Traffic Safety and Spatial Planning

Exploring Relationships between Road Design, Risky Driving Behaviour and Traffic Accidents in Groningen, the Netherlands

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Abstract

The decades-long decrease in yearly traffic deaths in the Netherlands has stagnated in recent years. This has created a renewed interest on the part of Dutch institutions in interventions which may further increase traffic safety, including spatial interventions targeting driver behaviour. Academic work on these spatial measures for traffic safety remains scarce, however, as does research targeting risky driving behaviour specifically. This research applies quantitative analysis to secondary data from the province of Groningen in order to expand the body of knowledge on the linkages between road design, risky driving behaviour and traffic accidents in the Netherlands in both urban and rural contexts, investigating factors such as network density, roadside features and speed limits. Findings suggest that road design and urban planning factors such as road type, speed limits and road width, as well as urban planning factors such as network density and address density are, to varying degrees, significant predictors of risky driving incidents and traffic accidents, and that risky driving incidents and traffic accidents are correlated with one another. Fatal traffic accidents are more difficult to predict, however, and the relationship between risky driving and traffic accidents depends on context.

Acknowledgements

This thesis is dedicated to my cat Blik, who unfortunately wandered off and disappeared while I was working on it.

I would like to thank my thesis supervisors, Samira Ramezani and Gerd Weitkamp, both at the University of Groningen, for their indispensable assistance and feedback in the creation of this thesis.

Furthermore, I would like to thank the ANWB and Menno Mimpen for generously providing the risky driving data used in this research.

Lastly, I would like to thank Hans Jeekel for proofreading and inspiring this thesis.

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1. Introduction

1.1 Background

Road Traffic Injury is a persistent public health challenge around the world (Mekonnen et al. 2019). 737 people died in traffic accidents in the Netherlands in 2022 (CBS, n.d.a), with 6,800 people being heavily injured in traffic accidents in 2021 (SWOV 2022). The total economic cost of traffic accidents in the Netherlands is estimated at €26.5 billion in 2020 (Wijnen 2022). Given the great social and economic impact of traffic accidents, it is not surprising that this subject holds great social currency in Dutch government and planning practice.

After an increase in the 1950s and 60s, the Netherlands experienced a gradual decrease in the annual number of traffic deaths after 1973 (SWOV 2023b). This decrease has, however, stagnated in the past 10 years (Ibid.). This stagnation has prompted the Dutch government to create the SPV (*Strategisch Plan Verkeersveiligheid 2030*, Strategic Plan for Traffic Safety 2030) (Rijksoverheid, n.d.), which includes a package of measures intended to improve traffic safety, including changes in road design. It appears that Dutch planning practice has identified the potential for spatial interventions to help curb risky driving behaviour (in addition to "soft" interventions, such as media campaigns). Existing scientific literature identifies a strong relationship between risky driving behaviour and traffic accidents, at least on an individual level (Ivers et al. 2009; Tronsmoen 2010) and the relationship between speeding (a form of risky driving) and traffic crashes is well-established (Perez et al. 2021; Yu, Chen & Bao 2019). Speeding was found to be a contributing factor in 30% of fatal crashes in Europe (Viallon & Laumon 2013). There are, therefore, reasons to believe that a design strategy focused on risky driving could help in reducing the frequency of traffic accidents.

The relationship between spatial planning/road design and traffic safety factors has previously received academic interest: research has already been done on the topic, such as by Dumbaugh & Gattis (2007), Ewing & Dumbaugh (2009) and Marshall & Garrick (2011). However, despite the aforementioned attention being given to spatial interventions in Dutch planning practice, the link between the spatial and environmental characteristics of roads and traffic safety has not yet been subject to academic work in a Dutch context. This link ties into ongoing academic debates regarding road safety, such as the concept of "forgiving roads". Evaluating the relationship between road design and driver behaviour would provide an empirical basis to draw on in these debates.

The knowledge gap in existing research is trifold. Firstly, this research mainly focuses on the United States, which presents a challenge in interpreting these results in a Dutch or European context, as the urban fabric in North American cities is different from those in Europe (Barrington-Leigh & Millard-Ball, 2019), which might influence how these design features affect traffic safety. Secondly, the topic of risky driving behaviour has not been subject to much comprehensive research in a spatial context. Existing research on the topic focuses mainly on personal, psychological factors in risky driving behaviour, such as in Iversen (2004) or Ulleberg & Rundmo (2003). Studies focusing on the link between spatial planning and traffic safety, such as Dumbaugh & Gattis (2007), Ewing & Dumbaugh (2009) and Marshall & Garrick (2011) meanwhile, tend to focus more broadly on traffic safety or traffic accidents. While there is a body of literature which relates road design to speeding (e.g. Shinar 2017; Perez et al. 2021), and speeding is generally considered a form of risky driving behaviour (e.g. Jonah 1997; Fernandes, Soames Job & Hatfield 2007), but this literature does not operationalise risky driving behaviour in a more general way. There is therefore a lack of research that relates spatial factors with pre-accident data, that is to say, that specifically relates it with risky driving behaviour. Lastly, existing research mainly focuses on an urban context, as in Marshall & Garrick (2011), who focus on cities in California: this demonstrates a lack of research that covers both urban and rural contexts. This knowledge gap suggests the need for work which focuses on the Netherlands and covers both urban and rural areas in order to gain a better understanding of the relations between spatial planning and street design factors that could affect risky driver behaviour and provide insights for Dutch planning practice.

The current Dutch ambition is to reach zero traffic deaths in 2050 (SWOV 2023c). Spatial interventions may prove an important tool in further decreasing the amount of traffic fatalities and injuries in the future – relevant information on the link between road design and traffic safety is indispensable in making sure these measures are implemented effectively.

1.2 Research Aim

The aim of this study is to gain insight into how spatial planning and road design are linked to traffic safety, especially as it pertains to risky driving behaviour. Specifically, the aim is to uncover the relations between the locations of traffic accidents, the locations of risky driving behaviour and the characteristics of these locations – the topology and geometry of local road networks and local socio-demographic and land-use factors. Questions which are relevant to this relationship are:

1. How do road design, urban planning factors and the number of vehicles affect the total number of incidents of risky driving behaviour, as well as specific types of risky driving?
2. How do road design, urban planning factors and the number of vehicles affect the total number of traffic accidents, as well as injury and fatal accidents?
3. How are risky driving behaviour and traffic accidents linked?

1.3 Reading Guide

Beyond this introduction, this paper is divided into four main sections: a *theoretical framework*, which develops the concept of risky driving behaviour and relates it with traffic accidents, road design and other spatial factors as they are relevant to this research; a *data and methodology* section which explains the nature and process of the research; a *results* section which describes the findings of this research; a *discussion* section which interprets these findings and discusses research limitations; and lastly, a *conclusion* section which summarises the results and gives research and policy recommendations.

2. Theoretical Framework

2.1 Risky Driving Behaviour

Many definitions and typologies of risky driving behaviours exist. Some focus more generally on aberrant, "asocial" and undesirable behaviour in traffic (such as the examples cited by Jafarpour & Rahimi-Movaghar (2014), which include double parking or blocking intersections) while others focus more specifically on behaviours and risk factors that are dangerous to the driver or to others, such as Zimbardo, Keough & Boyd (1997), who distinguish five items: "taking risks driving"; car racing; speeding; "taking risks biking" and driving under the influence of alcohol (p. 1010).

A third approach operationalises risky driving based on specific events that occur while driving. Such an approach can be seen in Ziakopoulos' (2021) spatial analysis of harsh driving behaviour, which defines it in terms of harsh braking and harsh acceleration, or in Guo et al. (2021), which distinguishes sharp acceleration, sharp deceleration, sharp turns and sharp merges. The benefit of such an approach is that risky driving events can be linked to a specific point in space, which allows spatial analysis of these events to take place. For this reason, this approach is also used in this research.

2.2 The Determinants of Risky Driving and Traffic Accidents

2.2.1 Determinants of Risky Driving Behaviour

According to Jafarpour & Rahimi-Movaghar (2014) factors contributing to risky driving behaviour fall into three categories: *environmental* factors, *vehicle* factors and *human* factors. They identify human factors as "by far the leading determinant" (p. 1) of risky driving behaviour. Personal factors such as risk-taking attitudes, beliefs and personality traits are also identified as the most important determinants by Fernandes, Soames Job & Hatfield (2007). It therefore appears that these factors are commonly identified as being most relevant, and, consequently, human factors such as age, gender, personality, socio-economic status and drug or alcohol use dominate in academic writing on risky driving behaviour (e.g. Jonah 1997; Fergusson & Swain 2003; Ulleberg & Rundmo 2003; Ivers et al. 2009). Academic work on the environmental or spatial determinants of the locations of risky driving behaviour is therefore comparatively scarce.

Nonetheless, some information on the link between spatial factors and risky driving is available. In a study focusing on Iran, Jafarpour & Rahimi-Movaghar (2014) named undivided, curved, inclined and "accident-prone" roads as specific risk factors. In a study specifically focusing on risky driving behaviour at work zones, Weng & Meng (2012) found that weather, light and road conditions play a role. With respect to road design specifically, the number of lanes and access control (i.e. whether a road may only be accessed through on- and offramps) was found to play a role in risky driving at work zones.

Landscape also plays an important role in driver behaviour. Yu, Chen & Bao (2019) found, in a driving study focusing mainly on two-lane rural roads, that roadside landscape features influence the incidence of speeding – trees and other plants, tunnels and mountainous areas all had lower amounts of speeding than open fields, and built-up areas had an especially strong negative effect on speeding incidence. Mok, Landphair & Naderi (2006) found that roadside landscape improvements have a positive effect on traffic safety by affecting driver behaviour: "interesting" natural settings have a positive influence on driver behaviour and roadside trees have the effect of reducing driving speed.

The effect of the number of vehicles on risky driving behaviour is unclear. The higher number of potential conflict points arising from higher traffic flows (and therefore more vehicles) may increase the probability of risky driving (Yang et al. 2024). However, higher traffic flows may make driving behaviour safer by reducing average speeds (Dickerson, Peirson & Vickerman 2000).

A larger amount of literature covers the determinants of locations of speeding more specifically – speeding is generally considered a form of risky driving behaviour (e.g. Jonah 1997; Fernandes, Soames Job & Hatfield 2007). For instance, Perez et al. (2021) found that the proportion of speeding is strongly influenced by the posted speed limit in a given area: areas with lower posted speed limits have significantly higher incidences of speeding. Shinar (2017) lists a large number of road design factors that may influence drivers' speed choice, including road width, road gradient (the steepness of a road's slope), road alignment (the route of a road, referring to horizontal curves and tangents), road layout and road surroundings.

Additionally, there is a body of research that utilises driving simulators to link road design elements to driving behaviour, especially on rural roads. Results, however, are mixed and at times contradictory. For instance, Antonson et al. (2009) find that forested landscapes surrounding rural roads lead to slower driving speeds and driving closer to the centre of the road. However, Van der Horst & De Ridder (2007) find that roadside trees have no effect on driving behaviour if trees are over 4.5 metres from the road and Abele & Møller (2011) find no effect at all. The use of driving simulators to test driving behaviour has been subject to criticism, as results are heavily dependent on research design, sample selection and the method of data acquisition (Bobermin et al. 2019), which may be an explanation for these discrepancies.

