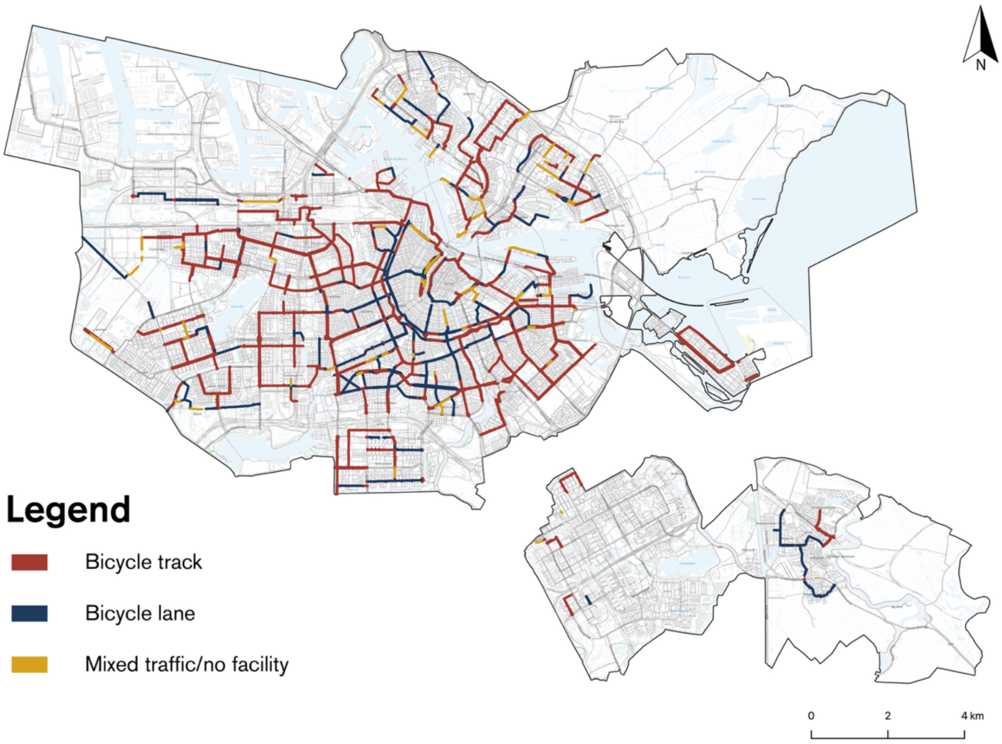

Figure 3.4. Bicycle facilities on GOW30 roads in Amsterdam. The map shows the bicycle facilities located along GOW30 roads in Amsterdam, classified as bicycle tracks, bicycle lanes, or mixed traffic/no dedicated bicycle facility.

3.2.1.3 Bicycle volume exposure

The dataset provided by Uijtdewilligen et al., (2022) was supplied as a CSV file containing bicycle-volume estimates for almost all distributor road segments, along with their respective WVK_ID identifiers. This identifier field could then be used to join the CSV to the master NWB road network.

However, some GOW30 segments still remained unmatched after running an attribute join. For these segments, an imputation method was applied, in which segments with an available bicycle volume value were used as donor segments, while unmatched segments served as target segments. For each target segment, up to a maximum of five donor segments within a range of 50 metres were identified. Using the street-name field, it was then checked whether the target and donor segments belonged to the same named street. Segment angle was also used to evaluate whether nearby donor segments followed a similar path, as donor segments with a similar angle were considered more likely to belong to the same road corridor. If one or more valid donor segments were available, their bicycle-volume values were averaged and subsequently assigned to the target segment as an imputed value.

3.2.1.4 Motor-vehicle speed and volume

The VIA dataset containing motor vehicle volumes and speeds could not be joined directly to the master road network as it lacked the WVK_ID identifier field used by the NWB. In addition, the two datasets use different line geometries and segmentation, which means that matching segments may only partially overlap. Therefore, the transfer of VIA values to the NWB network has to account for the proportion of the spatial overlap between the matched segments.

The first step in the matching process constituted the identification of candidate matches, which was done by creating a 5 metre buffer around each NWB segment and then considering all VIA segments intersecting with this buffer. However, this buffer-based selection was insufficient, especially near intersections. VIA segments from crossing streets intersecting with NWB buffers would be considered a potential candidate match, even though they did not belong to the same street corridor as the NWB segment. Candidate matches were therefore further filtered by considering the orientation of each segment. For each NWB and VIA segment, a line angle was calculated. By considering the absolute difference between these angles, it could be evaluated whether the segments from the two datasets followed a similar direction and thus belonged to the same street corridor.

After filtering the candidate matches, the VIA speed and volume values had to be transferred to the NWB segment while accounting for differences in segmentation. This was done by first calculating the length of each matched VIA segment within the NWB buffer, and this overlap length was then used as a weight when calculating the final NWB segment values. For each matched VIA segment, the V_{85} speed and motor-vehicle volume values were multiplied by its overlap length. These weighted values were then summed and divided by the total overlap length of all VIA segments matched to that NWB segment, yielding an overlap weighted average.

$$X_{NWB} = \frac{\sum(X_{VIA} \times L_{overlap})}{\sum L_{overlap}}$$

Figure 3.2. Calculation of the overlap weighted VIA values. X_{NWB} represents the value assigned to the NWB segment, X_{VIA} the value of each overlapping VIA segment, and $L_{overlap}$ the overlap length of the VIA and NWB segments overlap.

3.2.1.5 Segment crash counts

The last step in the preparation of the segment-level dataset entailed adding crash counts. First, the crash point layer was added, and crashes located within intersection areas were excluded to avoid double counting. The remaining crashes were then joined to the nearest NWB segment. After this assignment, the number of crashes was counted per segment. Because crashes located within intersection polygons were already excluded, NWB segments located entirely within these areas could not receive any crash, and were thus subsequently excluded from the final segment level dataset.