It should be noted that risky driving behaviours are generally assumed to be *generalisable,* that is, it is assumed that general conclusions can be drawn about all types of risky driving behaviour. This presupposition is challenged by Fernandes, Soames Job & Hatfield (2007), who assert that different types of risky driving behaviour are predicted by different factors: for instance, drinking and driving is predicted by different personality factors than speeding. It is unclear whether this is also the case for the locations of risky driving behaviour, however.

2.2.2 Determinants of Traffic Accidents

Road design is likely to influence the risk of traffic accidents. On rural roads in the Netherlands, the size of the road's safety zone, curvature and presence of roadside barriers are determinants of the risk of run-off-road crashes (Van Petegem & Wegman 2014). There is, however, "substantial disagreement" about the safety effects of road design features such as roadside trees (Dumbaugh & Gattis 2007). Turner & Mansfield's (1990) study of roadside trees in Huntsville, Alabama is considered "the definitive work on the subject" (Dumbaugh & Gattis 2007, p. 285) and recommends clearing roadsides of trees in the interest of traffic safety (Turner & Mansfield 1990). However, a number of studies have challenged this assumption. Marshall, Coppola and Golombek (2018) state that the safety benefits of roadside clear zones (that is, zones without any roadside obstacles) "may be overstated" (p. 136), and Naderi's (2003) study of curbside features in Toronto, Ontario found that curbside landscape treatment may actually improve driver safety by eliciting positive behavioural responses. Ewing & Dumbaugh (2009) similarly find that less "forgiving" design elements, such as narrow lanes and roadside trees, lead to enhanced safety.

The example of roadside trees can therefore be seen as emblematic of the complex relationship between road design, driving behaviour and traffic safety. This relationship ties into the concept of "forgiving roads". These are forms of roadside design which aim to mitigate the consequences of run-off-road accidents (Nitsche et al. 2012) through measures such as eliminating roadside obstacles or moving them further away from the road (Burlacu, Tarita-Cimpeanu & Dicu 2014). This form of thinking has received criticism from authors such as Dumbaugh (Dumbaugh & Gattis 2007) for taking a "passive" approach which does not focus sufficiently on driver behaviour.

Something of a contradiction can be identified between removing obstacles and widening roads to create “passive” safety, or creating narrower roads with more obstacles to encourage careful driving behaviour. This contradiction appears not to have been subject to much active debate thus far, with a notable exception being the exchange seen between Dumbaugh & Gattis (2007), which sees Dumbaugh developing a position which broadly fits the “active” approach, while Gattis presents a counterpoint. At least in the United States, removing roadside features and establishing “clear zones” has been a standard method in applying the principle of “forgiving roads” (Dumbaugh & Gattis 2007). On the other hand, through affecting driving behaviour, roadside features may actually reduce crash risk. This relationship is illustrated in Figure 1.

Figure 1. Controversies in the literature on the relationship between forgiving roads and traffic safety. (Figure by author)

Spatial planning factors other than road design also play a role in traffic safety. One important distinction to be made is between urban and rural areas. Rural roads are generally considered a risk factor for traffic accidents: In 2021, 49% of all traffic deaths in the Netherlands took place outside the built-up area, against 35% inside built-up areas (SWOV 2023b). Gonzalez et al. (2007) found that vehicular mortality rates are significantly higher in rural areas than in urban areas, and that this difference could be attributed to higher rates of speeding (an example of risky driving) in rural areas compared to urban areas. Additionally, rural-urban differences affect the way traffic mortality rates are affected by other factors: in rural areas, traffic mortality rates are inversely proportional to population density, but this relationship is not present in urban areas (Clark & Cushing 2004).

The number of vehicles on a road, measured in traffic flows, is also a major factor in traffic accidents, with the number of accidents increasing substantially with higher traffic flows (Dickerson, Peirson & Vickerman 2000). Guo et al. (2021) also identified traffic flow as a major predictor of traffic accidents. Decreasing traffic intensity is at present already a strategy for reducing the risk of traffic accidents (Goniewicz et al. 2016). However, the rate of traffic accidents may increase non-linearly with the number of road users – a phenomenon known as the “Safety in Numbers” effect (Tasic, Elvik & Brewer 2017).

2.3 Link between Risky Driving and Traffic Accidents

Risky Driving and Traffic Accidents are strongly linked to one another. However, research linking risky driving and traffic accidents has mostly taken place at the individual level so far. For instance, high scores on questionnaires for risky driving behaviours have been linked with an increased risk of getting into crashes (Ivers et al. 2009), and self-assessment of driving skill, safety attitudes and self-reported driving behaviour are strongly associated with crash involvement (Tronsmoen 2010). While risky driving behaviour is therefore very relevant to crash risk and traffic safety, it should be noted that most research thus far has focused on linking these concepts in individual drivers, rather than taking a spatial approach (i.e. investigating whether the frequency of risky driving behaviour in a given piece of street can be linked to the frequency of crashes). Additionally, the relationship between speeding (a form of risky driving behaviour) and traffic accidents is well-established (Perez et al. 2021; Yu, Chen & Bao 2019). The European Road Safety Observatory (ERSO) found that speeding was a contributing factor in approximately 30% of fatal crashes in Europe (Viallon & Laumon 2013).

However, traffic accidents may also affect risky driving the other way. Ram & Chand (2016) found, for instance, that drivers’ perception of road accidents (that is, the perception that they or others may be involved in a traffic accident on this road) makes driving behaviour more cautious and vigilant, improving driving safety.

2.4 Conceptual Model

A conceptual model encapsulating the theoretical framework upon which this research is based can be seen in Figure 2.

The three groups of factors investigated in this research (road design factors, urban planning factors and number of vehicles) are grouped into two categories. Road Design Factors and Urban Planning Factors are grouped together, as they both relate to spatial planning, while the number of vehicles is kept separate, as the variable does not relate directly to road infrastructure. Both categories affect both risky driving behaviour and traffic accidents. Risky driving behaviour and traffic accidents are connected with a double-sided arrow to illustrate the complex double-sided relationship between these phenomena. Lastly, the various subtypes of risky driving incidents and traffic accidents used in this research are shown individually.

Psychological and Environmental Factors, which may be a major factor in risky driving according to existing research, are included in the conceptual model, but greyed out to show that they are not the focus of this research.

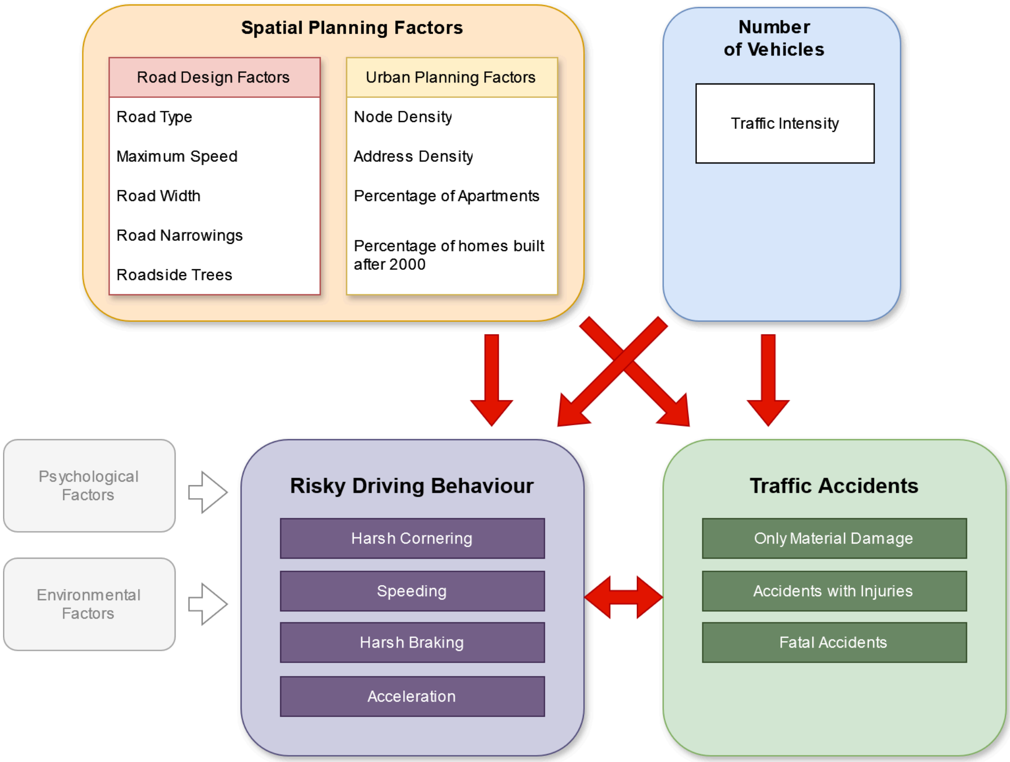

Figure 2. Conceptual model of the relationship between spatial planning and traffic safety. The relationship of Psychological and Environmental Factors on Risky Driving is not focussed on in this research.

2.5 Hypotheses

The answers to the research questions given in section 1.2 are hypothesised to be as as follows:

It is hypothesised that road design, urban planning factors and the number of vehicles affect the number of risky incidents. Spatial characteristics associated with "forgiving roads", such as wider roads, are expected to increase incidents of risky driving behaviour. On the other hand, "unforgiving" features, such as roadside trees or road narrowings, are expected to decrease the number of risky driving incidents. Higher speed limits are expected to be associated with lower numbers of speeding, but their effects on risky driving overall are unclear. The number of vehicles is also expected to be positively associated with the number of risky driving incidents. Lastly, given the emphasis on personal and psychological factors in the literature, it is expected that the overall explanatory value of these spatial factors will be rather low.

Furthermore, it is hypothesised that road design, urban planning factors and the number of vehicles affect the number of traffic accidents. Unlike the predictors for risky driving behaviour, factors associated with "forgiving roads", such as wider roads, are expected to decrease the number of traffic accidents. Conversely, roadside trees or road narrowings are expected to increase the number of traffic accidents. Additionally, rural areas, or areas with a lower population density, are expected to increase the number of traffic accidents, especially fatal traffic accidents. The number of vehicles is also expected to increase the number of traffic accidents. Similarly to research question one, the explanatory value of these spatial factors is expected to be limited.

Lastly, It is hypothesised that the number of risky driving incidents and the number of traffic accidents are correlated. However, as research has mostly focussed on these concepts on an individual scale so far, the exact nature of this link is difficult to predict. The association between speeding, self-reported risky driving behaviour and traffic accidents, which is described in existing literature, suggests that risky driving affects traffic accidents, but it is possible that this effect also works the other way: for instance, roads perceived as dangerous or accident-prone may affect risky driving from road users.

3. Data and Methodology

3.1 The Dutch Case

3.1.1 Research Area

The area covered by this research will be the province of Groningen, in the north of the Netherlands. The reasons for choosing this province are twofold: firstly, the province contains both strongly urbanised areas (mainly around the city of Groningen) and more rural contexts in the surrounding areas. This is a benefit as this research aims to capture both rural and urban areas for an overall picture of the effects of road design on traffic safety.