3.2.2 Intersection-level dataset

3.2.2.1 Polygon generation

The intersection dataset was generated from the final master road network, which contained the relevant segment-level variables used to create the aggregated intersection-level variables. Because the NWB road network also includes short connector links and parallel road segments, even a relatively simple four-way junction can be represented as a collection of several segments and nodes. Therefore, using raw nodes to represent intersections would have resulted in overcounting. To address this, intersections were generated as polygons rather than as individual network nodes.

The intersection polygons were generated from network nodes connected to at least one GOW30 segment. The selected nodes were then buffered using a 10 m buffer, with overlapping buffer areas dissolved, resulting in a set of intersection clusters. At this stage, the output only yielded the intersection geometries; the relevant variables were added later by linking and aggregating the values from the segments that connected to the intersections.

3.2.2.2 Bicycle facility classification

The first step in adding the relevant data to the intersection polygon geometries was deciding which bicycle facility could be assigned. For this, the GOW30 segments connecting to each intersection were aggregated, as the facility type was defined at the segment level. Because an intersection has multiple GOW30 segments connecting to them, which may not all have the same bicycle facility type, a classification rule was required. If more than 70% of the connected segments had the same bicycle facility, the intersection was then assigned that type. If an intersection failed to reach the 70% same facility threshold, they were considered as mixed, as no single bicycle facility dominated the intersection. After applying the classification rule, 241 intersections remained with a mixed facility classification. These cases were manually inspected using street view imagery and updated if the facility type could be determined. In the end, 87 intersections did not have any bicycle facility present, which were then classified as “mixed traffic”, and 29 ambiguous cases remained. The latter category was excluded from the regression model.

3.2.2.3 Exposure and speed variables

The exposure and speed variables were added to the intersection polygons to control for differences in traffic conditions between intersections. For each intersection, the sum, mean, and maximum bicycle volume values were aggregated from GOW30 segments connecting to it, which were already linked to the NWB master road network (Chapter 3.2.1.3).

Since motor-vehicle volume and V_{85} speed data were contained in the VIA road network, these variables were derived directly from the original VIA dataset. For each intersection polygon, the connecting VIA segments were selected and aggregated. For motor-vehicle volume, the sum, mean and maximum values were calculated; for V_{85} speed, both the mean and maximum values were calculated.

3.2.2.4 Intersection crash counts

After adding the BRON crash data, which was a point layer, crashes could be spatially matched to intersection polygons and subsequently counted. All successfully matched crashes were then removed from the crash layer before assigning crashes to road segments.

3.3 MODEL DESIGN

3.3.1 Crash prediction model

The objective of this study is to evaluate whether BMV crash frequency on GOW30 roads differs between bicycle facility types, for which several methodological approaches exist, such as a before-after study (Jensen, 2008) or behavioural observation methods (van der Horst et al., 2014). It should be noted that when making safety comparisons between bicycle facilities, Thomas and DeRobertis (2013) emphasise that exposure needs to be taken into account. A facility may have a higher number of observed crashes simply because it attracts more cyclists, while the relative risk per cyclist may actually be lower. Exposure is therefore commonly controlled for by using motor-vehicle or bicycle volumes, or by expressing crash risk relative to distance travelled (Petegem et al., 2021; Thomas & DeRobertis, 2013).

For this reason, this study does not directly compare the raw crash counts between facility types. Instead, it uses a crash prediction modelling approach in which the expected number of cyclist crashes is estimated as a function of exposure variables and risk factors, such as bicycle facility type or motor vehicle speed. This approach follows the model originally developed by Brüde and Larsson (1993), which is what most modern crash prediction models are based on (Schepers et al., 2011).

$$E(\mu) = \alpha N_M^{\beta_1} N_C^{\beta_2} e^{\sum y_i x_i}$$

$E(Y)$ = expected number of bicycle crashes
α = model constant
N_M = average daily number of motor vehicles
N_C = average daily number of cyclists
β_1 = estimated coefficient for motor-vehicle volume
β_2 = estimated coefficient for cyclist volume
x_i = risk factor i, such as bicycle facility type or speed
y_i = estimated coefficient for risk factor i
$e^{\sum y_i x_i}$ = combined effect of the additional risk factors on expected crash frequency

Figure 3.3. General crash prediction model. The model, based on Brüde and Larsson (1993), estimates expected crashes using motor-vehicle volume, cyclist volume, and risk factors.

The model consists of three main parts: motor-vehicle volume, cyclist volume, and lastly an exponential term that represents additional independent variables, which could be risk factors such as specific road environment characteristics. In addition to these input variables, the model includes parameters α, β, and y_i. Firstly, parameter α is a model constant and represents the baseline level of expected crashes before the effects of traffic volumes. Secondly, β_1 and β_2 are coefficients and describe how the expected number of crashes E changes, in relation to the volume variables N_M and N_C, respectively. Lastly, y_i is the estimated coefficient of each additional risk factor x_i included in the model (Schepers et al., 2011). In this study, x_i are comprised of bicycle facility type (categorical factor), and V_{85} motor vehicle speed (continuous covariate).

3.3.2 Statistical estimation

The crash prediction model described above defines the relationship between BMV crashes, exposure and additional risk factors. However, the strength of these relationships is not known in advance. The parameters in the model, such as α, β_1, β_2, and γ_i, therefore have to be estimated from the observed crash data. The appropriate estimation method depends on the dependent variable, which in this case is the number of BMV crashes observed per segment or intersection.

Since the number of BMV crash events is a count variable, it can only take on non-negative integer values, ordinary linear regression may not be appropriate as an estimation method as it assumes a continuous variable and can produce negative values. In addition, BMV crashes are typically infrequent occurring events (Theofilatos et al., 2019), which means that their distribution usually does not follow a normal distribution. Instead, it tends to have a positive skew, meaning many segments or intersections are expected to have zero crash events, with a small number having one or more crashes. Poisson regression is therefore a possible and suitable estimation method, as it is specifically designed for discrete count data. Moreover, it assumes a Poisson distribution, which unlike a normal distribution is bounded at zero and typically positively skewed (Hutchinson & Holtman, 2005).