Secondly, the province is in close proximity to the researcher, which creates both some personal familiarity with the area and allows, if needed, for on-site observation of certain areas. Given that the *Duurzaam Veilig* standards apply throughout the Netherlands, it is expected that results from the province of Groningen are relevant to the country as a whole.

Roads directly administered by the Dutch national government (*Rijkswegen,* national highways) will be excluded from this research. These tend to be high-speed, grade-separated, limited-access roads, which means that many features of road design or spatial planning investigated in this research (such as road width or roadside obstacles) are less applicable. There is precedence for excluding these types of roads: for instance, Marshall & Garrick (2011) exclude limited-access roads from their analysis on street network design and road safety.

3.1.2 Road Design in the Netherlands

Modern road design in the Netherlands is largely informed by the *Duurzaam Veilig* ("Sustainably Safe") paradigm established in the early 1990s (Wegman, Aarts & Bax 2008). At least in 2008, "Dutch road safety policy is often identified as good practice, and the Sustainable Safety vision as leading practice. Dutch road safety performance commands respect" (Wegman, Aarts & Bax 2008, p. 324), and the Netherlands boasted some of the lowest traffic fatality numbers in Europe, although in practice the guidelines set out in the Duurzaam Veilig paradigm have not been universally adopted yet: adjusting roads remains an ongoing process (SWOV 2023a).

Duurzaam Veilig introduces three design principles for Dutch roads: *functionality,* the principle that roads should have a single apparent function; *(bio)mechanics*, the principle that traffic flows and modes of transport are compatible in speed, mass, size and level of protection; and *psychology*, the principle that the road network should be adapted to the competencies and expectations of road users, especially older road users (Aarts & Dijkstra 2018).

Under the functionality principle, Dutch roads are divided into road types which are ordered based on their function: traffic *flow* versus traffic *exchange.* Flow refers to fast travel from one location to another, while exchange refers to interactions with other traffic and access to individual locations (Aarts & Dijkstra 2018). Based on these principles, the Dutch road network is ideally divided into three road types:

- *Stroomweg* (*SW,* through roads), which have a flow function at all points – these roads are generally designed to avoid conflict points between vehicles.
- *Gebiedsontsluitingsweg* (*GOW,* distributor roads), which have a flow function on road sections and an exchange function at intersections. These roads connect access roads and through roads to one another.
- *Erftoegangsweg* (*ETW,* access roads), which have an exchange function at all points. These roads may also function as social spaces, as in a *Woonerf* (Aarts & Dijkstra 2018).

A diagram of these road types can be seen in Figure 3.

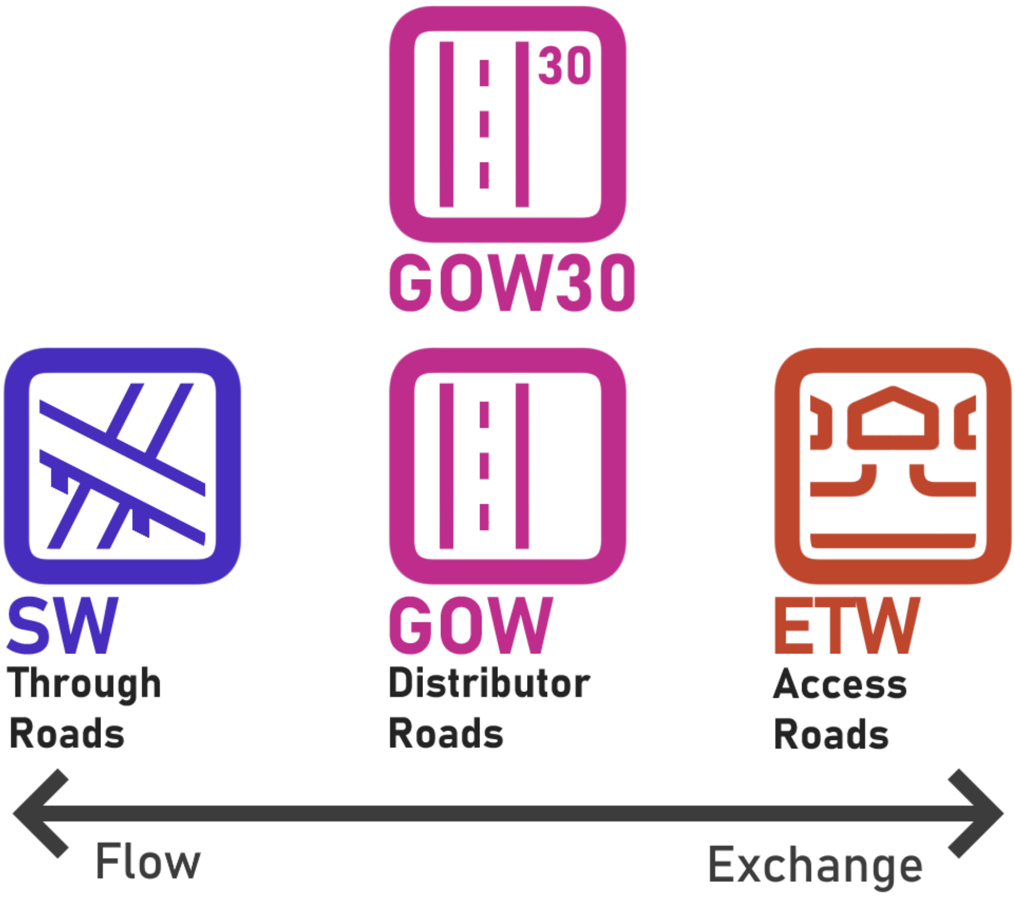

Figure 3. Road types under *Duurzaam Veilig*, including GOW30. (Figure by author)

The biomechanics principle entails that traffic flows are compatible with one another in terms of speed, mass, size and level of protection (Aarts & Dijkstra 2018). This principle is split into two sub-principles: *homogeneity* and *physical forgiveness.* Homogeneity refers to the principle that in a given traffic flow, there must be as much equality as possible in terms of speed, mass, size and direction of travel. Physical forgiveness refers to the principle that both the road design and other road users that may be in the area have the ability to absorb or react to mistakes made by the driver as much as possible – this is similar to the concept of forgiving roads discussed in the theoretical framework.

Lastly, the psychology principle entails that the road network should be adjusted to the competencies and expectations of road users, especially older road users (Aarts & Dijkstra 2018). This means that the information that road users are exposed to through road layout, road environment, traffic signs and traffic rules should be understandable, believable, relevant and feasible for all traffic users.

The design principles introduced in *Duurzaam Veilig* have not universally been applied yet, which leads to the existence of so-called *grey roads.* These are roads that have an unclear function or where incompatible traffic flows coexist: for example, an urban distributor road with a 50 km/h speed limit where bikes share the road surface with cars. An example of a grey road can be seen in Figure 4.

One solution to the problem of grey roads, proposed by SWOV (Stichting Wetenschappelijk Onderzoek Verkeersveiligheid, a Dutch institute for road safety research), is the creation of a new sub-category, *GOW30* (Dijkstra & Van Petegem 2019). These would be urban distributor (GOW) roads with a 30 km/h speed limit, as opposed to the usual 50 km/h limit. This new category would be applied in places where separating bike traffic is not a realistic proposition. In essence, these roads would still be distributor roads, except with a lower speed limit – SWOV emphasises that the road should be designed such that this 30 km/h speed limit is "believable". "Believability" of a speed limit is defined here based on road design elements which invite a road user to speed up or slow down – straight road sections, speed bumps, openness of the environment, road width and the type of road surface (Aarts & Van Nes 2007). This ties back to the road design factors that may influence risky driving behaviour.

Figure 4. A "grey road": faster distributor function is combined with slower bike traffic. (Verkeersnet 2021)

The link between road design, risky driving and traffic safety has some prominence in Dutch planning practice. Spatial and road design measures play a role in the SPV (*Strategisch Plan Verkeersveiligheid 2030*, Strategic Plan for Traffic Safety 2030), a plan for road safety introduced by the Dutch government in 2018 (Ministry of Infrastructure and Water Management 2018). Road design measures are mentioned in multiple of the plan's 9 themes, notably theme 9 (Traffic Offenders), which includes measures intended to make traffic offences "practically impossible" – examples are tighter turns, roundabouts and speed bumps (Ministry of Infrastructure and Water Management 2018). The plan also emphasises the need for "believable" speed limits that match up to the road's design (and, conversely, road design features that match up to the speed limit) – lower speed limits are accompanied by road design features that invite a road user to slow down (Aarts & Van Nes 2007).

3.2 Data Collection

3.2.1 Data Sources

This research utilises a number of secondary datasets, some of which are publicly available. An overview of the various data sources used in this research is given:

1. **ANWB Veilig Rijden dataset**
   The *ANWB Veilig Rijden* dataset is an anonymised dataset based on data collected by the ANWB, the main automobile association in the Netherlands, through its *Veilig Rijden* ("Safe Driving") vehicle insurance plan. This plan includes a smartphone app which collects data on the user's driving behaviour through the phone's built-in sensors. The dataset contains point data of risky driving incidents of four types: *harsh cornering, speeding, aggressive braking* and *aggressive acceleration.* The dataset contains data collected between January 1st, 2017 and July 19th, 2023. It was provided by the ANWB for the purpose of this research.
   It should be noted that the *Veilig Rijden* insurance plan is specifically targeted at drivers who are committed to safe driving – measurements from the smartphone app are used to grant customers a discount on their insurance. It is therefore likely that the drivers represented in the dataset are not a representative sample of the general population of Dutch drivers. However, as this research aims to measure the factors underlying risky driving behaviour, rather than draw conclusions about the *occurrence* of risky driving in the general Dutch population, this is judged to not be an issue.

2. **BRON (Bestand geRegistreerde Ongevallen Nederland)**
   The *Bestand Geregistreerde Ongevallen Nederland* ("Dataset Registered Accidents Netherlands) is a dataset published by *Rijkswaterstaat*, the Dutch executive agency for road infrastructure and flood management. It is a national dataset of all traffic accidents in the Netherlands which have been reported by either the Dutch police or Rijkswaterstaat's road inspectors. Much information about individual accidents is also available, such as the number of deaths or injuries from a traffic accident. The data in this dataset is linked to the road segments in the NWB dataset. This dataset is publicly available.

3. **NWB (Nationaal Wegenbestand)**
   The *Nationaal Wegenbestand* ("national road database") is a dataset published by the Dutch Ministry of Infrastructure and Water Management. It is a national dataset containing every road managed by the Dutch state, provinces, municipalities and water boards. The set is divided into road segments and contains data on road width, road narrowing, the presence of roadside trees, width of the road median and whether a road is within city limits or not. This dataset is publicly available.

4. **WKD (Wegkenmerkendatabase)**
   The *Wegkenmerkendatabase* is a group of datasets linked to the NWB which contain various properties of road segments. Of note for the purposes of this research are the datasets on maximum speed, road category, road narrowing, road types and roadside trees.

5. **CBS Wijk- en buurtkaart**
   The *Wijk- en buurtkaart* (District and neighbourhood map) is a geographical dataset published by CBS (the Dutch statistical agency). It contains data on the boundaries of each neighbourhood in the Netherlands, plus statistics about these neighbourhoods. This dataset is publicly available.

6. **NDW (Nationaal Dataportaal Wegverkeer)**
   The *Nationaal Dataportaal Wegverkeer* is a partnership of 19 Dutch government partners which distributes data on mobility and public space. Measured historical data on traffic intensities is provided through the NDW's *Dexter* data portal. This data is used to estimate traffic intensities for roads, which are used as a control variable.

The exact ways these datasets are used will be elaborated in the rest of this chapter. Tables 1, 2, 3 and 4 give an overview of the relevant data fields used from each dataset.

Table 1. Relevant data fields from the ANWB dataset.

Name	Format	Description
WVK_ID	Nominal	ID of road segment on which the event took place; corresponds to the NWB dataset.
categorie	Code, nominal	Type of risky driving event: ● *HARSH CORNERING* ● *SPEED* ● *BRAKING* ● *ACCELERATING*

Table 2. Relevant data fields from the BRON dataset.

Name	Format	Description
WVK_ID	Nominal	ID of road segment on which the accident took place; corresponds to the NWB dataset.
AP3_CODE	Code, nominal	Code for type of road accident. There are three categories: ● *UMS* (*"Uitsluitend Materiële Schade"*, only material damage) ● *LET ("Letsel"*, injury) ● *DOD* (*"Dodelijk"*, deadly accidents)

Table 3. Relevant data fields from the NWB and WKD datasets.

Name	Format	Description
maxshd	Ratio	Maximum speed on a road segment in km/h.
breedte	Ratio	Median width of a road segment, in metres.
vrsml	Nominal	Whether this road segment has a road narrowing or not.
weg_cat	Code, nominal	Category of this road. These roughly correspond to the road types prescribed by *Duurzaam Veilig*, although there are more categories: ● *Autosnelweg* (highway) ● *Autoweg* (through road) ● *Regionale weg* (regional road) ● *Lokale weg* (local road) ● *Stadshoofdweg* (main urban road) ● *Straat* (street) ● *Erf* (private road) ● *Onverharde weg* (unpaved road)
aant_bomen	Ratio	Number of trees within 10m of the road segment.

Table 4. Relevant data fields from the CBS dataset.

Name	Format	Description
OAD	Ratio	Address density of the neighbourhood, in addresses/km^2
P_MGEZW	Ratio	Percentage of apartments in the neighbourhood.
P_WONV2000	Ratio	Percentage of homes built after 2000 in the neighbourhood.

3.2.2 Outcome Variables: Risky Driving and Traffic Accidents

For data on risky driving, this research relies on *naturalistic* driving data. A distinction can be made between naturalistic driving data and driving data based on surveys. Naturalistic driving data refers to data gathered directly from observation, which avoids biases inherent in self-reported data on acts such as speeding (Perez et al. 2021). Based on the available data, this research utilises a narrow and specific definition of risky driving. Four types of risky driving behaviour are distinguished: *harsh cornering, speeding, aggressive braking* and *aggressive acceleration*. These risky driving items pertain specifically to rough handling of the vehicle at a specific time and place, rather than more general risk factors such as driving under the influence of alcohol or car racing.

Data on traffic accidents is gathered from the BRON dataset (Rijkswaterstaat n.d.). BRON divides accidents into three types based on their effects. "*Uitsluitend Materiële Schade"* (only material damage) is used for accidents that did not cause deaths or injury. *"Letsel"*, injury, is used if at least one person involved in the accident was admitted to a hospital or treated in an intensive care facility (Rijkswaterstaat - CIV 2022). *"Dodelijk"*, deadly, is used for accidents that caused the death of at least one person within 30 days after the accident (CBS, n.d.b).

3.2.3 Independent Variables

This section lists each independent variable and how it was derived from the secondary data. Modelling traffic intensity was a more complex process, which is described separately in section 3.2.4.

- ***Road Type*** was calculated from the *weg_cat* variable in the WKD dataset. *Through road* is recoded to *through road*; *main urban road* and *regional* *road* are recoded to *distributor road*; and *local road* and *street* are recoded to *access road.* All other road types in the WKD dataset are excluded from the research. Of note is that a small number of roads with either missing data or the type "other" remains.

- ***Maximum Speed*** is taken directly from the WKD dataset.
- ***Has Road Narrowing*** is taken directly from the WKD dataset. In some cases, the WKD dataset splits larger road segments into smaller sub-segments to report data more accurately. In these cases, if at least one of the sub-segments contains a road narrowing, the road segment is marked as having a road narrowing.
- ***Tree Density on Road Segment*** is calculated by dividing the total amount of trees on the road segment (given in the WKD dataset) by the total length of the road segment (calculated manually in QGIS). This gives a measurement of the number of trees per metre of road.
- ***Mean Width on Road Segment*** is taken directly from the WKD dataset.
- ***Local Node Density*** was calculated by taking the amount of nodes (intersections of road segments) within a 200 metre buffer of each road segment and dividing it by the total area of the buffer. The 200 metre buffer was chosen as this is judged to represent, roughly, the portion of the road network that a road user is directly affected by. This gives a measurement of the amount of nodes per square kilometre in the area of the road segment, which represents the density of the local road network.
- **Address Density** is taken from the CBS dataset. Each road segment is spatially joined to a neighbourhood in the CBS dataset using QGIS. The *OAD* field is then linked to each road segment. ***Percentage of Apartments*** and ***Percentage of homes built after 2000*** are determined the same way, from the *P_MGEZW* and *P_WONV2000* fields, respectively.
- **Traffic Intensity** was derived from a weighted average of modelled traffic intensity based on space syntax analysis and traffic intensity measures from the *NDW (Nationaal Dataportaal Wegverkeer)*. The exact modelling process is described in section 3.2.4.

3.2.4 Modelling Traffic Intensity

Traffic intensity (i.e. the amount of vehicles on a given segment of road in a given period of time) is an important variable in studying risky driving and traffic safety, as a higher number of road vehicles can reasonably lead to a corresponding higher amount of risky driving incidents and traffic accidents. The province of Groningen has no publicly available data on traffic intensity that covers all road segments, modelled or measured. This necessitates approximating traffic intensity for this research.

Traffic intensity is approximated based on a weighted average of traffic intensities collected from a secondary data source and intensity modelled through space syntax analysis. The exact process of conducting this analysis will be elaborated later in this section. Traffic intensity measures are sourced from the NDW (Nationaal Dataportaal Wegverkeer). A number of road segments of each road type were sampled from the NDW in order to calculate averages per road type, with the aim to create a somewhat representative measurement of the traffic intensity this road type would experience. The average measured traffic intensity per road type is given in Table 5.

Table 5. Corresponding traffic intensity for each road segment type, based on an average of intensities gathered from the NDW dataset.

Road Type	**Intensity (cars/weekday)**
Autosnelweg (highway)	*[Not included in research]*
Autoweg (through road)	20709,5
Regionale weg (regional road)	5261,0
Lokale weg (local road)	664,1
Stadshoofdweg (main urban road)	3431,7
Straat (street)	433,0
Erf (private road)	*[Not included in research]*
Onverharde weg (unpaved road)	*[Not included in research]*

Angular Analysis is “a method for the quantification of a spatial layout for the purposes of prediction of movement through or occupancy of the space” (Turner 2000, p. 1). More broadly, it is part of a broader set of techniques known as *space syntax*, which aim to analyse spatial configurations. Space Syntax works on the assumption that a body moving through a given space will aim to travel in as straight a line as possible (Turner 2000). Angular Analysis then aims for the lowest angle between road segments on a route. Based on this assumption, a path between two points in a network can be calculated. If this process is repeated many times for many different points, a *choice* measurement per road segment can be calculated, which shows the amount of paths running through this road segment. The results of

Angular Analysis are demonstrably correlated with actual traffic flows (Serra & Hillier 2019), which means that it is a viable tool to provide a basic approximation of traffic intensities.

The program used for conducting angular analysis in this research is *DepthMapX* (University College London n.d.). As doing analysis on the entire road network of the province of Groningen is very computationally demanding, the road network was split up by municipality in order to conduct the analysis on smaller, more manageable pieces of road. This division can be seen in Figure 5. It should be noted that this does lead to some loss of accuracy, especially near the borders between municipalities. However, this appears to be the most realistic method of modelling traffic intensity, and as the results are intended to be used mainly as a control variable, it is not of the highest importance that the results are absolutely accurate. The result of the space syntax analysis is shown in Figure 6.

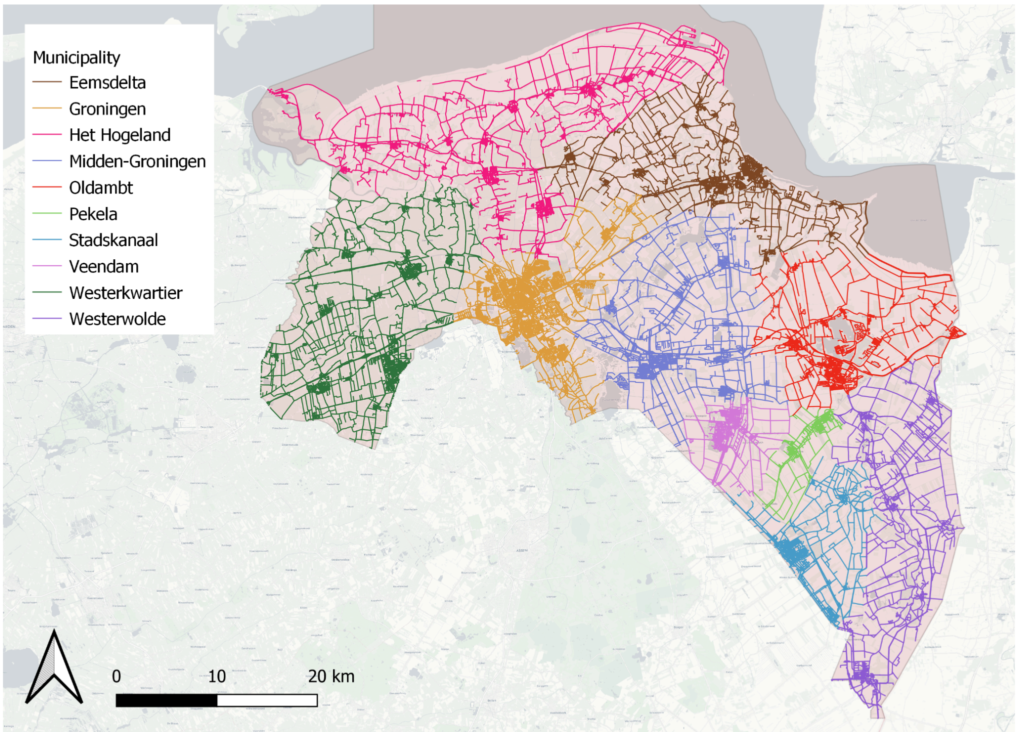

Figure 5. Division of road segments in Groningen based on municipalities.