As a result, traffic safety research commonly uses Poisson regression to model crashes (Deliali et al., 2023). It should be noted that a key assumption of Poisson regression is that the mean and variance of the crash counts are equal. However, as crashes are usually unevenly distributed across the road network, it often does not adhere to this assumption. In such cases where the variance is larger than the mean, the data is overdispersed. In this case, quasi-Poisson or negative binomial (NB) regression can be considered as a fallback model (Akin, 2011; Ver Hoef & Boveng, 2007). To evaluate whether overdispersion is present in the crash data, the Pearson chi-square statistic can be divided by the degrees of freedom; if this value is close to one, the Poisson model is considered acceptable. If it results in a moderate or high value, meaning that it exceeds 1.3, the use of alternative regression models should be considered instead to account for overdispersion (Schepers et al., 2011; Ver Hoef & Boveng, 2007).

However, in some cases, neither Poisson or NB would be the most appropriate: crash datasets can have highly sparse observed crash counts, meaning that most segments or intersections have zero crashes and very few have more than one crash. The observed crash count variable then effectively becomes binary. In such cases, the logistic regression model may be more suitable, a method that has also been widely used to examine how different risk factors contribute to crash risks (Wang et al., 2019). As opposed to modelling the expected number of crashes like Poisson regression does, logistic regression models whether a crash occurred, and is therefore better suited for datasets with sparse crash counts that are nearly binary.

3.3.3 Model specification

The data preparation described in §3.2 yielded two separate datasets: one for road segments and one for intersections.

For the segment-level model, the dependent variable is the number of BMV crashes assigned to each GOW30 road segment. The independent variables that explain the dependent variable, are bicycle facility type, bicycle volume, motor-vehicle volume, and V_{85} speed of motor-vehicles. Bicycle tracks served as the reference category for the bicycle facility type variable, which allows for the coefficients of bicycle lanes and mixed traffic to be interpreted relative to bicycle tracks. Because road segments differ in length, the model needs to account for the fact that longer segments expose cyclists to a longer stretch of road and therefore to more potential crash locations. To correct for length, the natural logarithm of the length of segment i, $\log(L_i)$, was included as an offset.

For the intersection-level model, the dependent variable is the number of BMV crashes assigned to each intersection containing at least one GOW30 leg. The model includes the same explanatory variables as the segment-level model. Ideally, the intersection-level model should account for intersection complexity, as more complex intersections provide more chances for crashes to occur. This can be done by including variables such as the number of intersection approaches (Cai et al., 2021). However, due to limitations of this study, these variables could not be established reliably for all intersections. Therefore, exposure and complexity are accounted for through bicycle volumes at the intersections.

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4 RESULTS

4.1 DESCRIPTIVE STATISTICS

The final segment-level dataset contained 4609 GOW30 segments. In total, 161 BMV crashes were assigned to segments. These crashes were distributed across 154 unique segments, which corresponds to 96.7% of segments having zero crashes and 3.3% having at least one crash.

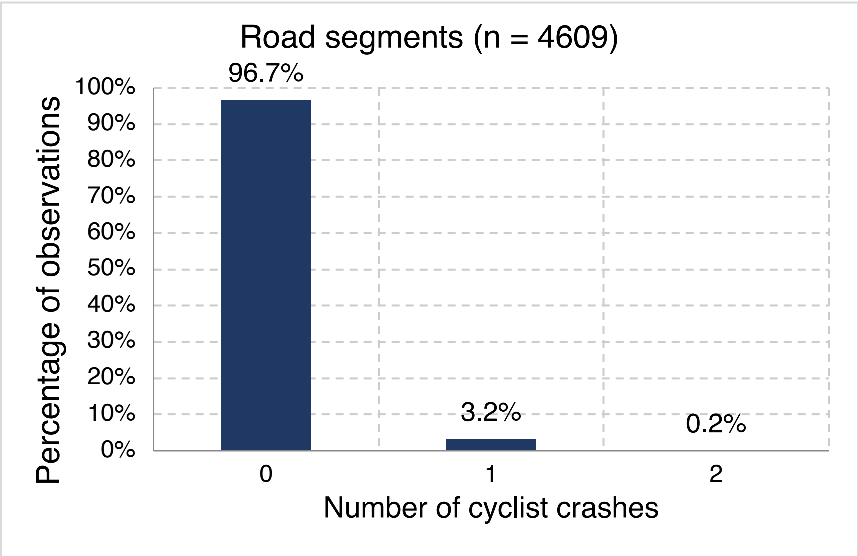

Figure 4.1. Distribution of observed BMV crash counts at road segments. The 3 bars show the percentage of road segments with 0, 1, or 2 crashes during the study period (n = 4609).

It should be noted that some variables had low minimum values, for example, the minimum motor-vehicle volume was 1 vehicle per day. This can likely be explained by very short links or temporary road closures that occurred during April 2026, the month of the VIA data.

Descriptives

	N	Missing	Mean	Median	Std. Dev.	Minimum	Maximum
Segment crashes	4609	0	0.03	0	0.19	0	2
Segment length	4609	0	96.96	73.70	75.76	16.20	906
Bicycle volume (daily)	4306	303	3304.13	2876.40	1767.06	951	15750
Motor vehicle volume (daily)	4609	0	1556.03	1182	1457.38	1	11820
V_{85} speed (km/h)	4609	0	38.36	39.90	5.21	12.50	56.50

Table 4.1. Descriptive statistics of GOW30 road segments. Summary of the segment dataset, consisting of 4609 GOW30 road segments.