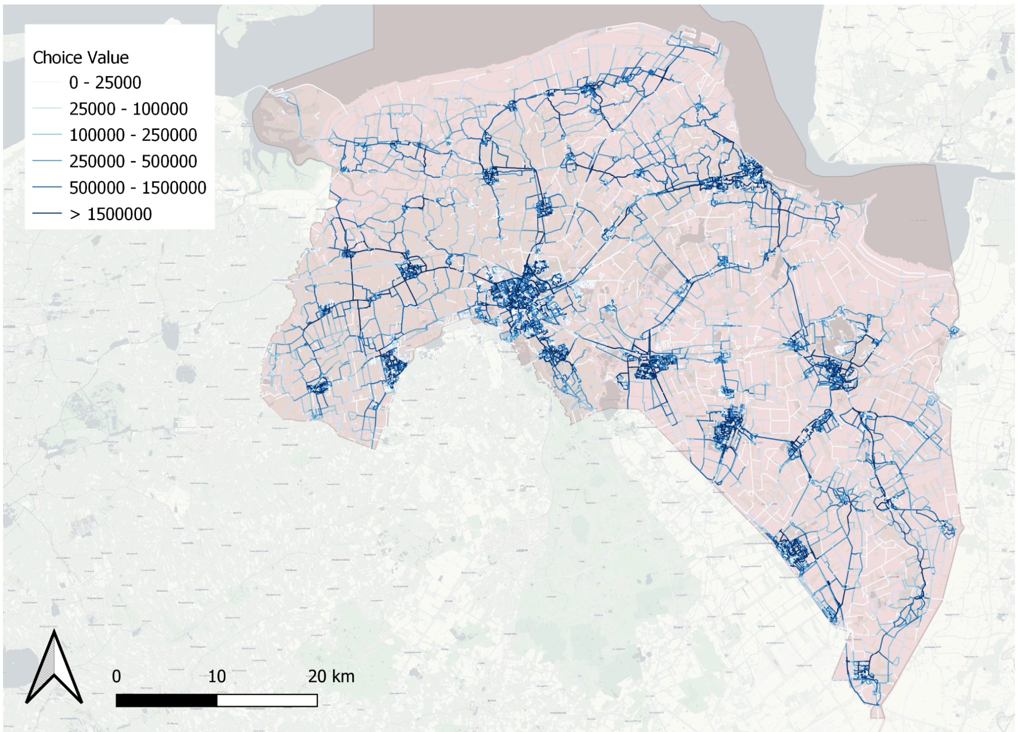

Figure 6. Choice value (5000m) for road segments in Groningen.

These modelled values were then weighted by measured traffic data to produce a final modelled measurement of traffic intensity. This simply consists of multiplying both values with one another. The final values derives from this process are given in Figure 7.

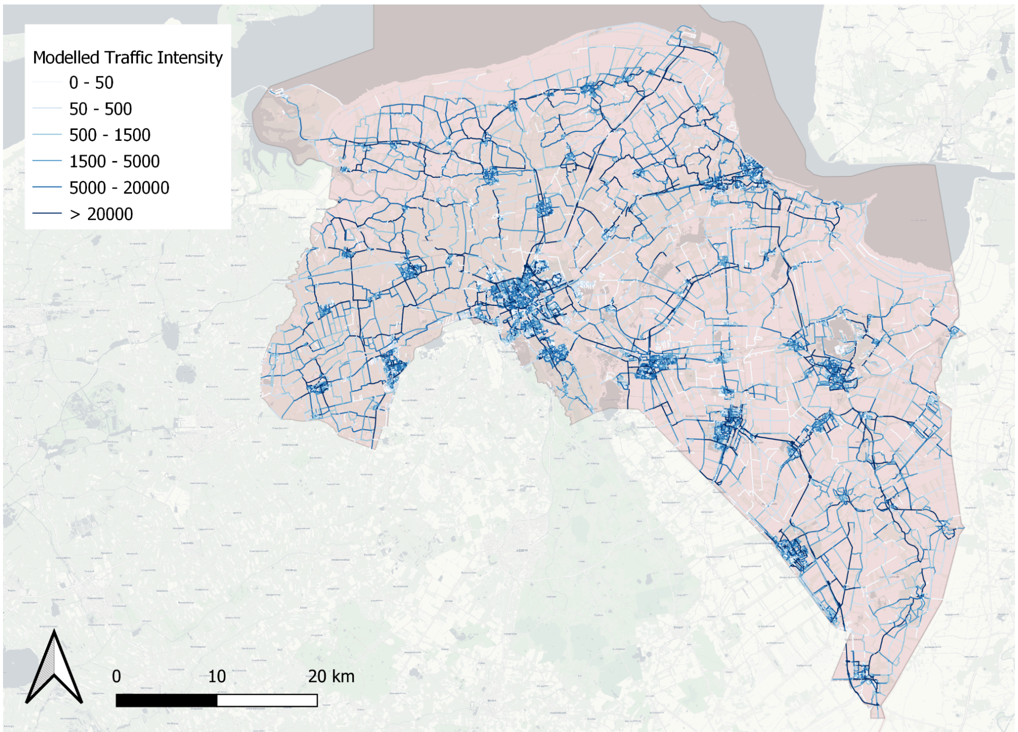

Figure 7. Modelled Traffic Intensity for road segments in Groningen (Vehicles/work day)

3.2.5 Joining Risky Driving, Traffic Accidents and Road Segments

In this research, road segments make up the basic unit of analysis. Road segments make up the basic unit of the NWB dataset, and other datasets such as the ANWB dataset and BRON dataset refer to these same road segments. Road segments are parts of roads, with boundaries between road segments being at, for example, intersections or curves in a road. The average length of a road segment in the research area is 164 metres, but some can be upwards of a kilometre. Individual incidents of risky driving are joined with road segments so that the number of risky driving incidents of each type (*harsh cornering, speeding, aggressive braking* and *aggressive acceleration*), as well as total numbers, can be aggregated per road segment. Traffic accidents are also aggregated per road segment. Both the ANWB dataset and BRON datasets already contain road segment IDs where risky driving events and traffic accidents took place, corresponding to the IDs used in the NDW dataset.

The numbers and types of risky driving events and traffic accidents joined to each road segment are then enumerated into totals. To correspond with the timescale of the ANWB data, only traffic accidents that occurred after the 1st of January, 2017 are included. Each road segment is joined to data from the WKD dataset and spatially joined to neighbourhoods in the CBS dataset.

3.2.6 Missing Data

Missing data was a major issue throughout the analysis process. One issue that affected the dataset is that there was something of a mismatch between the road segment IDs used in the NWB dataset and the IDs referred to in the ANWB dataset; this is most likely caused by road segments appearing or disappearing as roads are removed, rerouted, constructed or renovated – the data in the ANWB dataset ranges from 2017 to 2023, while the NWB dataset is based on the road network as it was in September 2022, as this was the earliest date where all data was available. This mismatch means that some road segments have risky driving data, but cannot be linked to other variables. This issue affects 15.4% of all cases.

On low-traffic roads, the amount of risky driving incidents even over the 6-year period covered by the ANWB dataset is rather low. This means that only using risky driving data from after 2022 would result in significant amounts of information being lost on large numbers of road segments, as these low-traffic road segments might have no cases of risky driving at all in the 2022-2023 period. It was therefore decided to use the entire dataset spanning 2017-2023, despite the issue of missing data.

Since almost no data is available for these cases, data imputation is not a realistic option. It was therefore decided to not take these cases into account in the analysis. Of note is that in order for a road segment to appear in the aggregated ANWB dataset but not the NWB dataset, this segment must have at least one incident of risky driving. This means that the mean number of risky driving incidents for road segments affected by this issue is 54.62, much higher than the dataset's overall average of 24.65. If only taking cases with at least one risky driving incident into account, this average rises to 49.10, which lessens this gap. Nonetheless, not having taken these cases into account could affect the results of this research.

Some missing values remain, mainly because many variables in the WKD dataset are incomplete. An overall summary of missing values is given in Figure 8, and a table of percentages of missing cases is given in Table 6. Of note here is the very high number of missing values for tree density and, to a lesser extent, road narrowings and road width, which would create unsatisfactory results if the missing values were deleted listwise – listwise deletion means an entire case gets excluded from the analysis if even a single value is missing. Data imputation is also not a realistic option because tree density has such a high number of missing values, and little relation to other variables. Therefore, pairwise deletion was used for the analyses – pairwise deletion only excludes cases if one of the particular variables being evaluated in a model is missing. This creates ambiguity in the exact sample size, but does improve statistical power by increasing the number of cases available for the analysis.

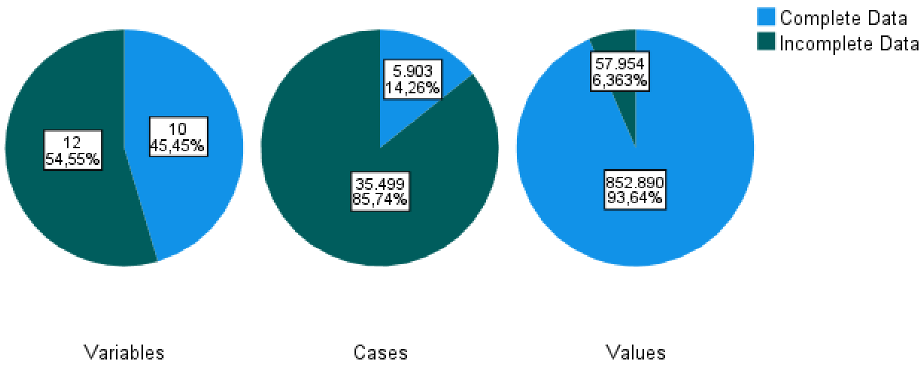

Figure 8. Summary of missing values before imputation. *Variables* shows the number of variables that have complete data, *cases* shows the number of cases that have complete data and *values* shows how many data fields are complete or missing in total.

Table 6. Number and percentage of missing variables.

Variable	Missing values (N)	Missing values (%)
	(Total: 41402)	(100%)
Density of trees on road segment	32571	78.7%
Contains Road Narrowing	7660	18.5%
Mean width of road segment	7660	18.5%
Modelled Traffic Intensity	2248	5.4%
Percentage of homes built after 2000	2008	4.9%
Percentage of apartments	2008	4.9%
Other Road *(Dummy variable)*	890	2.1%
Through Road *(Dummy Variable)*	890	2.1%
Distributor Road *(Dummy Variable)*	890	2.1%
Maximum Speed of road segment	490	1.2%
Maximum Speed is 70	490	1.2%
Address Density	149	0.4%

3.3 Analysis

3.3.1 Exploratory Analysis and Preliminary Testing

Descriptive statistics for the dependent variables are shown in Table 7. Of particular note is the strong difference in the frequency of different types of risky driving and traffic accidents. Speeding incidents make up an outright majority of all risky driving incidents in the dataset (538,181 of 817,681 incidents), and, similarly, accidents with only material damage make up a large percentage of all traffic accidents (6007 of 7545 accidents). This effect is illustrated in Figure 9. The large variation in number of observations for the different categories of risky driving incidents and traffic accidents means that some variables may prove easier to model than others: for instance, 54 fatal traffic accidents occurred in the province of Groningen over the period 2017-2022 – this low of a number of observations over 41,402 road segments only gives limited information.

Table 7. Descriptive statistics for the independent variables.

	N	Min.	Max.	Sum	Mean	Std. Deviation	Variance	Skewness	Kurtosis
Total number of Risky Driving Incidents	41402	0	23040	817681	19.75	187.639	35208.400	62.118	6264.132
Number of Speeding Incidents	41402	0	11950	538181	13.00	125.968	15868.035	42.388	2973.671
Number of Harsh Acceleration Incidents	41402	0	35	2631	0.06	0.523	0.274	22.303	923.995
Number of Harsh Braking Incidents	41402	0	213	23740	0.57	3.540	12.534	28.390	1268.833
Number of Harsh Cornering Incidents	41402	0	23021	253129	6.11	136.452	18619.174	127.553	20215.051
Total number of Traffic Accidents	41402	0	35	7545	0.18	0.747	0.558	10.109	216.280
Number of Accidents with only material damage	41402	0	34	6007	0.15	0.640	0.410	11.473	300.872
Number of Accidents with injuries	41402	0	5	1484	0.04	0.225	0.051	8.423	98.778
Number of Deadly Accidents	41402	0	3	54	0.00	0.038	0.001	34.108	1514.143

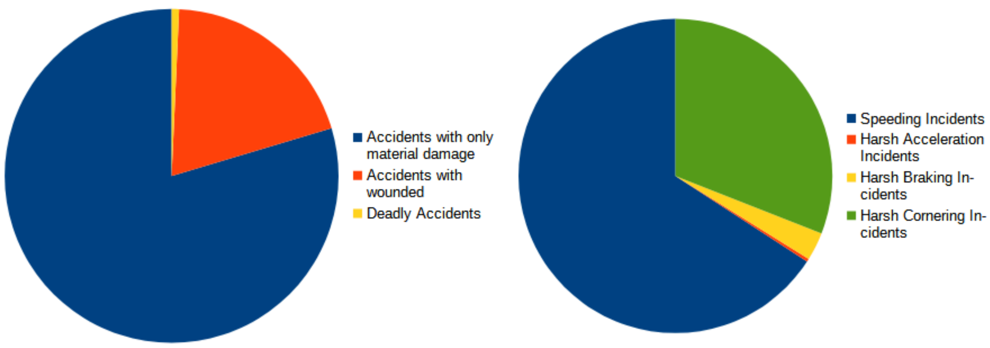

Figure 9. Pie charts showing the frequency of the various categories that make up traffic accidents and risky driving behaviour.

Descriptive statistics for the numerical independent variables are given in Table 8.

Table 8. Descriptive statistics for numeric independent variables.

	N	Min.	Max.	Mean	Std. Deviation	Variance	Skewness	Kurtosis
Maximum Speed of road segment (km/h)	40912	15	100	42.09	16.589	275.193	1.141	0.476
Density of trees on road segment (trees/m)	8831	0.000	1.348	0.058647	0.0750873	0.006	3.235	32.915
Mean width of road segment (m)	33742	0.00	19.80	5.2885	1.51256	2.288	1.135	4.221
Local Node Density (points/km2)	41402	0.00	343.25	84.9537	59.84324	3581.213	0.630	0.111
Address Density (addresses/km2)	41253	6.00	6548.00	960.3758	1283.75946	1648038.340	2.471	6.180
Percentage of Apartments	39394	0	99	20.51	25.189	634.488	1.552	1.427
Percentage of Homes built after 2000	39394	0	100	15.10	18.920	357.959	3.076	10.236
Modelled Traffic Intensity	39154	0.00	2062200.65	15410.7700	59567.22845	3548254705.218	13.110	279.093

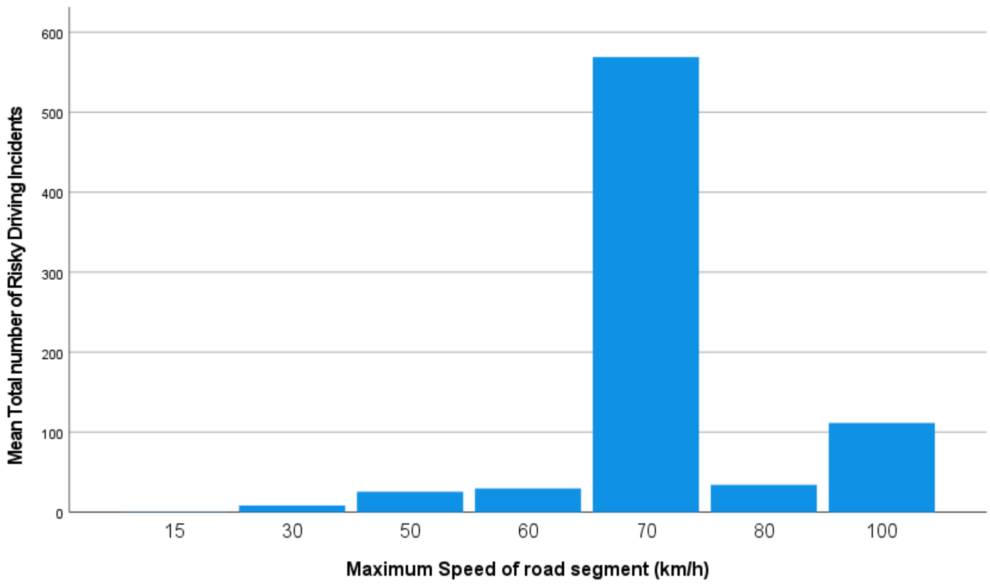

Figure 10. Bar chart of mean number of risky driving incidents

One notable phenomenon that became apparent during exploratory analysis is that the occurrence of risky driving incidence peaks strongly around a speed limit of 70 km/h. This effect can be observed in Figure 10. Because of this observation, a categorical variable was created that indicates whether a road has a speed limit of 70 or not in order to capture the possible effect that this speed limit has on risky driving and/or traffic accidents in the models.

Frequencies for all categorical independent variables are given in Table 9. For all categorical variables, one category seems to dominate: access roads, roads with a speed limit other than 70, and roads without a road narrowing. As access roads are by far the most common road type, access road is chosen as the reference type for road category's dummy coding.

Table 9. Frequency table for categorical independent variables.

		Frequency (Total: 41402)	Percent (100%)	Valid Percent (100%)
Road Category	Access Road	31333	75.7%	77.3%
	Distributor Road	8124	19.6%	20.1%
	Through Road	410	1.0%	1.0%
	Other Road	645	1.6%	1.6%
	Valid Total	40512	97.9%	100.0%
	Missing	890	2.1%	
Maximum Speed is 70	No	40701	98.3%	99.5%
	Yes	211	0.5%	0.5%
	Valid Total	40912	98.8%	100.0%
	Missing	490	1.2%	
Contains Road Narrowing	No	33346	80.5%	98.8%
	Yes	396	1.0%	1.2%
	Valid Total	33742	81.5%	100.0%
	Missing	7660	18.5%	

3.3.2 Statistical Analysis

Two analysis methods are used in this research. For research questions one or two, which pertain to the determinants of risky driving incidents and traffic accidents respectively, multiple linear regression is used. For research question three, on the relationship between risky driving and traffic accidents, a Spearman Rank-Order Correlation is used. This is because the literature does not clearly demonstrate the direction of the effect – that is, risky driving may impact traffic accidents, and the other way around. Since neither the risky driving data nor the accident data are normally distributed, (see Table 10, significance levels for normality tests are below 0.05 for each dependent) a non-parametric test – a Spearman Rank-Order Correlation Coefficient – is used.

Table 10. Results of a Kolmogorov-Smirnov test of normality on the dependent variables. A Kolmogorov-Smirnov test is used due to the very large sample.

	Statistic	df	Sig.
Total number of Risky Driving Incidents	0.447	8043	0.000
Number of Speeding Incidents	0.446	8043	0.000
Number of Harsh Acceleration Incidents	0.514	8043	0.000
Number of Harsh Braking Incidents	0.442	8043	0.000
Number of Harsh Cornering Incidents	0.476	8043	0.000
Traffic Intensity (vehicles/work day, measured)	0.335	8043	0.000
Maximum Speed of road segment (km/h)	0.389	8043	0.000
Number of trees on road segments	0.296	8043	0.000
Density of trees on road segment (trees/m)	0.219	8043	0.000

4. Results

Three sets of tests were conducted: the determinants of (various types of) risky driving behaviour, the determinants of (various types of) traffic accidents and correlations between risky driving and traffic accidents. These three sets of tests are covered in sections 4.1, 4.2 and 4.3, respectively.

In this chapter, the independent variables are split into three categories:

1. *Road Design Variables*, which includes variables that relate to design at the level of a single road: road type, maximum speed, road narrowings, tree density and road width.
2. *Urban Planning Variables,* which includes variables which relate to network and urban design at the neighbourhood level: node density, address density, percentage of apartments and percentage of buildings built after 2000.
3. *Number of Vehicles*, which includes only the modelled traffic intensity variable.

4.1 Determinants of Risky Driving Behaviour

Table 11 contains R, R square, and the significance levels for each of the Risky Driving models. Significance for each model is below the 0.05 threshold, implying that, for each model, the independent variables significantly predict the dependent variable. Additionally, it contains the Beta and standardised Beta values for each independent variable across all five models. Overall, all independent variables except for the "other road" dummy variable were found to be significant for at least one model.

4.1.1 Road Design Variables

Of the *Duurzaam Veilig* road type categories, both distributor roads and through roads showed a significant effect on the number of risky driving incidents relative to the reference category, access roads. This effect is present for all types of risky driving on through roads, and on all types except harsh cornering on distributor roads. The effect appears to be rather strong: for a distributor road, roughly 28.9 more risky driving incidents would be expected over the research period relative to an access road. For distributor roads, this number is roughly 161.7. *Other Road,* a catch-all variable for all roads that did not fit into one of the three *Duurzaam Veilig* categories, showed no significant effect for any of the models. Maximum speed showed no significant linear effect for risky driving as a whole, nor for harsh cornering incidents or speeding incidents

Table 11. Beta and standardised Beta values for each model. Blue indicates positive effect, yellow indicates negative. No colour indicates an insignificant effect.

		Total Risky Driving	Harsh Cornering	Speeding	Braking	Acceleration
R		0.260	0.203	0.183	0.303	0.202
R Square		0.068	0.041	0.034	0.092	0.041
Significance (p)		< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Constant		-14.936	-10.241	-4.358	-1.430	-0.201
Distributor Road	B	28.874	2.740	24.859	1.021	0.089
	Std. B	0.062	0.008	0.079	0.115	0.068
Through Road	B	161.699	65.548	92.040	3.972	0.315
	Std. B	0.086	0.048	0.073	0.112	0.060
Other Road	B	-7.868	-1.910	-5.694	-0.139	-0.012
	Std. B	-0.005	-0.002	-0.006	-0.005	-0.003
Maximum Speed	B	-0.127	0.049	-0.177	0.006	0.001
	Std. B	-0.011	0.006	-0.23	0.049	0.038
Maximum Speed is 70	B	367.672	232.723	127.669	7.053	0.383
	Std. B	0.140	0.122	0.073	0.143	0.052
Has Road Narrowing	B	34.233	6.377	27.002	0.824	-0.001
	Std. B	0.020	0.005	0.023	0.025	0.000
Tree Density on Road Segment	B	54.314	4.442	57.537	1.184	0.160
	Std. B	0.022	0.002	0.034	0.025	0.023
Mean Width of Road Segment	B	5.969	1.049	4.728	0.223	0.029
	Std. B	0.048	0.012	0.057	0.095	0.084
Local Node Density	B	-0.138	-0.007	-0.127	-0.001	0.000
	Std. B	-0.044	-0.003	-0.060	-0.020	0.005
Address Density	B	0.002	0.001	0.001	0.000	0.000
	Std. B	0.011	0.005	0.009	0.055	0.047
Percentage of Apartments	B	-0.021	0.013	-0.047	0.008	0.000
	Std. B	-0.003	0.002	-0.009	0.056	0.010
Percentage of homes built after 2000	B	0.250	0.236	0.014	0.001	0.000
	Std. B	0.025	0.033	0.002	-0.003	-0.002
Modelled Traffic Intensity	B	0.000	0.000	0.000	0.000	0.000
	Std. B	0.052	0.064	0.009	-0.022	0.029

The presence of a road narrowing has no significant effect on risky driving incidents overall. Road narrowings only had a significant effect on harsh braking incidents. Tree density does not have a significant effect on risky driving as a whole and only has a significant (though slight) positive effect on speeding. Road width has a significant and positive impact on risky driving behaviour in general, and on all subtypes except for harsh cornering.