As hypothesised in the adapted conceptual framework (Figure 2.3), A Welch's one-way analysis of variance (ANOVA) was conducted to evaluate the relationship between bicycle facility type and motor vehicle speed. The analysis found a statistically significant difference in the motor vehicle V_{85} speed across the three different bicycle facility types ($F(2, 577) = 65.0$, $p < .001$). Road segments with bicycle tracks were found to have the highest motor vehicle speeds, while in contrast, those with bicycle lanes had the lowest.

To interpret the differences in mean speed, Cohen's *d*, which measures the standardised difference between two groups, can be calculated. When considering the 1.9 km/h difference in mean motor vehicle V_{85} speed between segments with tracks and lanes, Cohen's *d* amounts to 0.38, which represents a small to medium effect size (Cohen, 2013).

Descriptives

	N	Missing	Mean	Median	Std. Dev.	Minimum	Maximum
Bicycle track	3182 (69.0%)	0	38.9	39.4	4.99	12.5	56.5
Bicycle lane	1198 (26.0%)	0	37.0	37.6	5.21	14.5	56.5
Mixed traffic (no dedicated facility)	229 (5.0%)	0	37.6	38.9	6.60	20.3	53.2

Table 4.2. Descriptive statistics of V_{85} speed by bicycle facility type. Summary of V_{85} speeds (km/h) across the 4609 GOW30 road segments, categorised by bicycle facility.

The intersection-level dataset contained a total of 2447 intersections. In total, 411 BMV crashes were assigned to intersections, distributed across 343 intersections. This corresponds to 86.0% of intersections having zero crashes and 14.0% having one or more crashes.

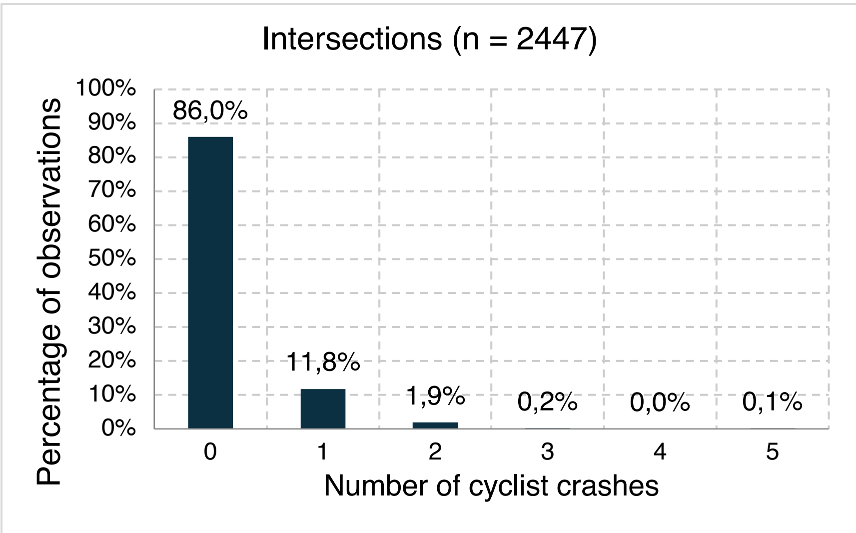

Figure 4.2. Distribution of observed BMV crash counts at intersections. The 6 bars show the percentage of intersections with 0-5 crashes during the study period (n = 2447).

Descriptives

	N	Missing	Mean	Median	Std. Dev.	Min.	Max.
Intersection crashes	2447	0	0.17	0.00	0.47	0	5
Mean bicycle volume (daily)	2447	0	2997.26	2761.50	1804.81	0	10447
Mean motor vehicle volume (daily)	2394	53	1063.26	772.00	1073.87	1	11432
Max. V_{85} speed (km/h)	2394	53	41.27	41.50	5.62	17.00	56.50
Facility type							
Bicycle track	1641 (67.1%)						
Bicycle lane	690 (28.2%)						
Mixed traffic (no dedicated facility)	87 (3.6%)						
Unknown (excluded from model)	29 (1.2%)						

Table 4.3. Descriptive statistics of intersections. Summary of the intersection dataset, consisting of 2447 intersections with at least one GOW30 road segment.

4.2 REGRESSION ANALYSIS

4.2.1 Quasi-Poisson regression

Both regression models only used observations with complete data in the model estimation. This meant that some observations with missing values for any of the model variables were excluded. For the segment-level model, this resulted in 4306 segments with all data complete. The intersection-level model included 2217 intersections after filtering out observations with missing data.

Both the bicycle and motor-vehicle volume variables displayed positive skewness in the two datasets. At the segment level, skewness values were 1.28 and 2.55 for bicycle and motor-vehicle volume, respectively, while for the intersection level, the values were 0.77 and 3.25. The volume variables were log transformed before model estimation, to account for relative changes in volume rather than absolute (Barrera-Gómez & Basagaña, 2015). For example, an increase from 100 to 200 cyclists is a doubling, whereas an increase from 5000 to 5100 cyclists is only a small relative increase.

The regression models were estimated with Jamovi, an open-source data analysis software programme that provides a graphical user interface for the R programming language. The GAMLj3 module is developed to be used within Jamovi and adds support for generalised linear models, including (quasi-)Poisson and logistic regression (Gallucci, 2026; The jamovi project, 2026).

Running the Poisson regression yielded the Pearson χ^2/df values for each dataset, which was then used to diagnose whether under- or overdispersion was present in the data. Following Schepers et al. (2011), overdispersion was considered present in the data if this value exceeded 1.3. The segment-level model had a Pearson χ^2/df value of 0.895, which is below the value of 1 and thus indicates slight underdispersion (Lynch et al., 2014). The intersection-level model had a Pearson χ^2/df value of 1.180; which remained below the overdispersion threshold of 1.3. Because both values varied slightly from 1, quasi-Poisson regression was used as a small correction. By doing so, it estimates an additional dispersion parameter, and adjusts the standard errors, confidence intervals and p-values for the observed dispersion.

Model	Pearson χ^2	Residual df	Pearson χ^2 / df
Segment level Poisson	3848.5	4300	0.895
Intersection level Poisson	2609.0	2211	1.180

Table 4.4. Model dispersion. Summary of the Pearson dispersion statistics used to assess whether overdispersion was present.

However, separately from dispersion, the distribution of observed crash counts was highly sparse for both datasets, as figures 4.1 and 4.2 show. At the segment level, 96.7% of the segments had zero crashes recorded, and the maximum observed count was two. Therefore, it takes on a nearly binary nature. The intersection level dataset was slightly less sparse, with 86.0% of intersections having no recorded crash, and the observed counts ranging from zero to five. Due to this sparsity, logistic regression was additionally conducted as a sensitivity analysis for both datasets (Chapter 4.2.2). The tables below present the results of the quasi-Poisson modelling.

4.2.1.1 Segment level regression results

				Exp(B) 95% Confidence Intervals		
Variable	Coefficient (B)	Std. Error	Exp(B)	Lower	Upper	p
(Intercept)	-10.065	1.440	4.25e-5	2.53e-6	7.15e-4	<.001
Bicycle track (reference)	-	-	1.000	-	-	-
Bicycle lane	1.084	0.163	2.956	2.148	4.068	<.001
Mixed traffic	1.102	0.328	3.011	1.584	5.725	<.001
ln(bicycle volume)	0.498	0.157	1.646	1.210	2.240	.002
ln(motor-vehicle volume)	0.230	0.077	1.258	1.082	1.463	.003
V_{85} speed	-0.084	0.015	0.919	0.892	0.946	<.001

Table 4.5. Segment level quasi-Poisson regression model. Overview of quasi-Poisson regression results, with bicycle track as the reference category.

In the segment-level model, the dependent variable was the number of observed BMV crashes. Bicycle facility type was included as a categorical factor, with bicycle tracks used as the reference category. Bicycle volume, motor-vehicle volume and V_{85} speed were included as covariates, and segment length was included as an offset. The first column that shows the coefficients (B) represents the estimated change in the log expected crash count associated with each independent variable listed in the rows. Because these values are expressed on a logarithmic scale and thus unintuitive to interpret, the base of the natural logarithm *e* raised to the power of a regression coefficient B was calculated, which yielded the values in the Exp(B) column. These resulting values represent the relative change in the expected crash count: values below 1 would indicate a lower expected crash count, and values above 1 indicate a higher crash count.

The results show statistically significant differences between the various bicycle facility types. Compared to bicycle tracks (reference), bicycle lane segments were associated with an expected crash count that was approximately 3.0 times higher (Exp(B) = 2.956) after accounting for segment length, bicycle volume, motor vehicle volume and V_{85} speed. Segments without dedicated bicycle facilities were also associated with a higher expected crash count, approximately 3.0 times higher than bicycle track segments (Exp(B) = 3.011). Both these results were statistically significant ($p < .001$)

Bicycle and motor-vehicle volumes were both positively related to expected bicycle crash counts. For bicycle volume, Exp(B) was 1.646 and the effect was statistically significant ($p = .002$). For motor-vehicle volume, the Exp(B) was 1.258 and statistically significant ($p = .003$). These results indicate that segments with higher traffic volumes had higher expected crash counts, after accounting for segment length.

The modelling results show that V_{85} motor-vehicle speed had a negative coefficient (Exp(B) = 0.919; $p < .001$), which indicates a statistically significant negative association between V_{85} speed and expected crash count. This result however should not be interpreted as proof of higher motor-vehicle speeds reducing bicycle crash risk, as the result may also reflect other risk factors that were not included in the model. Additionally, since the negative direction of the association between the two variables was unexpected, several alternative Poisson model specifications were estimated to examine whether it was caused by controlling for the other model variables. V_{85} speed was first included on its own, after which the other independent variables were added one by one, with segment length kept as the offset. During these estimations, the Exp(B) value for V_{85} speed remained relatively stable at approximately 0.90 to 0.92, which indicates that the negative direction of the association was not specific to the full model specification. In the Discussions chapter, possible explanations for the negative association will be discussed in further detail.

4.2.1.2 Intersection level regression results

				Exp(B) 95% Confidence Intervals		
Variable	Coefficient (B)	Std. Error	Exp(B)	Lower	Upper	p
(Intercept)	−6.820	130.277	0.00109	1.22e-114	9.780e+107	.958
Bicycle track (reference)	-	-	1.000	-	-	-
Bicycle lane	-0.049	0.127	0.952	0.742	1.220	.699
Mixed traffic	-15.120	390.830	2.71e-7	0.000	Inf	.969
ln(mean bicycle volume)	0.447	0.120	1.563	1.236	1.980	<.001
ln(mean motor-vehicle volume)	0.318	0.063	1.374	1.215	1.550	<.001
Maximum V_{85} speed	0.013	0.011	1.013	0.992	1.030	.238

Table 4.6. Intersection level quasi-Poisson regression model. Overview of quasi-Poisson regression results, with bicycle track as the reference category.

For the intersection model, mean bicycle volume and mean motor-vehicle volume were used rather than summed values. This choice was made because the intersection data was aggregated from the NWB segments connected to the same intersection, which could include short links and parallel segments near junctions. Since the VIA motor-vehicle and speed data could not be joined directly to the NWB master road network, these had to be matched spatially. As a result, there was a risk that some values were assigned to multiple segments in close to another. In that case, summed traffic volumes could be artificially inflated, and thus mean values were chosen to reduce the influence of possible duplicate matches. For speed, the value of the intersection approach with the highest V_{85} speed was used.

In the intersection model, the expected crash count was very similar for bicycle lane and bicycle track intersections, after accounting for mean bicycle and motor-vehicle volume and maximum V_{85} speed (Exp(B) = 0.952; p = 0.699). Since the p-value far exceeds the 0.05 significance level, this result provides no statistical evidence of a difference between the two facility types. The mixed-traffic results had a very large standard error and confidence interval, which indicates that the model was unable to reliably estimate this variable. This may be related to the small number of mixed-traffic intersections (N=87), among which only a total of 7 crashes were observed.