4.1.2 Urban Planning Variables

Local node density has a significant and decreasing effect on the total number of risky driving incidents and on the number of speeding incidents, but not on any other risky driving subtypes. Address density only had a significant effect on harsh braking and acceleration, which it slightly increased. The neighbourhood percentage of apartments had a slight increasing effect on the number of harsh braking incidents, while the percentage of homes built after 2000 had a slight increasing effect on harsh cornering incidents and risky driving incidents overall.

4.1.3 Number of Vehicles

Modelled Traffic Intensity has a moderate positive, significant effect on the total number of risky driving incidents and on harsh cornering incidents. No other significant effects are present.

4.2 Determinants of Traffic Accidents

Table 12 contains R, R square, and the significance levels of each traffic accident model. Significance for each model is below 0.05, which again means that all models are significant for predicting (some of) the independent variable. Similar to the models in section 4.1, R square values are low, which implies that the amount of variance explained by the model is low – these models therefore have limited predictive power. R square for deadly traffic accidents is especially low, at only 0.004.

Table 12. Beta and standardised Beta values for each model. Blue indicates positive effect, yellow indicates negative. No colour indicates an insignificant effect.

		Traffic Accidents	**Only Material Damage**	**Injured**	**Deadly**
R		0.318	0.311	0.189	0.065
R Square		0.101	0.097	0.036	0.004
Significance (p)		< 0.001	< 0.001	< 0.001	0.007
Constant		-0.313	-0.244	–0.070	-0.001
Distributor Road	B	0.200	0.148	0.048	0.003
	Std. B	0.107	0.093	0.086	0.027
Through Road	B	1.188	1.034	0.138	0.015
	Std. B	0.159	0.162	0.061	0.040
Other Road	B	-0.021	-0.010	-0.011	0.000
	Std. B	-0.004	-0.002	-0.006	-0.001
Maximum Speed	B	0.003	0.002	0.001	0.000
	Std. B	0.063	0.053	0.056	0.018
Maximum Speed is 70	B	0.356	0.367	-0.003	-0.007
	Std. B	0.034	0.041	-0.001	-0.013
Has Road Narrowing	B	0.165	0.120	0.043	0.002
	Std. B	0.024	0.020	0.021	0.004
Tree Density on Road Segment	B	0.452	0.258	0.202	0.010
	Std. B	0.045	0.030	0.068	0.019
Mean Width of Road Segment	B	0.055	0.046	0.009	0.000
	Std. B	0.110	0.108	0.059	0.005
Local Node Density	B	-0.001	-0.001	0.000	0.000
	Std. B	-0.058	-0.054	-0.034	-0.017
Address Density	B	0.000	0.000	0.000	0.000
	Std. B	0.094	0.068	0.114	0.008
Percentage of Apartments	B	0.001	0.001	0.000	0.000
	Std. B	0.031	0.043	-0.014	-0.012
Percentage of homes built after 2000	B	0.000	0.000	0.000	0.000
	Std. B	-0.011	-0.011	-0.005	-0.002
Modelled Traffic Intensity	B	0.000	0.000	0.000	0.000
	Std. B	0.015	0.024	-0.018	-0.003

4.2.1 Road Design Variables

Table 12 contains Beta and standardised Beta values for each of the models. Through roads show a significant increasing effect on all types of traffic accidents, while distributor roads show a significant increasing effect on all types except fatal traffic accidents. Through roads show a particularly strong effect, with a through road being expected to have, on average, one more traffic accident over the research period compared to an access road. However, the standardised beta value for accidents with injuries is higher for distributor roads than it is for through roads.

Maximum speed being exactly 70 and maximum speed overall both have significant effects on risky driving. However, this effect of a maximum speed of 70 is relatively weak compared to its effect on risky driving incidents and, conversely, the effect of maximum speed is stronger. Road narrowings show little effect, with only a weak positive effect being reported on traffic accidents overall. Roadside tree density shows a significant increasing effect on traffic accidents as a whole, as well as on traffic accidents with only material damage and with injuries. This is according to expectations, as roadside features such as trees have historically been singled out as a cause for traffic accidents (Turner & Mansfield 1990). In contrast to their effect on risky driving, the expected effect of roadside trees is therefore replicated in this research. A notable omission is that there is no significant effect of roadside trees on deadly accidents, although this may be due to the relatively limited total number of deadly traffic accidents.

Road width shows a statistically significant and relatively strong positive effect on all types of traffic accidents, except for deadly accidents. Based on standardised Beta values, road width is the second strongest predictor of the total number of traffic accidents, behind only road type. For every added metre of width, a road is expected to have 0.055 more traffic accidents over the research period. This result stands in contrast to the application of wider roads and lanes for the purpose of improving road safety, a technique that has historically been applied in, for example, the United States (Dumbaugh & Gattis 2007). The effect is weaker on injury accidents, which is in line with previous research by Marshall & Garrick (2011).

4.2.2 Urban Planning Variables

As with risky driving, local node density has a significant effect on the number of traffic accidents on a road segment. A higher node density (that is, a denser road network in the surrounding 200 metres) is associated with less expected traffic accidents, traffic accidents with only material damage and traffic accidents with injuries on this road segment. This is in line with expectations, given that denser networks have been associated with a lower incidence of traffic accidents in previous research (Marshall & Garrick 2011).

Address density has a significant effect on traffic accidents, with higher address density being associated with higher expected numbers of total accidents, accidents with material damage and injury accidents. One reason for this may be the higher amount of foot traffic in densely built-up areas compared to less dense areas. The percentage of apartments and percentage of homes built after 2000 have little notable effect, however: the only significant effect reported is a slight increase in the expected number of accidents with material damage on road segments in neighbourhoods with a higher percentage of apartments. It appears that, when controlling for address density, the exact nature of the built-up area has little effect on traffic accidents.

4.2.3 Number of Vehicles

Modelled traffic intensity has absolutely no significant effect on traffic accidents, which is a highly notable result. The number of vehicles was expected to contribute to numbers of traffic accidents through traffic intensity, given that it implies more road users to potentially be involved in an accident. It is possible that this result is due to the limitations of modelled traffic intensity data, or due to the fact that other variables which may be associated with traffic intensity (such as road type or width) already control for traffic intensity in the model.

4.3 Correlations between Risky Driving and Traffic Accidents

Table 13 shows the results of a Spearman rank-order correlation between Traffic Accidents and Risky Driving. The significance values in the table show that risky driving is correlated with traffic accidents, and every individual type of risky driving is correlated with every individual type of traffic accident, as all significance values are below 0.05. All correlations are relatively weak, however, and the strength of the correlation differs somewhat between different types of risky driving and traffic accidents.

Overall, of the various types of risky driving, harsh braking is most strongly associated with total traffic accidents. From there, in descending order, speeding and harsh cornering are also correlated with traffic accidents, with harsh acceleration showing the weakest correlation. This same pattern (harsh braking, speeding, harsh cornering and harsh acceleration, from most to least correlated) is also present for accidents with only material damage and accidents with injuries. Speeding is more strongly correlated with specifically fatal traffic accidents than the other types of risky driving are, although it must be pointed out that fatal accidents show very weak correlations in general, including for speeding.

Traffic accidents with only material damage are more strongly correlated with risky driving than accidents with injuries, and, respectively, accidents with injuries are more strongly correlated with risky driving than deadly accidents. The relatively higher numbers of accidents with only material damage over injury accidents and fatal accidents mean that they may show a more easily predictable regularity. Nonetheless, the difficulty of correlating more severe types of accidents complicates the interpretation of these results.

Table 13. Spearman rank-order correlation coefficients and two-tailed significance for each type of risky driving and each type of traffic accident, as well as totals. Colour-coding shows the strength of the correlation.

		Traffic Accidents	**Only Material Damage**	**Injured**	**Deadly**
Risky Driving Incidents	Correlation Coeff.	0.308	0.286	0.178	0.043
	Sig. (two-tailed)	0.000	0.000	< 0.001	< 0.001
Harsh Cornering	Correlation Coeff.	0.258	0.244	0.143	0.028
	Sig. (two-tailed)	0.000	0.000	< 0.001	< 0.001
Speeding	Correlation Coeff.	0.272	0.253	0.165	0.049
	Sig. (two-tailed)	0.000	0.000	< 0.001	< 0.001
Braking	Correlation Coeff.	0.294	0.279	0.178	0.033
	Sig. (two-tailed)	0.000	0.000	< 0.001	< 0.001
Acceleration	Correlation Coeff.	0.178	0.175	0.118	0.020
	Sig. (two-tailed)	< 0.001	< 0.001	< 0.001	< 0.001

5. Discussion

5.1 Discussion

5.1.1 Effects on Risky Driving

Each risky driving model had a significance level below the 0.05 threshold, implying that the independent variables significantly predict the dependent variable for each model. The R Square value for these models is rather low, however (all are below 0.1), which implies that the explanatory value of the models is rather low – less than one tenth of the total variance in the dependent variables can be explained by the models. This may be explained by the fact that individual (such as psychology and age) and environmental (such as weather and time of day) factors were not included in this research, or by limitations inherent to the data (such as missing data for some variables, or the use of modelled rather than directly measured data on traffic intensity).

It was found that the amount of risky driving incidents on a road segment is significantly affected by a number of spatial factors: road type, maximum speed being 70, mean width of the road segment, traffic intensity and the percentage of homes built after 2000 all have an increasing effect on the amount of risky driving incidents, with road type and a speed limit of 70 having the strongest effects, relatively. The only spatial factor that was found to decrease the amount of risky driving incidents is local node density: road segments located in areas with dense road networks are expected to experience less risky driving incidents. A number of factors were also found to have no significant effect: address density, maximum speed, road narrowings, the percentage of apartments and roadside trees had no significant effect on the number of risky driving incidents as a whole, although some had a significant effect on specific types of risky driving incidents.

Road type has a significant and relatively strong effect on risky driving incidents. Compared to the reference category (access roads), through roads have a significant increasing effect on risky driving incidents overall, and on each subtype of risky driving. Distributor roads have a significant increasing effect on risky driving overall and all subtypes except harsh cornering. *SWOV* identifies distributor roads as a safety risk if infrastructure such as cycling lanes is not properly separated (SWOV 2023a), and this result is relevant to this observation: spatial interventions, such as the proposed GOW30 category (Dijkstra & Van Petegem 2019), may be relevant to increasing road safety on this road type – however, as will be noted later, speed limit shows no significant effect on risky driving, which somewhat calls into question the effectiveness of a road category with a different speed limit.