Both the bicycle and motor-vehicle volume variables were statistically significant ($P < .001$). Mean bicycle volume had a positive coefficient (Exp(B) = 1.56), which suggests that intersections with higher bicycle volumes had higher expected crash counts. Mean motor-vehicle volume was also positively associated with crash count (Exp(B) = 1.374). Maximum V_{85} speed had a small positive coefficient (Exp(B) = 1.013, but since the p-value was exceeded the .05 significance, this result was not significant.

Because the mixed traffic variable could not be estimated reliably, a sensitivity analysis was conducted in which the bicycle facility variable was simplified from 3 categories into two categories: separated facilities, which include bicycle tracks, and non-separated facilities, which include bicycle lanes and mixed-traffic intersection approaches. This simplification follows Schröter et al. (2023), who collected bicycle-facility data per intersection approach but aggregated this to the intersection level, and distinguished between bicycle tracks and other facility types in their regression models.

Variable	Coefficient (B)	Std. Error	Exp(B)	Exp(B) 95% Confidence Intervals Lower	Upper	p
(Intercept)	-1.844	0.067	0.158	0.139	0.181	<.001
Separated facilities (reference)	-	-	1.000	-	-	-
Non-separated facilities	-0.137	0.130	0.872	0.676	1.124	.290
ln(mean bicycle volume)	0.489	0.121	1.631	1.286	2.070	<.001
ln(mean motor-vehicle volume)	0.328	0.064	1.388	1.224	1.574	<.001
Maximum V_{85} speed	0.013	0.011	1.013	0.992	1.035	.226

Table 4.7. Intersection level sensitivity analysis. Overview of sensitivity quasi-Poisson regression results, with separated versus non-separated bicycle facilities.

Compared with the original model, the bicycle facility results became more stable after simplification, but the overall conclusion did not change. In the sensitivity analysis, non-separated facilities had an Exp(B) value of 0.872 compared with separated facilities, which suggests a lower expected crash count. However, this difference was not statistically significant ($p = .290$). Therefore, even after running the sensitivity model, no clear statistical evidence that suggests non-separated facilities differ in expected crash count was found. The other independent variables retained similar Exp(B) values and significance levels.

4.2.2 Logistic regression

As explained earlier in Chapter 3.3.2, logistic regression is an alternative regression model appropriate for sparse crash data. It examines how the independent variables are associated with the presence of a crash, rather than the number of crashes like quasi-Poisson does. The resulting regression coefficients (B) can be exponentiated which then yields an Exp(B) value, which represents an odds ratio if logistic regression is used. For example, an Exp(B) of 2.00 for bicycle lanes would indicate that the odds of observing at least one crash is two times that of the reference, which in this study were bicycle tracks.

To perform the logistic regression, the observed crash count variable first had to be transformed, as the original segment dataset had values ranging from 0 to 2, and 0 to 5 for the intersection dataset. These values were recoded to 0 if no crash was recorded, and 1 if at least one crash was observed. In the segment level model,

For the segment-level model, the segment length variable was log-transformed and subsequently included as a covariate rather than as an offset, as was the case with the quasi-Poisson model. This allows the association with the probability of a crash occurring to be estimated, unlike using it as an offset which would have fixed the coefficient at one. Ma et al. (2015) used a similar approach by including segment length as an independent variable in their logistic model.

				Exp(B) 95% Confidence Intervals		
Variable	Coefficient (B)	Std. Error	Odds ratio, Exp(B)	Lower	Upper	p
(Intercept)	-10.210	1.675	3.680e-5	1.380e-6	9.810e-4	<.001
Bicycle track (reference)	-	-	1.000	-	-	-
Bicycle lane	1.107	0.182	3.026	2.120	4.320	<.001
Mixed traffic	1.185	0.364	3.270	1.603	6.671	.001
ln(bicycle volume)	0.518	0.176	1.679	1.189	2.370	.003
ln(motor-vehicle volume)	0.235	0.086	1.265	1.068	1.499	.006
V_{85} speed	-0.091	0.018	0.913	0.881	0.946	<.001
ln(segment length)	1.055	0.138	2.871	2.193	3.759	<.001

Table 4.8. Segment level logistic regression. Overview of sensitivity logistic regression results, with bicycle track as the reference category.

The Exp(B) values from the logistic models represent odd ratios, which cannot be compared directly against the Exp(B) values from the quasi-Poisson model, as the latter represents an expected-count ratio and thus measures a different aspect. Instead, it allows for comparing the direction and statistical significance of the associations across the two models.

Applying logistic regression yielded results that were consistent with quasi-Poisson. In both models, segments with bicycle lanes and mixed traffic were positively and significantly associated with crash occurrence, compared to bicycle tracks. Bicycle and motor-vehicle volumes also had positive and statistically significant associations, while V_{85} speed had a negative and statistically significant association. It can be concluded that, given how all variables retained the same direction and statistical significance, the quasi-Poisson results were supported by the logistic sensitivity analysis despite the sparse crash count data.

Variable	Coefficient (B)	Std. Error	Odds ratio, Exp(B)	Exp(B) 95% Confidence Intervals		p
				Lower	Upper	
(Intercept)	-9.357	1.272	8.640e-5	7.150e-6	0.001	<.001
Separated facilities (reference)	-	-	1.000	-	-	-
Non-separated facilities	-0.091	0.139	0.913	0.696	1.198	.512
ln(mean bicycle volume)	0.540	0.133	1.716	1.323	2.226	<.001
ln(mean motor-vehicle volume)	0.387	0.071	1.472	1.281	1.691	<.001
Maximum V_{85} speed	0.016	0.012	1.017	0.993	1.041	.168

Table 4.9. Intersection level logistic regression. Overview of sensitivity logistic regression results, with separated versus non-separated bicycle facilities.