A very notable effect is the concentration of risky driving incidents of all types on roads with a speed limit of 70 km/h. This result creates both questions for future research, as well as a challenge to planners. One fact that may contribute to the incidence of risky driving on these roads is that 70 km/h is a relatively uncommon speed limit: it is only present for 0.5% of all roads in the sample. Road users not being used to this speed limit could be an explanation for it increasing the frequency of speeding incidents – however, a speed limit of 70 km/h is actually associated more strongly with harsh cornering and harsh braking.

Maximum speed overall showed no significant linear effect for risky driving as a whole, however, nor for harsh cornering incidents or speeding incidents. This is not in line with expectations: previous research suggests that speeding is more common at lower speed limits (Perez et al. 2021). However, it did show a significant (but slight) effect on harsh braking and acceleration incidents. It is possible that the effect of maximum speed is not present when other related factors, such as address density or road type, are considered.

A surprising result is that the presence of a road narrowing has no significant effect on risky driving incidents overall. The only type of risky driving behaviour that road narrowings are associated with is harsh braking, which it slightly increases – a road with a road narrowing is expected to have 0.8 more incidents of harsh braking over the research period (which may be because road narrowings might prompt road users to brake). Given that road narrowings are frequently used as a traffic-calming measure (Gonzalo-Orden et al. 2016), the expected result would be that a road narrowing is associated with less risky driving overall. This may not be represented in the model because of limitations in the data – only the presence of a road narrowing is represented in the data, not the total number, nor the individual characteristics of each road narrowing.

Tree density does not have a significant effect on risky driving as a whole and only has a significant (though slight) positive effect on speeding. This is not according to expectations, as the literature suggests that roadside trees reduce driving speed (Yu, Chen & Bao 2019) and can encourage safer driving behaviour (Mok, Landphair & Naderi 2006). One possible explanation that this expected effect does not translate into the model is the relatively low amount of data for roadside trees: a majority of road segments had missing data for this field, as described in section 3.4.3. Nonetheless, these findings may demonstrate that the role of roadside trees in driving behaviour is more multifaceted than initially anticipated.

Road width has a significant and positive impact on risky driving behaviour in general, and on all subtypes except for harsh cornering. This is according to expectations, as existing literature suggests that wider roads “invite” road users to higher speeds and riskier behaviours (Ewing & Dumbaugh 2009). The effect being absent for harsh cornering incidents may be explained by the fact that wider roads allow road users more space to engage in wider, safer cornering manoeuvres.

The density of the local road network has a decreasing effect on total risky driving behaviour and on speeding, but no significant effect on other types of risky driving. Every added point (node) per square kilometre creates an expected reduction of -0.138 risky driving incidents or -0.127 speeding incidents. This is largely in line with expectations based on previous research, which suggest that denser road networks generally lead to lower driving speeds (Marshall & Garrick 2011). Address density had a very slight increasing effect on harsh cornering and harsh acceleration incidents, possibly because drivers have to brake and accelerate more often in densely built-up areas because of driveways and roadside buildings, but had no significant effect on other types of risky driving or risky driving overall. A higher percentage of apartments is associated with slightly higher numbers of harsh braking incidents, while a higher percentage of homes built after 2000 is associated with more harsh cornering incidents, as well as with more risky driving incidents in general. This latter result may suggest that newer urban forms (i.e. those built after the year 2000) are more likely to cause risky driving.

Modelled Traffic Intensity, representing the number of vehicles, has a moderate positive effect on the total number of risky driving incidents, and on harsh cornering incidents specifically. Other types of risky driving show no significant effects. This is a somewhat surprising result, as traffic intensity was added to the model in order to control for the (seemingly) logical fact that road segments with higher levels of traffic would also display higher numbers of risky driving. The absence of this effect may be explained by the limited accuracy of modelled, rather than directly measured, data on traffic intensity.

One road design factor which may significantly impact risky driving behaviour (but was not included in this research) is road curvature. Road curvature is identified as a risk factor for risky driving in, for example, Jafarpour & Rahimi-Movaghar (2014). The absence of this factor means that the model likely does not cover -all- aspects of road design.

5.1.2 Effects on Traffic Accidents

The number of traffic accidents on a road segment is significantly affected by various factors. Road type, maximum speed, maximum speed being 70, road narrowings, roadside trees, mean width of the road segment and address density were all found to have an increasing effect on the number of traffic accidents, with road type, road width and address density having the strongest effects, relatively. As with risky driving incidents, the only factor that was found to decrease the number of traffic accidents on a road segment is local node density. Factors that were not found to have any significant effect on traffic accidents overall are the percentage of homes built after 2000 and traffic intensity.

As with risky driving, road type has a strong effect on traffic accidents. The effect of through roads is particularly notable, with a through road being expected to have, on average, one more traffic accident over the research period compared to an access road. Of note, however, is that for accidents with injuries, the standardised Beta value is higher for distributor roads. This implies that distributor roads have a greater effect on accidents with injuries compared to through roads, which distinguishes accidents with injuries from other types of traffic accidents. This also further singles out Distributor Roads as a potential area of focus for planners, as well as a potential topic for future research.

The effects of maximum speed on traffic accidents can be distinguished from its effects on risky driving. Relative to the models for risky driving, the maximum speed being exactly 70 does not have nearly as strong an effect, with significant (and rather weak) effects only being reported for accidents with only material damage and accidents overall. This suggests that the effect of maximum speed on risky driving does not necessarily directly carry over to traffic accidents. Conversely, speed limit in itself has a more prominent effect: significant effects exist on accidents with only material damage, accidents with injuries and traffic accidents as a whole. Speed limit overall has a relatively strong effect on traffic accidents compared to the speed limit being 70, while the inverse is true for risky driving incidents.

Road narrowings show little effect, with only a weak positive effect being reported on traffic accidents overall. As with risky driving, limitations in the data may provide a partial explanation for this, although it is also possible that road narrowings simply do not strongly affect the occurrence of traffic accidents.

Roadside tree density shows a significant increasing effect on traffic accidents as a whole, as well as on traffic accidents with only material damage and with injuries. This is according to expectations, as roadside features such as trees have historically been singled out as a cause for traffic accidents (Turner & Mansfield 1990). In contrast to their effect on risky driving, the expected effect of roadside trees is therefore replicated in this research. A notable omission is that there is no significant effect of roadside trees on deadly accidents, although this may be due to the relatively limited total number of deadly traffic accidents.

One final point to note with respect to traffic accidents is that deadly traffic accidents proved particularly difficult to predict. The difficulty of predicting deadly accidents may be due to the relative rarity of such accidents: only 54 deadly accidents were recorded in the province of Groningen over the research period.

5.1.3 Link between Risky Driving and Traffic Accidents

Findings suggest a correlation between the number of risky driving incidents and the number of traffic accidents on a given road segment. However, this correlation remains rather weak, and since this is a correlation, no conclusions can be drawn about the direction of the effect. A positive correlation between risky driving and traffic accidents confirms the hypothesis that risky driving is likely related to traffic accidents, but not that drivers respond to roads which are perceived as accident-prone. This may be the case because this analysis focuses on the spatial aspects of these phenomena, rather than focusing on the psychology of individual drivers.

Traffic accidents with only material damage are more strongly correlated with risky driving than accidents with injuries, and, respectively, accidents with injuries are more strongly correlated with risky driving than deadly accidents. The relatively higher numbers of accidents with only material damage over injury accidents and fatal accidents mean that they may show a more easily predictable regularity. Nonetheless, the difficulty of correlating more severe types of accidents complicates the interpretation of these results.

5.2 Reflection and Limitations

The nature of secondary data necessarily presents limitations for research of this type, as results are entirely dependent on the quality of the data being sourced. While all data used in this research is from reputable, authoritative sources, limitations exist nonetheless. First of all, missing data presented an issue throughout the research process. The most prominent example of this is roadside trees, for which data was missing for 78.7% of cases, but the issue is present to a lesser extent for other variables, such as road narrowings and road width. Missing data can reduce statistical power by decreasing the total number of cases being analysed, and, in case there is a regularity to the types of cases that are missing, can also skew the results. This fact serves to nuance the more surprising results of this research, such as the lack of effect of roadside trees on the occurrence of risky driving behaviour.

Additionally, in absence of measured traffic intensity data for use as a control variable, traffic intensity was modelled instead through a combination of secondary data and space syntax analysis. This data ended up only having a limited effect in the final models. The exact reason for this is unclear: it is possible that risky driving behaviour and traffic accidents are simply not as strongly associated with traffic intensity as anticipated, or it is possible that the modelled traffic intensity data is not of a sufficiently high quality. Another complicating factor is that the traffic modelling process does not produce a number with a definite “meaning”, that is, a certain number of cars per work day. While traffic intensity on road segments can be compared against other road segments, the models remain unclear on the exact effect of traffic intensity.

Lastly, despite the large sample size in this analysis – over 40,000 road segments with over 800,000 risky driving incidents and over 7,000 traffic accidents – the relative rarity of certain types of outcomes complicates predicting these outcomes. This issue is most prominent with fatal accidents, as only 54 fatal accidents were recorded in the BRON database in the province of Groningen over the research period. This complicated the modelling process for deadly traffic accidents, and therefore, the lack of significant effects in this model should not be taken at face value.

6. Conclusion

This research has aimed to investigate the relationship between risky driving behaviour, traffic accidents and a variety of road design and urban planning factors, focussing on the province of Groningen, the Netherlands. By comparing aggregated naturalistic data on risky driving with data on traffic accidents and spatial factors gathered from secondary sources, the research shows both that these spatial factors have significant effects on risky driving and traffic accidents, and that risky driving and traffic accidents are correlated with one another.

This research is intended as a broad overview of the effects of road design on traffic safety. It is because of this that the results of this research may carry valuable lessons for the spatial planning field, as well as possible opportunities for future research, despite the relative weakness of the models and correlations determined in this research.

For the spatial planner, some immediate conclusions can be made. The relationship between roads with a speed limit of 70 km/h and risky driving is of significant interest. The exact effect that these roads have on traffic safety should be evaluated or otherwise looked into by policymakers: if this effect is also present in other parts of the Netherlands, this may be cause for significant concern. Secondly, the results of this research call into question the effectiveness of roadside features or road narrowings in reducing the number of risky driving incidents. Given that roadside trees do seem to increase the number of traffic accidents on a road segment, this would suggest that the usefulness of "forgiving" roads that absorb mistakes by the driver could be further evaluated.

Future research may focus on either factors which were left out of this research, such as road curvature; or more specifically analyse specific factors, such as the number of vehicles or network density. Research may also look into how spatial measures affect specific road segments, for example through comparisons before and after such measures were implemented. Additionally, given the small research area and the advanced state of Dutch infrastructure, it is unlikely that these results are generalisable to the rest of the world. The link between spatial planning, risky driving and traffic accidents may be researched in other spatial contexts, such as locations outside Europe or in developing countries. Lastly, the relative importance of spatial, environmental and psychological factors in predicting risky driving or traffic accidents is well worth investigating.

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