The intersection level logistic sensitivity analysis results remained consistent with the earlier quasi-Poisson model that considered separated versus non-separated bicycle facilities. Non-separated facilities remained negatively but non-significantly associated with crashes. Both bicycle and motor-vehicle volume remained positive and significant ($p < .001$), while the maximum V_{85} speed Exp(B) value remained positive but non-significant, similar to the quasi-Poisson model.

5 DISCUSSION

This chapter aims to interpret the findings presented in Chapter 4, together with the existing body of academic literature, and is structured as follows. Section 5.1 contextualises the results of the segment and intersection models within findings of previous literature. Section 5.2 discusses the results observed for exposure and motor vehicle speeds, and proposes possible explanations for the negative association between motor vehicle speed and crash frequency. Lastly, Section 5.3 discusses the limitations, suggestions for future research, and recommendations for road authorities.

5.1 FACILITY TYPE AND SEGMENT-INTERSECTION DIFFERENCES

This study found that at the segment level, bicycle tracks were associated with substantially lower expected crash counts than bicycle lanes, which is in line with previous studies (Madsen & Lahrmann, 2017; Petegem et al., 2021; Thomas & DeRobertis, 2013; Welleman & Dijkstra, 1988). In the segment level quasi-Poisson model, bicycle lanes were associated with an expected crash count approximately 3.0 times that of bicycle tracks, after accounting for segment length, bicycle volume, motor vehicle volume and V_{85} speed. Based on the modelling results, the hypothesis that bicycle lanes would perform more similarly as bicycle tracks safety-wise at GOW30 road segments could not be proven, despite the lower observed speeds, with mean motor vehicle V_{85} speeds ranging from 37.0 to 38.9 km/h across facility types.

In addition, bicycle tracks substantially reduce the exposure of cyclists to lateral interactions with motor vehicles on the carriageway and thus also the possibility of crashes to occur. Lusk et al. (2011) note that segment crashes include cyclists being hit from behind, sideswiped, or struck by a car door, which physical separation can reduce along road segments. In addition, they further argue that since overtaking is a common cause of fatal BMV crashes, which means that if injury severity was taken into consideration as well, bicycle tracks would appear even safer in comparison, especially when considering that on bicycle lanes, cyclists are still exposed to lateral interactions.

These clear safety benefits of bicycle tracks were not found at intersections. In the intersection level model, no statistically significant difference in expected crash count was found between bicycle tracks and bicycle lanes. Therefore, the modelling results of this study do not corroborate the findings of earlier studies that found bicycle tracks to perform worse than bicycle lanes or other facility types at intersections (Liu & Marker, 2020; Welleman & Dijkstra, 1988). An explanation for the lack of a statistically significant difference could relate to the importance of the intersection design itself rather than bicycle facility type alone. Liu and Marker (2020) mention this importance of context when evaluating the safety of intersections, and refer to intersection infrastructure such as special treatments. This is supported by Schepers et al. (2011), who found that setbacks, a type of intersection treatment, was a determining factor in bicycle safety. Based on these results and earlier studies, the results seem to suggest that intersection-specific design characteristics may be important in explaining safety differences that were not captured by the present model.

5.2 Traffic volumes and speed

In both models, bicycle and motor-vehicle volume were positively associated with the expected crash count. Since the volume variables were log-transformed, the coefficients can be interpreted as an elasticity. This means that for bicycle volume, a 1% increase was associated with an approximately 0.50% increase in expected crash count in the segment model and an approximately 0.45% increase in the intersection model. For motor-vehicle volume, these values were approximately 0.23% and 0.32%, respectively. These values are mostly in line with the range reported by Elvik (2009), who argues that traffic volume coefficients in crash prediction models often vary between 0.30 and 0.90 (Schepers et al., 2014). Based on these results, crash count thus increased with higher traffic volumes, but this increase is less than proportional. This is consistent with the non-linear relationship between exposure and crash frequency as described by Elvik (2017).

A noteworthy result is that the bicycle-volume coefficient was larger than the motor-vehicle-volume coefficient in both models: 0.498 versus 0.230 in the segment model, and 0.447 versus 0.318 in the intersection model. All four coefficients were statistically significant. These results thus seem to suggest that bicycle volume is more strongly associated with expected crash count than motor-vehicle volume.

The motor vehicle V_{85} speed was not significantly associated with crash frequency in the intersection model. For segments however, V_{85} speed displayed a negative association with crash count. This result should be interpreted with caution: Arias et al. (2021) and Mahmoud et al. (2023) found similar results and argue that this negative coefficient is better understood as reflecting other factors such as exposure or congestion, rather than as evidence that higher motor-vehicle speeds are safer for cyclists.

A possible explanation is that lower V_{85} speeds may occur on road segments with a more complex road environment. These segments may have more intersections crossing with them, parking manoeuvres, public transport activity, congestion, and interactions with cyclists or pedestrians. Such factors may lead to both lower V_{85} speeds, and at the same time an increase in the number of potential conflicts. Future research could further explore this relationship by including additional variables that capture road complexity, such as intersection density, land use, or presence of public transport.

5.3 LIMITATIONS AND RECOMMENDATIONS

5.3.1 Limitations and recommendations for further research

There were several additional data and methodological limitations that must be acknowledged. First, a methodological limitation in this study would be the sparsity of the observed crash count data, with a large proportion of intersections or segments having zero crashes. Given this, combined with the narrow range of crash counts (0-2 for the segment dataset; 0-5 for the intersection dataset), may bring the reliability of applying (quasi-)Poisson regression into question, as they are designed for discrete count data, while the actual data used behaved nearly binary. To address this limitation, a methodological strength was including logistic regression as a sensitivity analysis, which models the probability of a crash occurring, rather than expected crash counts like (quasi-)Poisson does. This sensitivity analysis then allowed for the verification of the coefficient directions and significance levels, which were all consistent with the quasi-Poisson models across both the segment and intersection datasets.

A second limitation is related to the intersection level crash prediction modelling. In the intersection models, no statistically significant difference in expected crash count was found between bicycle tracks and bicycle lanes. A possible explanation for this lack of statistically significant difference may be limitations of the models. Due to time and data constraints, the intersection models did not include additional contextual or geometric variables aside from the bicycle facility present, even though Chapter

2.2.2 establishes the importance of considering these factors when evaluating intersection safety. Furthermore, intersections were classified based on the dominant bicycle facility on the intersection approaches, whereas on the intersection itself, the distinction between tracks and lanes may not be present anymore. Future research could therefore incorporate more relevant variables, such as setback distances, rather than relying on intersection approach bicycle facility type alone.

Third, a limitation stemming from the data that was availability would be bicycle volumes. The crash prediction model required bicycle volume data on a segment level, which was provided by Uijtdewilligen et al.'s network level estimates (2022). The volume counts in this dataset are modelled rather than empirical counts, and while these were calibrated against bicycle count stations, Uijtdewilligen et al. note that the model tends to slightly overpredict night and off-peak volumes, while at the same time underpredicting extreme peak-hour traffic. This could have potentially affected the bicycle volume coefficients.

Fourth, while the road network geometry was derived from the National Road Database (NWB), the attribute data required for the analysis, such as volumes, facility type, and speed, were sourced from various different datasets. Linking these independent datasets to the NWB master road network could have potentially introduced errors, as the NWB dataset assigns each segment with an unique segment identifier (WVK_ID), but several datasets either lacked this identifier or were incomplete. Therefore, these attributes had to be spatially matched in GIS using e.g. buffers and overlap-weighted averages, which may have led to allocation errors due to e.g. incorrect or duplicate matches.

Fifth, the study was unable to include ambulance-registered crash data from MOVE RAV. As Chapter 3.1.3 notes, police registered crash data, as used in this study, tends to underreport bicycle crashes. Although a query for BMV crashes in 2024 and 2025 yielded 600 MOVE RAV recorded crashes, permission to export and use their dataset was not granted. Supplementing the police registered crash dataset with MOVE RAV data would have increased the observed crash sample, which could potentially reduce crash count sparsity, and additionally, result in more reliable regression coefficients. Future research should therefore aim to include ambulance-registered crash data to obtain a more complete sample of crashes.

Lastly, the scope of this study only considered expected crash frequency and did not include injury severity, which meant the crashes in the models are treated equally regardless of their outcome. This could be considered a limitation, as measuring crash frequency alone may understate the safety advantages of bicycle tracks. Lusk et al. (2011) note that overtaking is a common cause of fatal BMV crashes, which the physical separation offered by bicycle tracks can effectively help prevent. In future research, the observed severe or fatal crashes could be assigned weights, which would allow for taking the actual outcome of a crash into account, without the need to filter non-severe crashes from the sample.

5.3.2 Policy recommendations

The empirical results found in this study can help inform road authorities in their design of GOW30 roads. First, as the modelling results indicate that bicycle lanes are associated with approximately three times as many expected crashes on segments compared to bicycle tracks, road authorities should retain existing tracks when converting distributor roads to the GOW30 standard, as it would compromise cyclist safety.

Second, although segments with bicycle tracks showed a 1.9 km/h higher mean motor vehicle V_{85} speed than those with lanes, its effect size (d = 0.38) was merely small to medium. Therefore, in the design and decision-making process, using the lower motor vehicle speeds that lanes would offer, does not provide a sound justification for replacing existing bicycle tracks with lanes, given that this reduced speed comes at the expense of cyclist safety.

Lastly, while bicycle facility type alone showed no statistically significant safety difference at intersections in the modelling results, prior research shows that the safety of bicycle tracks at intersections is influenced by other infrastructural factors, and can be improved through e.g. intersection treatments. Schepers et al. (2011) found that bicycle tracks with a setback of 2-5 metres from the carriageway were safer than lanes. Road authorities should therefore apply the appropriate intersection treatments when redesigning roads to a GOW30 standard.

6 CONCLUSION

This paper tried to answer the research question: "What is the relationship between bicycle facility type and bicycle-motor vehicle (BMV) crash frequency on GOW30 distributor roads, when controlling for traffic volumes and speeds, and distinguishing between road segments and intersections?".

At the road-segment level, bicycle lanes and mixed-traffic conditions had approximately 3.0 times the expected crash frequency of bicycle tracks, after controlling for traffic volumes and V_{85} speed. Therefore, the hypothesis that bicycle lanes could perform more similarly to bicycle tracks in terms of safety due to the lower speeds as a result of the GOW30 standard could therefore not be supported. Although the observed motor vehicle V_{85} speeds were lower on segments with bicycle lanes and mixed traffic than on those with bicycle tracks, the latter still provided the lowest crash frequency for cyclists.

No statistically significant difference could be found between bicycle tracks and bicycle lanes on the intersection level, and thus their comparative safety performance remains inconclusive. Traffic volumes were also found to be relevant factors: higher volumes of both bicycles and motor vehicles were associated with more expected crashes, but the volume of bicycles actually showed a stronger association than motor-vehicle volume. Another interesting finding was that higher V_{85} motor-vehicle speeds had a negative association with crashes on segments, which was hypothesised that lower speeds happen on roads that are more complex or congested, where interactions such as parking manoeuvres create more opportunities for crashes.

In conclusion, the results of this study show that the lower speed limit on GOW30 roads does not increase the safety of bicycle lanes to a level comparable to physically bicycle tracks. As more distributor roads are converted to GOW30, existing bicycle tracks should not be replaced by bicycle lanes, and on roads where bicycle lanes are already present, additional measures should be considered to further improve cyclist safety.

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